Galactic Center Molecular Arms, Ring and Expanding Shells. I
Kinematical Structures in Longitude-Velocity Diagrams

Yoshiaki SOFUE

Institute of Astronomy, The University of Tokyo
Mitaka, Tokyo 181, Japan
sofue@mtk.ioa.s.u-tokyo.ac.jp

(To appear in PASJ Vol. 47, No.5)

Abstract

Analyzing the \((l, b, V_{\text{LSR}})\) data cube of \(^{13}\text{CO}(J = 1 - 0)\) line emission obtained by Bally et al, we have investigated the molecular gas distribution and kinematics in the central \(\pm 1^\circ\) (\(\pm 150 \text{ pc}\)) region of the Galaxy. We have applied the pressing method to remove the local- and foreground-gas components at low velocities in order to estimate the intensity more quantitatively. Two major dense molecular arms have been identified in longitude-radial velocity \((l, V)\) diagrams as apparently rigidly-rotating ridges. The ridges are spatially identified as two arms, which we call the Galactic Center molecular Arms (GCA). The arms compose a rotating ring of radius 120 pc (the 120-pc Molecular Ring), whose inclination is \(i \simeq 85^\circ\). The Sgr B molecular complex is associated with GCA I, and Sgr C complex is located on GCA II. These arms are as thin as 13 to 15 pc, except for vertically extended massive complexes around Sgr B and C. The \((l, V)\) behavior of the arms can be qualitatively reproduced by a model which assumes spiral arms of gas. Assuming a small pitch angle for the arms, we tried to deconvolve the \((l, V)\) diagram to a projection on the galactic plane, and present a possible face-on CO map as seen from the galactic pole, which also reveals a molecular ring and arms. We have estimated masses of these molecular features, using the most recent value of the CO-to-H\(_2\) conversion factor taking into account its metallicity dependency and radial gradient in the Galaxy. The estimated molecular masses and kinetic energy are about a factor of three smaller than those reported in the literature using the conventional conversion factor.

Key words: Galactic center – Galaxy – Interstellar matter – Molecular gas – Spiral arms.

1. Introduction

The galactic center region has been extensively observed in the molecular lines, par-
ticularly in the CO line emission (Oort 1977; Scoville et al 1974; Liszt 1988; Liszt and Burton 1978, 1980; Burton and Liszt 1983, 1993; Brown and Liszt 1984; Heiligman 1987; Bally et al 1987; 1988; Genzel and Townes 1987; Stark et al 1989; Güsten 1989). Besides the 4-kpc molecular ring, the CO emission is strongly concentrated in the central a few degree (Dame et al 1987). Moreover, the molecular gas in the central region has a strong concentration within $|l| < 1^\circ$ (150 pc) where the majority of the nuclear disk gas is confined (Scoville et al 1974; Bally et al 1987; Heiligman 1987). This high concentration of dense interstellar matter in a small region is also clearly visible in the far IR emission (e.g., Cox and Laureijs 1989) and in the CII emission (Okuda et al 1989). The radio continuum emission also indicates a highly concentrated nuclear disk of ionized gas (Altenhoff et al 1978; Handa et al 1987). On the other hand, the region between galactocentric distances $\sim 200$ pc ($l \sim 1^\circ 4$) and $\sim 2$ kpc ($15^\circ$) appears almost empty in the CO emission (Bally et al 1987; Knapp et al 1985).

The total molecular mass in the $|l| < 1^\circ$ region estimated from the CO emission amounts to $\sim 1.4 \times 10^8 M_\odot$ for a traditional CO-to-H$_2$ conversion factor, or, more probably, $\sim 4.6 \times 10^7 M_\odot$ for a new conversion factor (see section 3). On the other hand, the HI mass within the 1.2 kpc tilted disk ($l < 8^\circ$) is only of several $10^6 M_\odot$ (Liszt and Burton 1980). Hence, we may consider that the central $\sim 1$ kpc region is dominated by the molecular disk of $\sim 150$ pc ($\sim 1^\circ$) radius, outside of which the gas density becomes an order of magnitude smaller.

Various molecular gas features in the central $\sim 100-200$ pc region have been discussed by various authors, such as a disk related to the 1.2 kpc tilted rotating disk (Liszt and Burton 1980; Burton and Liszt 1992), molecular rings and spiral arms of a few hundred pc scale (Scoville et al 1974; Heiligman 1987; Bally et al 1987), and the expanding molecular ring of 200 pc radius (Scoville 1972; Kaifu et al 1972, 1974). On the other hand, Binney et al (1991) have modeled the “expanding-ring feature” or the “parallelogram” on the $(l, V)$ (longitude-velocity) plot in terms of non-circular kinematics of gas by a closed orbit model in a bar potential. It is known that the gas in this parallelogram shares only a small fraction of the total molecular mass in the galactic center: the majority of the gas composes more rigid-body like features in the $(l, V)$ plots.

The CO gas in the central 100 - 200 pc regions in nearby galaxies have been observed by high-resolution mm-wave interferometry, and their distribution and kinematics have been extensively studied (e.g., Lo et al 1984; Ishiguro et al 1989; Ishizuki et al 1990a,b). The central gas disks of galaxies appear to comprise spiral arms or circum-nuclear rings of a few hundred pc size. Such a gaseous behavior can be reproduced to some extent by theoretical simulations of accretion of gas clouds in a central gravitational potential (e.g., Noguchi 1988; Wada and Habe 1992).

In this paper, we revisit the major part of the nuclear molecular disk ($|l| <\sim 1^\circ$) by analyzing the molecular line data in the premise that the nuclear disk may comprise accretion ring or spiral structures similar to those found in external galaxies. In this paper we reanalyze the data cube of the $^{13}$CO ($J = 1 - 0$)-line emission observed by Bally et al (1987) with the 7-m off-set Cassegrain telescope of the Bell Telephone Laboratory. The distance to the Galactic Center is assumed to be 8.5 kpc throughout this paper.
2. Longitude-Velocity \((l, V)\) Diagrams

2.1. Data

The angular resolution of the observations with the Bell-Telephone 7-m antenna at \(^{13}\)CO line was 1'.7. The data used here are in a \((l, b, V_{\text{LSR}})\) cube in FITS format. The cube covers an area of \(-1^\circ.1 \leq l \leq 0^\circ.92, -21' \leq b \leq 17'\), or 300 pc \(\times\) 94 pc region for a 8.5 kpc distance. The velocity coverage is \(-250 \leq V_{\text{LSR}} \leq 250\) km s\(^{-1}\). The cube comprises 127, 39, and 183 channels at 1', 1', and 2.75 km s\(^{-1}\) intervals, respectively. We also use the CS line data in a \((l, b, V)\) cube with dimensions 151, 42, and 163 channels at intervals 2', 1', and 2.75 km s\(^{-1}\), which covers an area of \(-1^\circ \leq l \leq 4^\circ, -25' \leq b \leq 16'\), and \(-250 \leq V_{\text{LSR}} \leq 190\) km s\(^{-1}\). The intensity scale of the data is the main-beam antenna temperature approximately equivalent to brightness temperature in Kelvin. The observational details are described in Bally et al (1987, 1988). We made use of the AIPS and IRAF software packages for the reduction.

2.2. Subtraction of the Local and Foreground Components

In order to analyze molecular gas features in the Galactic Center region, we first subtract contaminations by local and foreground molecular clouds at low velocities. Since \(^{13}\)CO line is optically thin for the foreground clouds, the contaminations appear as emission stripes superposed on the galactic center emission. The subtraction of foreground emission is essential when we derive the mass and kinetic energy of molecular gas features. Such a “cleaning” also helps much the morphological recognition of features on the \((l, V)\) and \((b, V)\) diagrams.

Fig. 1a shows an \((l, V)\) diagram averaged in a latitude range of \(-17' \leq b \leq 12'\). The diagram is strongly affected by “stripes” at a low velocities elongated in the direction of longitude with narrow velocity widths, including the 3-kpc expanding arm at \(-52\) km s\(^{-1}\). In order to eliminate these stripes, we applied the “pressing method” as developed for removing scanning effects in raster scan observations (Sofue and Reich 1979). We briefly describe this method below.

Fig. 1a, b –

The original \((l, V)\) map \(M_0\) is trimmed by \(-70 \leq V_{\text{LSR}} \leq 50\) km s\(^{-1}\) to yield \(M_1\) where the local and foreground gas contribution is significant. The trimmed map \(M_1\) is smoothed only in the \(V\) direction by 5 channels (14 km s\(^{-1}\)) using a boxcar or Gaussian smoothing task, yielding \(M_2\). Smoothed map \(M_2\) is subtracted from \(M_1\) to yield \(M_3 (= M_1 - M_2)\). Map \(M_3\) is then smoothed only in \(l\) direction by 20 channels (20') (boxcar or Gaussian) to yield \(M_4\). This \(M_4\) map approximates the contribution from the local gas that is dominated by elongated features in the longitudinal direction. We then subtract \(M_4\) from \(M_1\) to obtain \(M_5 (= M_1 - M_4)\). This \(M_5\) is, thus, a map in which the local gas contribution has been roughly subtracted. \(M_5\) is then smoothed in \(V\) direction by 5 channels. Then we replace \(M_2\) by this smoothed map, and repeat the above procedures twice (or more times) until
we obtain the second (or \( n \)-th) \( M_5 \). Finally, the \(-70 \leq V_{\text{LSR}} \leq 50 \text{ km s}^{-1} \) part of the original map \( M_0 \) is replaced by \( M_5 \) to yield \( M_6 \). Now, we have a “pressed” map \( M_6 \) in which corrugations due to local gas clouds have been removed out. Fig. 1b shows the thus obtained map \( M_6 \) for the same \((l, V)\) diagram as in Fig. 1a.

We have applied this algorithm (the pressing method) to all \((l, V)\) and \((b, V)\) diagrams in the cube, and created a new \((l, b, V)\) cube, which is almost free from local and foreground contaminations. In the present paper we use this new cube. We also applied the pressing method to remove scanning effects, which had originated during the data acquisition, in every diagram such as intensity maps in the \((l, b)\) space.

By comparing the original and the thus ‘pressed’ maps, we estimated the contribution of the local/foreground emission to be 5\% of the total emission, and 9\% of the emission with \(|V_{\text{LSR}}| < 100 \text{ km s}^{-1}\). Thus, without the subtraction, the mass and energetics would be overestimated by about 5 to 9\%. Moreover, if the gas out of the disk component at \(|b| > 10'\) is concerned, this local contribution would amount to more than 10\%. Hence, the subtraction of the foreground emissions is crucial in a quantitative discussion of the features discussed in this paper.

2.3. “Arms” in Longitude-Velocity \((l, V)\) Diagrams

Fig. 2 shows \((l, V)\) diagrams near the galactic plane averaged in 4\' latitude interval after subtraction of the local/foreground components. Various features found in these diagrams have been discussed in Bally et al (1987, 1988). In this paper we highlight continuous features (ridges) traced in the \((l, V)\) diagrams. The major structures of the “disk component” at low latitude \(|b| <\sim 10'=25 \text{ pc}\) are “rigid-rotation” ridges, which we call “arms”. Fig. 3 illustrate these ridges (arms) which can be identified in the diagrams as coherent structures. In Table 1 we summarize the identified features, and describe below the individual arms. Heiligman (1987) has used these ridges to derive a rigid rotation curve. At higher latitudes \(|b| >\sim 10'\) the so-called expanding ring features at high velocities \(|V_{\text{LSR}}| > 100 \text{ km s}^{-1}\), which will be discussed in a separate paper.

2.3.1. Arm I

The most prominent \((l, V)\) arm is found as a long and straight ridge, slightly above the galactic plane at \( b \sim 2' \), which runs from \((l, V)=(0^\circ.9, 80 \text{ km s}^{-1})\) to \((-0^\circ.7, -150 \text{ km s}^{-1})\), and extends to \((-1^\circ.0, -200 \text{ km s}^{-1})\). This arm intersects the line at \( l = 0^\circ \) at negative velocity \( V_{\text{LSR}} = -40 \text{ km s}^{-1} \), indicating that the gas is approaching us at \( l = 0^\circ \). We call this ridge Arm I. A part of this arm can be traced also below the galactic plane at \( b = -0.1^\circ \), running from \((l, V)=(-0.8^\circ, 60 \text{ km s}^{-1})\) to \((0^\circ.1, -20 \text{ km s}^{-1})\). Its positive longitude part is connected to the dense molecular complex Sgr B, which is extended both in space and velocity, from \( b = -0.25 \) to \( 0.07^\circ \) and \( V_{\text{LSR}}=20 \) to \( 100 \text{ km s}^{-1} \).
2.3.2. Arm II

Another prominent arm is seen at negative latitude at $b \sim -6^\circ$, running from $(l, V) = (0.1, 60 \text{ km s}^{-1})$ to $(-0.6, -80 \text{ km s}^{-1})$. We call this ridge Arm II. It is bent at $l \sim 0^\circ.1$ and appears to continue to $(l, V) = (1^\circ, 100 \text{ km s}^{-1})$, and merges with Arm I at the Sgr B complex region. The negative longitude part also merges with Arm I, and is connected to the Sgr C complex. Arm II intersects $l = 0^\circ$ at positive velocity of $V_{\text{LSR}} = 50 \text{ km s}^{-1}$.

2.3.3. Arms III and IV

At positive latitude ($b \sim 0^\circ.01$ to $0^\circ.2$), another arm can be traced running from $(l, V) = (0^\circ, 140 \text{ km s}^{-1})$ to $(-0^\circ.15, 10 \text{ km s}^{-1})$. Its counterpart to the negative longitude side appears to be present at $(l, V) = (-0^\circ.45, -120 \text{ km s}^{-1})$ to $(-0^\circ.55, -180 \text{ km s}^{-1})$. We call this ridge Arm III. Bally et al (1988) called this the “polar arc”, and discussed its connection to Sgr A.

A branch can be traced from $(l, V) = (0^\circ.1, 60 \text{ km s}^{-1})$ to $(0^\circ, -20 \text{ km s}^{-1})$, apparently being bifurcated from Arm II at $l \sim 0^\circ.1$. This ridge intersects $l = 0^\circ$ at negative velocity ($V_{\text{LSR}} = 50 \text{ km s}^{-1}$). We call this ridge Arm IV.

2.4. “Rigid-rotation” in $(l, V)$ Plane and “Arms and Ring” in the Galactic Plane

We emphasize that “rigid-rotation” ridges in $(l, V)$ diagrams for edge-on galaxies, whose rotation curves are usually flat, are generally interpreted as due to spiral arms and rings. Indeed, the rigid-rotation ridge in the CO $(l, V)$ diagram of the Milky Way is identified with the 4-kpc molecular ring (e.g., Dame et al 1987; Combes 1992). Many edge-on spiral galaxies like NGC 891 are found to show similar $(l, V)$ ridges in HI and CO, which are also interpreted to be spiral arms and rings (e.g., Sofue and Nakai 1993, 1994).

The circular rotation velocity as defined by $V_{\text{rot}} = \left( R \frac{\partial \Phi}{\partial R} \right)^{1/2}$, remains greater than at least 150 km s$^{-1}$ from the nuclear few pc region till the 1 kpc radius region (Genzel and Townes 1987). Here, $\Phi$ is the potential and $R$ is the distance from the nucleus. Hence, the actual rotation should not be rigid at all: The rigid-rotation ridges in the $(l, V)$ plane such as Arms I to IV in the Galactic Center can thus be more naturally attributed to real arms and rings.

3. Intensity Distribution and the Galactic Center Arms

3.1. Intensity Maps and Masses

Fig. 4a shows the total intensity map integrated over the full range of the velocity
\[-250 \leq V_{\text{LSR}} \leq 250 \text{ km s}^{-1}\]. This map is about the same as that presented by Stark et al (1989), except that the local gas has been removed. Fig. 4b shows the same in grey scale and a that with the vertical scale in \(b\) direction enlarged twice.

First of all the intensity map can be used to obtain the molecular mass. However, the conversion of the CO intensity to \(\text{H}_2\) mass is not straightforward. We have recently studied the correlation of the conversion factor \(X_{12}\) for the \(^{12}\text{CO}(J = 1 - 0)\) line with the metal abundance in galaxies (Arimoto et al 1994). We have obtained a clear dependency of \(X\) on the galacto-centric distance \(R\) within individual galaxies, which is almost equivalent to the metallicity dependence. For the Milky Way we have

\[
X_{12}(R) = 0.92(\pm 0.2) \times 10^{20} \exp\left(R/R_e\right)
\]

where \(R_e = 7.1\) kpc is the scale radius of the disk. Applying this relation to the Galactic center, we obtain a conversion factor at the Galactic center as \(X_{12} = 0.92(\pm 0.2) \times 10^{20} \text{ [H}_2\text{ cm}^{-2}/\text{K km s}^{-1}]\), about one third of the solar vicinity value. We then assume that the \(^{12}\text{CO}\) and \(^{13}\text{CO}\) intensities are proportional, and estimate the ratio by averaging observed intensity ratios for the inner Galaxy at \(l \leq 20^\circ\) (Solomon et al 1979); \(I_{12\text{CO}}/I_{13\text{CO}} \simeq 6.2 \pm 1.0\). Then, we obtain a conversion factor for the \(^{13}\text{CO}\) line intensity in the galactic center region as \(X_{13}(R = 0) \simeq 5.7 \times 10^{20} \text{ [H}_2\text{ cm}^{-2}/\text{K km s}^{-1}]\), and we use this value throughout this paper.

The correction factor from the H mass to real gas mass is given by \(\mu = 1/X = 1.61\), where \(X\) is the hydrogen abundance in weight. Here, the following relation has been adopted (Shaver et al 1983): \(Y = 0.28 + (\Delta Y/\Delta Z)Z = 0.34\) in weight, where \(Z = 0.02\) is the abundance of the heavy elements and \(\Delta Y/\Delta Z = 3\) is the metallicity dependence of the helium abundance \(Y\) in the interstellar matter, and so, the hydrogen abundance is \(X = 0.62\). So, the surface mass density of molecular gas after correction for the mean weight of gas is given by

\[
\sigma \sim 14.6(\pm 3) I/\eta \text{ [M}_\odot \text{pc}^{-2}],
\]

where

\[
I \equiv \int T_A^* dv \text{ [K km s}^{-1}]
\]

is the integrated intensity of \(^{13}\text{CO}(J = 1 - 0)\) line emission and \(\eta = 0.89\) is the primary beam efficiency of the antenna. The total mass of molecular gas (including He and metals) can be estimated by

\[
M [M_\odot] = 14.6 \int I/\eta dxdy \text{ [K km s}^{-1} \text{ pc}^2].
\]

Using these relations, we have estimated the total molecular gas mass in the observed area \((-1^\circ.0 \leq l \leq 0^\circ.92, -21' \leq b \leq 17')\) after removing the local and foreground contribution to be \(4.6(\pm 0.8) \times 10^7 M_\odot\). We have also estimated the total molecular mass of the “disk” component, which comprises most of the ridge-like features in the \((l, V)\) diagrams, excluding the expanding ring feature (or the parallelogram) at high velocities

---
(|V_{LSR}| >\sim 100 – 150 km s^{-1}). The disk component has the mass $3.9 \times 10^7 M_\odot$, which is 85% of the total in the observed region. On the other hand, the expanding ring (or the parallelogram) shares only $6.7 \times 10^6 M_\odot$ (15%) in the region at |l| < 1°.

### 3.2. Ring and Arms in Intensity Maps

In order to clarify if each of the arms traced in the (l, V) diagrams (Fig. 1-3), particularly Arms I and II, is a single physical structure in space, we have obtained velocity-integrated intensity map in the (l, b) plane for each of the arms. Thereby, we integrated the CO intensity in the velocity ranges as shown in Fig. 5 individually for Arms I and II. Fig. 6 show the integrated intensity maps corresponding to Arms I and II, together with a summation of I and II. In Table 1 we summarize the derived parameters.

#### 3.2.1. Galactic Center Arms I, II

In the intensity map, Arm I can be traced as a single, thin arc-like arm from $l = 0.9$ near the Sgr B complex toward negative longitude at $l = -1.9$. We call this spatial arm the Galactic Center Arm I (GCA I). The angular extent is as long as 1.9 (280 pc) in the longitudinal direction, whereas the thickness in the $b$ direction is as thin as $\sim 5'$ (13 pc; see section 3.2.2). The Sgr B molecular complex is much extended in the $b$ direction by about 0.9 (20 pc), and composes a massive part of the arm. A “return” of this arm can be traced from $(l, b) = (0.9, 0')$ to $(0.2, -0.07)$, and is more clearly recognized in Fig. 4 at $V = 83 \sim 167$ km s^{-1}. This can be also clearly seen in the (l, V) diagram in Fig. 2 at $b \sim -0.1$. In the negative l side, the arm appears to be bifurcated at $l \sim -0.65$, and linked to Arm II. This can be more clearly observed in Fig. 4 at $V = -83 \sim 0$ km s^{-1}. The intensity in Fig. 6a has been integrated to give a total mass of molecular gas involved in GCA I (in the velocity range as shown in Fig. 5a) to be $M = 1.72 \times 10^7 M_\odot$.

Arm II can be traced as a a single bright ridge from $l \sim 0.3$ to $-0.7$, and the thickness is about 6' (15 pc), and makes GCA II. The mass of Arm II is estimated to be $1.35 \times 10^7 M_\odot$. Thus, the total mass involved in GCA I and II is estimated to be $3.07 \times 10^7 M_\odot$, and shares almost 67% of the total gas mass in the observed region, and 78% of the disk component.

#### 3.2.2. The 120-pc Molecular Ring

As shown in Fig. 4 and 6, GCA I and II compose a global ring structure, which is tilted and slightly bent. If we fit the GCA I and II by a ring, its angular extent in the major axis is $1.6$ from $l = -0.7$ to $0.9$, and so, the major axis length (diameter) is 240 pc, and the radius 120 pc. The minor axis length is estimated to be $7.9$ from the maximum separation between Arm I and II at $l \sim -0.2$ (see Fig. 7). Therefore, the inclination of the I+II ring is $i = 85^\circ$ from the minor-to-major axis ratio. The center of the ring, as
fitted by the above figures, is at \((l, b) = (0^\circ.1, 0^\circ.0)\) We call this ring the 120-pc Molecular Ring.

From these we conclude that the spatial distribution of the molecular gas associated with the principal ridges in the \((l, V)\) diagrams comprises a circum-nuclear ring of radius \(R \approx 120\) pc inclined by \(5^\circ\) from the line of sight.

3.2.3. Cross Section of the Arms

Fig. 7 shows the intensity variation perpendicular to the galactic plane across GCA I and II averaged from \(l = 0^\circ.24\) to \(-0^\circ.33\), where the arms are most clearly separated. Since the effective resolution of the present data is \((\theta^2 + \Delta b^2)^{1/2} = 2'.0\), where \(\theta = 1'.7\) is the beam width and \(\Delta b = 1'.0\) is the grid interval, the arms are sufficiently resolved. The two peaks in the figure at \(b = 1'.8\) (Arm I) and \(b = -6'.0\) (Arm II) can be fitted by a Gaussian intensity distributions as \((T_{B, \text{peak}}, \text{FWHM}) = (0.27 \text{ K, } 5'.3)\) and \((0.33 \text{ K, } 5'.5)\), respectively. Namely, the arms are as thin as 13.0 (GCA I) and 13.5 pc (GCA II). If we subtract the contributions from these two arm components, the residual intensity in the whole area in Fig. 7 is only 36% of the total intensity. The intensity coming from the inter-arm region between the arms shares only 12% of the intensity from the two arms. This would be an upper limit, as the region displayed in this figure is the weakest part along the arms without any significant molecular clumps and condensations. Thus, we conclude that the molecular gas as observed in the CO line emission in the region discussed in this paper is almost totally confined within the two major arms. Therefore, the central 100 pc radius region is almost empty, making a hole of molecular gas, except the nuclear few pc region surrounding Sgr A.

3.3. Velocity Field

Fig. 8a shows a velocity field as obtained by taking the first moment of the \((V_{\text{LSR}}, l, b)\) cube, and therefore, an intensity-weighted velocity field. A general rotation characteristics is clearly seen along the major axis of the ring feature at \(b \simeq -6'\). Sgr C molecular spur is seen as a negative velocity spur extending toward negative \(b\). GCA III is seen as the tilted high-velocity plume at \((l, b) \sim (0^\circ.2, 0^\circ.1)\).

In addition to these individual velocity structures, a large-scale velocity gradient in the latitude direction is prominent in the sense that the positive \(b\) side has positive velocity and negative \(b\) side negative velocity. This can be attributed to the fact that the high-velocity expanding shell (ring) is more clearly seen in positive velocity at \(b > 0^\circ\), while the negative velocity part more clearly at \(b < 0^\circ\) (see section 4). This can be explained by a tilted nature of the expanding oblate molecular shell, as will be discussed in section 4 based on an analysis of \((b, V)\) diagrams. In fact, if we construct a velocity field, excluding the expanding ring features, we obtain a rather regular velocity field as shown in Fig. 8b.
3.4. Possible Models for the Galactic Center Arms and Ring

We here try to reproduce the \((l, V)\) diagram based on a simple spiral arm model. According to the galactic shock wave theory (Fujimoto 1966; Roberts 1969) and the bar-induced shock wave theory (Sorensen et al 1976; Huntley et al 1978; Roberts et al 1979; Noguchi 1988; Wada and Habe 1992), flow vectors of gas in the densest part along the shocked arms are almost parallel to the potential valley that is rigidly rotating at a pattern speed slower than the galactic rotation. In such shocked flows, the gas cannot be on a closed orbit, but is rapidly accreted toward the center along deformed spirals.

As the simplest approach to simulate an \((l, V)\) diagram, we assume that the flow vector of gas is aligned along a spiral with a constant velocity equal to the rotation velocity in the potential. Fig. 9a shows a model, where we have assumed two symmetrical spiral arms with a pitch angle \(p = 10^\circ\). In addition to a constant circular rotation of gas \((V_{\text{rot}} = \text{constant}; \text{flat rotation curve})\), radial infall motion of \(V_{\text{rot}} \sin p\) is superposed, so that the gas is flowing along the arms into the central region. The density distribution in the arms are shown by the spiral-like contours. The azimuthally averaged density of gas has a hole at the center, or it corresponds to a ring distribution of gas on which two arms are superposed. A calculated \((l, V)\) diagram is shown by the superposed contours with a tilted X shape. The characteristic features in the observed \((l, V)\) diagrams can be now qualitatively reproduced.

Fig. 9b and 10c show cases where the spiral arms are oval in shape whose major axis is inclined by \(\pm 30^\circ\) from the nodal line. Such a case may be expected when the oval potential or a bar in the center is deep enough to produce a non-circular motion. Fig. 9d-f are the same, but the density distribution along the arms has the maximum at the center and the pitch angle is taken larger: \(p = 20^\circ\). Again, the case of a circular rotation appears to reproduce the observation, while the oval orbit cases result in more complicated \((l, V)\) plots than the observation. Among these models, the case shown in Fig. 9a or 9b appears to reproduce the observed characteristics in the \((l, V)\) plot (e.g. Fig. 3) reasonably well. The model in Fig. 9d or 9e with the averaged gas density increasing toward the center may explain observed Arms III and IV. However, the cases corresponding to Fig. 9c and 9f may be excluded.

3.5. Deconvolution into Projection on the Galactic Plane: A Face-on View

We may thus assume that the molecular gas is on a ring or spiral arms whose pitch angle is not so large. Then, it is possible to deconvolve the \((l, V)\) diagram into a spatial distribution in the galactic plane by assuming an approximately circular rotation. Thereby, we make use of the velocity-to-space transformation (VST), which has been extensively
applied to derive the HI gas distribution in our Galaxy (Oort et al 1957). Suppose that a
gas element is located at a projected distance $x \ (\simeq l \times 8.5 \text{ kpc})$ along the galactic plane
from the center of rotation, and has a radial velocity $v$. If the rotation is circular at velocity $V_0$,
the line of sight distance $y$ of the element from the nodal line can be calculated by

$$y = \pm |x| \sqrt{\left(\frac{V_0}{v}\right)^2 - 1}. \quad (5)$$

The signs must be opposite for Arms I and II. Here, we assume that Arm I is near side, and
Arm II far side, so that the signs are $-/+$, respectively. The center of rotation is
assumed to be at Sgr A, and $v$ is measured from the intersection velocity at $l = -0^\circ.06$ on
each arm ridge.

Fig. 10 shows a thus obtained “face-on” map of the molecular gas for $V_0 = 150 \text{ km}\ \text{s}^{-1}$. The arms appear to construct a circum-nuclear ring of radius $\sim 120 \text{ pc}$. Here, we used $(l, V)$ diagrams averaged within latitude ranges $-2' \leq b \leq 6'$ for Arm I and $-5' \leq b \leq 3'$ for
Arm II, so that vertically extended clumps such as Sgr B complex are only partly mapped
in this figure. During the deconvolution, we used only the arm component concentrated
near the ridges within $\pm 20 \text{ km}\ \text{s}^{-1}$ in velocity (as illustrated in Fig. 5). Diffuse gas and
clumps with velocities far from the arms are not taken into account. The same VST was
applied to the HII regions Sgr B1, B2 and C using their H recombination line velocities
(Downes et al 1980). We plotted their positions in Fig. 10. The HII regions lie along
the arms associated with the molecular complexes, though slightly avoiding the molecular
gas peaks. Sgr B and C appear to be at symmetrically opposite locations with respect to
the nucleus. We have assumed that Arm I is near side. However, in this kind of simple
deconvolution, we cannot distinguish the exact orientation, as is the case of deconvolution
of gas distribution inside the solar circle from kinematical information. Hence, it may be
possible to assume an opposite configuration of the arm locations: Arm I in far side, and
Arm II in near side.

Fig. 10 –

The connection of Arms I and II is not clear from this deconvolution. This is mainly
because of the ambiguous position determination near the node, which arises from unknown
precise rotation curve. The error is also large at $|l| < 0^\circ.1$, where we applied interpolation
from both sides along each arm. Obviously, this kind of deconvolution is not unique, but it
was possible here because of the separation of Arms I and II in the $(l, b)$ plane. Therefore,
this deconvolution should be taken as a possible hint to the spatial distribution of gas.

3.6. Comparison with Other Galaxies and Models

Accretion spirals, either shocked or not, and rings of molecular gas have been indeed
observed in the CO line in many extragalactic systems such as IC 342 (Lo et al 1984;
Ishizuki et al 1990a) and NGC 6946 (Ishizuki et al 1990b). The ring structure of molecular
gas of 100 to a few hundred pc size is commonly observed in the central regions of spiral
galaxies (Nakai et al 1987; Ishiguro et al 1989). See Sofue (1991) for a more number of
galaxies with a nuclear molecular ring. Thus, the ring/spiral structure of molecular gas
of radius 120 pc in the Milky Way, would be similar to the situation found in external galaxies.

There have been various numerical simulations of the accretion of gas toward the central region in spiral and oval potential by gas-dynamical simulations (Sorensen et al 1976; Huntley et al 1978; Roberts et al 1979; Noguchi 1988; Wada and Habe 1992). The models predict a rapid accretion of gas along spiral orbits, and the gas behavior in these models somehow mimic the models illustrated in Fig. 9.

A number of simulations of position-velocity diagrams along the galactic plane have been constructed and compared with the observations, in order to understand larger-scale \((l,V)\) diagrams for our Galaxy both in HI and CO (Mulder and Liem 1986; Liszt and Burton 1978; Burton 1988). Position-velocity diagrams for extragalactic edge-on galaxies in CO have been extensively studied (Sofue and Nakai 1993, 1994; Sofue 1994) and a numerical simulation has been attempted to reproduce the PV characteristics based on the gas dynamics in an oval potential (e.g., Mulder and Liem 1986; Wada et al 1994).

Binney et al (1991) have noticed the “parallelogram” and calculated theoretical \((l,V)\) diagrams, and have shown the presence of a bar of 2 kpc length in the Galactic bulge. However, the parallelogram (the expanding ring feature) in Fig. 1b shares only 15% of the total emission. However, we emphasize that the major structures, which contain 85% of the molecular mass within 150 pc of the center, are due to the Arms discussed above.

### 3.7. Relationship with Radio Sources

Fig. 11 shows superposition of a 10-GHz radio continuum map (Handa et al 1987) on the \(^{13}\)CO and CS intensity maps. We here briefly comment on a global relationship of the major radio sources with molecular features at a spatial resolution of a few arc minutes. Detailed internal structures of individual sources are out of the scope of the present paper, for which the readers may refer to a review by Liszt (1988).

#### 3.7.1. Sgr A

The relationship of molecular features of scales less than a few arc minutes with Sgr A has been discussed by many authors (e.g., Oort 1977; Bally et al 1987; Güsten 1989). However, these nuclear features, which are of 1’ (~ 3 pc) scales, are not well visible in the present plots in so far as the \((l,V)\) plots are concerned. We only mention that Arm III is a largely tilted out-of-plane plume with high positive velocity, which Bally et al (1988) called the polar arc. Arm IV shows also large velocity gradient, and appears to be an object related to a deep gravitational potential around the nucleus.

#### 3.7.2. Sgr B

The molecular complex at \(l \sim 0^\circ.6 - 0^\circ.9\) on Arm I is associated with the star forming regions Sgr B1 at \((l, b) = (0^\circ.519, -0^\circ.050)\), and Sgr B2 at \((0^\circ.670, -0^\circ.036)\). Sgr B1 and B2, whose radial velocities in H recombination line emission are \(V_{\text{LSR}}=45\) and 65 km s\(^{-1}\),
respectively (Downes et al 1980), are also located in the \((l, V)\) plane at the upper (higher-velocity) edges of molecular clumps. Thus, the de-convolved positions of these continuum sources are slightly displaced from the de-convolved arm, as indicated in Fig. 10. The molecular gas distribution is highly extended in the direction of latitude for about \(0^\circ.4\) (60 pc), largely shifted toward the lower side of the galactic plane \((b < 0^\circ)\). This complex is also much extended in the velocity space: the velocity dispersion amounts to as high as 50 km s\(^{-1}\). The internal structure of Sgr B molecular complex has been discussed in detail in relation to the star formation activity, and it was shown that the molecular gas is distributed in a shell, spatially surrounding the continuum peak (Bally et al 1988; Sofue 1990; Hasegawa et al 1993). The present ring model is consistent with the CII line \((l, V)\) diagram as obtained by Okuda et al (1989), which indicates a rotating ionized gas feature with Sgr B and C on the tangential points of the ring.

Fig. 11 –

3.7.3. Sgr C

The star forming region Sgr C is associated with a molecular complex, and is located on Arm II at \(l \sim -0^\circ.6\). However, the spatial proximity is less significant than that for Sgr B: The radio continuum peak of Sgr C, \((l, b, V_{\text{LSR}}) = (-0^\circ.57, -0^\circ.09)\), is located at the western edge of the molecular complex, but displaced by about 6' (15 pc) from the molecular peak. The LSR velocity of the H recombination line also agrees with the molecular gas velocity, and so, it is located on the de-convolved arm in Fig. 10. The molecular gas in this complex is extended vertically, and molecular spurs are found to extend both toward positive and negative latitude directions. We emphasize that the positive-latitude spur is clearly associated with the inner edge of the western ridge of the Galactic Center Lobe observed in the radio continuum emission (Sofue and Handa 1984; Sofue 1985), as is shown in Fig. 11.

3.7.4. Orbital Displacement vs Alignment of Star Forming Regions and Molecular Arms

The close association of Sgr B and C with GCA I and II may have a crucial implication for the orbits of gas and stars: If the arms are shock lanes in a bar during a highly non-circular motion, the HII regions of a million years old should already be displaced from the molecular arms. Therefore, the fact that Sgr B and C are still near the gas complexes from which they may have been born (after one or more rotations) can be explained only if the stars and gas are circularly co-rotating in the arms at a small pitch angle. This would argue for the validity of the deconvolution process applied in section 3.5.

Consider a spiral arm which is a shocked density wave. Star formation from a molecular cloud will be triggered in the arms. It will take about \(t \sim 10^6\) years for proto stars to form and shine as OB stars, and therefore, until HII regions are produced. On the other hand, the rotation period of the stars is only \(\sim 10^6\) years for \(r = 100\) pc and \(V_{\text{rot}} = 200\) km s\(^{-1}\). According to the density wave theory, the velocity difference between the rotation velocity and the shocked gaseous arm, which is about the same as the pattern speed of
density wave, is of the order of

\[ V_{\text{rot}} - V_p = (\Omega_{\text{rot}} - \Omega_p)r. \] (6)

The azimuthal phase difference between the HII region and the gaseous arm is then

\[ \Delta \phi \sim (\Omega_{\text{rot}} - \Omega_p)t. \] (7)

The phase difference for Sgr B2 and its corresponding molecular peak in Fig. 10 (darkest part in Arm I) is roughly \( \Delta \phi \sim 5^\circ \), and a similar value is found for Sgr C. If \( t \sim 10^6 \) yr, we obtain \( \Omega_{\text{rot}} - \Omega_p \sim 0.1 \) radian/\( 10^6 \) years \( \sim 100 \) km s\(^{-1}\) kpc\(^{-1}\). This is an order of magnitude greater than the value near the solar circle (\( \sim 10 \) km s\(^{-1}\) kpc\(^{-1}\)). For older HII regions (weaker radio sources) the phase difference would be much greater. Moreover, orbits of stars, and therefore, HII regions, are no longer closed, and must be largely displaced from the orbits of gas. Thus, the HII regions in the central 100 pc of the Galaxy, except for young cases as Sgr B2, would not be associated with molecular gas arms. This will simply explain why the molecular gas features are not directly correlated with the weaker radio sources in the Galactic center (Fig. 11).

4. Discussion

By analyzing the \(^{13}\)CO line BTL data cube, we have shown that most (85\%) of the total molecular gas within \( |l| < 1^\circ \) comprises rigid-body-like structures in the \((l, V)\) diagrams, which can be attributed to arms on a ring. Moreover, 66\% of the total gas in the region, and 78\% of the disk component (\( |b| < \sim 10^\prime=25 \) pc), was found to be confined in the two major Arms I and II. The spiral/ring structures are consistent with the picture drawn by Scoville et al (1974) based on the earlier data, while the scale obtained here is slightly smaller. The structures will be common in external galaxy nuclei in the sense that the gas distribution is spiral- and ring-like.

Numerical simulations for a few kpc scale disks have suggested that the features would be understood as the consequence of spiral accretion by a density wave in an oval potential, either shocked or not. Based on qualitative consideration, we have suggested possible models to explain the observed \((l, V)\) features as shown in Fig. 9a.

The molecular mass in the Galactic Center has been derived by using the most recent CO-to-H\(_2\) conversion factor about one third of the conventional value, which has been obtained by detailed analyses of the dependency on the metallicity as well as on the galacto-centric distance (Arimoto et al 1994). This has resulted in a factor of three smaller mass and energetics than the so far quoted values in the literature: The molecular mass within 150 pc radius from the center is estimated to be only \( 3.9 \times 10^7 M_\odot \).

Thus, the molecular gas mass is only a few percent of the total mass in the region estimated as \( M_{\text{dyn}} = R V_{\text{rot}}^2/G \sim 8 \times 10^8 M_\odot \) for a radius \( R \sim 150 \) pc and rotation velocity \( V_{\text{rot}} \sim 150 \) km s\(^{-1}\). This implies that the self-gravity of gas is not essential in the galactic center, and a given-potential simulation would be sufficient to theoretically understand the region.
The expanding molecular ring (or the parallelogram) was shown to share only 15 percent of the total gas mass within the central 1° region. This feature has been shown to be extending vertically over ~100 pc above and below the galactic plane (Sofue 1989). For the very different \( b \) distribution, it is a clearly distinguished structure from the arms and the ring described in this paper. On the \((l, V)\) plot, the feature can be fitted by an ellipse of radius 1°.2 (Bally et al 1987), slightly larger than the disk discussed in this paper. There have been controversial interpretations about this feature: either it is due to some explosive event (Scoville et al 1972; Kaifu et al 1972, 1974) or due to non-circular rotation of disk gas (Burton and Liszt 1992; Binney 1991). We will discuss this feature based on the present data in a separate paper.

**Acknowledgement:** The author would like to express his sincere thanks to Dr. John Bally for making him available with the molecular line data in a machine-readable format.

**References**

Altenhoff, W. J., Downes, D., Pauls., T., Schraml, J. 1979, AAS 35, 23.
Arimoto, N., Sofue, Y., Tsujimoto, T. 1994, in preparation.
Bally, J., Stark, A.A., Wilson, R.W., and Henkel, C. 1987, ApJ Suppl 65, 13.
Bally, J., Stark, A.A., Wilson, R.W., and Henkel, C. 1988, ApJ 324, 223.
Binney, J.J., Gerhard, O.E., Stark, A.A., Bally, J., Uchida, K.I., 1991 MNRAS 252, 210.
Brown, R.L., and Liszt, H.S. 1984, ARAA 22, 223.
Burton, W. B. 1988, in Galactic and Extragalactic Radio Astronomy, ed. G. L. Verschuur and K. I. Kellermann, 2nd edition (Springer-Verlag, New York) p 295.
Burton, W. B., and Liszt, H. S. 1983, in Surveys of the Southern Galaxy, ed. W. B. Burton and F. P. Israel (Reidel Pub. CO, Dordrecht), p. 149.
Burton, W. B., and Liszt, H. S. 1992 AAS 95, 9.
Combes F 1992 ARAA, 29, 195.
Cox, P., Laureijs, R. 1989, in The Center of the Galaxy (IAU Symp. 136), ed. M.Morris (D.Reidel Publ. Co., Dordrecht) p. 121.
Dame, T. M., Ungerechts, H., Cohen, R. S., de Geus, E. J., Grenier, I. A., et al. 1987 ApJ 32, 706
Downes, D., Wilson, T. L., Beiving, J., Wink,J. 1980, AA Suppl. 40, 379.
Fujimoto, M. 1966, in Non-stable Phenomena in Galaxies, IAU Symp. No 29, ed. Arakeljan (Academy of Sciences of Armenia, USSR), p.453.
Genzel, R., and Townes, C.H 1987, ARAA 25, 377.
Güsten, R. 1989, in The Center of the Galaxy (IAU Symp. 136), ed. M.Morris (D.Reidel Publ. Co., Dordrecht) p. 89.
Handa, T., Sofue, Y., Nakai, N. Inoue, M., and Hirabayashi, H. 1987, PASJ 39, 709.
Hasegawa, T., Sato, F., Whiteoak, J. B., Miyawaki, R. 1993, ApJ 419, L77.
Heiligman, G. M. 1987 ApJ 314, 747.
Huntley, J. M., Sanders, R. H., and Roberts, W. W., 1978, ApJ 221, 521.
Ishiguro, M., Kawabe, R., Morita, K.-I., Okumura, S. K., Chikada, Y. et al. 1989, ApJ
Ishizuki, S., Kawabe, R., Ishiguro, M., Okumura, S. K., Morita, K-I., et al. 1990a Nature 344, 224.
Ishizuki, S., Kawabe, R., Ishiguro, M., Okumura, S. K., Morita, K.-I. et al. 1990b ApJ 355 436.
Kaifu, N., Iguchi, T., and Kato, T. 1974, PASJ 26, 117.
Kaifu, N., Kato, T., and Iguchi, T. 1972, Nature 238, 105.
Knapp, G. R., Sttgark, A. A., Wilson, R. W. 1985 AJ 90, 254.
Liszt, H. S. 1988 in Galactic and Extragalactic Radio Astronomy, ed. G. L. Verschuur and K. I. Kellermann, 2nd edition (Springer-Verlag, New York) p 359.
Liszt, H. S., Burton, W. B. 1978 ApJ 226, 790.
Liszt, H. S., and Burton, W. B. 1980 ApJ 236, 779.
Lo, K. Y., Berge, G. L., Claussen, M. J., et al. 1984, ApJ 282, L59.
Mulder, W.A., Liem, B.T., 1986, AA 157, 148
Nakai, N., Hayashi, M., Handa, T., Sofue, Y., Hasegawa, T., and Sasaki, M., 1987, PASJ 39, 685.
Okuda, H., Shibai, H., Nakagawa, T., Matsuhara, T., Maihara, T., et al. 1989 in The Center of the Galaxy (IAU Symp. 136), ed. M.Morris (D.Reidel Publ. Co., Dordrecht) p. 145.
Oort, J. H., Kerr, F. J., Westerhout, G. 1958, MNRAS 118, 379.
Oort, J. H. 1977, ARAA 15, 295
AA Suppl 58, 197.
Roberts, W. W. 1969, ApJ 158, 123.
Roberts, W. W., Huntley, J. M., van Albada, G. D. 1979, ApJ, 233, 67.
Shaver, P. A., McGee, R. X., Newton, L. M., Danks, A. C., Pottasch, S. R. 1983, MNRAS, 204, 53.
Scoville, N.Z. 1972, ApJ 175, L127.
Scoville, N.Z., Solomon, P. M., and Jefferts, K. B. 1974 ApJ 187, L63.
Sofue, Y. 1985 PASJ 37, 697
Sofue, Y. 1989, in The Center of the Galaxy (IAU Symp. 136), ed. M.Morris (D.Reidel Publ. Co., Dordrecht) p. 213.
Sofue, Y. 1990 PASJ 42, 827
Sofue, Y. 1991 PASJ 43, 671
Sofue, Y., and Handa, T. 1984, Nature 310, 568.
Sofue, Y., Nakai, N. 1993 PASJ 45, 139.
Sofue, Y., Nakai, N. 1994 PASJ 46, 147.
Sofue, Y., and Reich, W. 1979, AA Suppl 38, 251.
Solomon, P.M., Scoville, N.Z., and Sanders, D.B., 1979, ApJ 232, L89.
Sørensen, S. -A., Matsuda, T., and Fujimoto, M. 1976, A. Sp. Sci. 43, 491.
Stark, A. A., Bally, J., Wilson, R. W., Pound, M. W., 1989, in The Center of the Galaxy (IAU Symp. 136), ed. M.Morris (D.Reidel Publ. Co., Dordrecht) p. 213.
Tsuboi, M. 1989 in The Galactic Center (IAU Symp. 136), ed. M.Morris (D.Reidel Publ. Co., Dordrecht) p. 135
Wada, K., Habe, A., Taniguchi, Y., Hasegawa, T. 1994, submitted to Nature
Wada, K., Habe, A. 1992 MNRAS 258, 82
Table 1: Galactic Center Arms and Ring.

| Parameters                  | Ring (I+II) | Arm I     | Arm II    | Arm III   | Arm IV    |
|-----------------------------|-------------|-----------|-----------|-----------|-----------|
| From \((l, V) (°, \text{km s}^{-1})\) | (+0.9, 90)  | (0.9, 80) | (0.1, 60) | (0, 140)  | (0.1, 60) |
| \(\sim\)                    | (1, 100)    |           |           |           |           |
| To \((l, V) (°, \text{km s}^{-1})\) | (−0.65, −140) | (−0.7, −150) | (−0.6, −80) | (−0.15, 10) | (0, −20)  |
| \(\sim\)                    | (−1, −200)  |           |           |           |           |
| \(V_{\text{LSR}}\) at \(l = 0°\) (\text{km s}^{-1})\) | .....       | −40       | +50       | +70       | −50       |
| From \((l, b) (°, °)\)       | (+0.9, 0.0) | (+0.9, −0.1) | (0.25, −0.05) | (0.25, 0.25) | .....     |
| To \((l, b) (°, °)\)       | (−0.65, −0.08) | (−1.0, −0.2) | (−0.65, −0.17) | (0, 0)    | .....     |
| \(b\) at \(l = 0°\) (°) | 0.050       | −0.067    | (0, 0)    | .....     |           |
| Length (°/\text{pc}) | .....       | 1.9/280   | 0.9/133   | 0.35/52   | .....     |
| Min. \(b\) width (°/\text{pc}) | .....       | 0.088/13  | 0.091/13.5 | .....     |           |
| Max. \(b\) width (°/\text{pc}) | .....       | 0.33/50   | 0.2/30    | .....     |           |
| Maj. ax. len. (°/\text{pc}) | 1.55/230    | .....     | .....     | .....     |           |
| Min. ax. len. (°/\text{pc}) | 0.132/19.5  | .....     | .....     | .....     |           |
| Inclination (°)           | 85.1        | .....     | .....     | .....     |           |
| Ring cen. \((l, b) (°, °)\) | (0.12, 0.0) | .....     | .....     | .....     |           |
| Ring radius (pc)          | 120         | .....     | .....     | .....     |           |
| Rot. Velo (\text{km s}^{-1}) | +90/−140   | .....     | .....     | .....     |           |
| Mol. Mass† \((10^7 M_\odot)\) | 3.07        | 1.72      | 1.35      | .....     | .....     |
| Remarks                    | Circum Nuc. asso. Sgr B Sgr C Sgr A? Sgr A? | \(1.61\) times the \(H_2\) mass obtained from the \(^{13}\text{CO}\) intensity to \(H_2\) conversion [see eq. (1)-(3)], where the metal abundance has been assumed to be twice the solar. This also applies to mass in Table 2. The statistical error which occurs during intensity integration is only a few %, while the error arising from ambiguity of the conversion factor is about 20 to 30% (Arimoto et al 1994). |
Figure Captions

Fig. 1: (a) The \((l, V_{\text{LSR}})\) diagram of the \(^{13}\text{CO} (J = 1 - 0)\) line emission of the central region of the Milky Way by averaging the data from \(-0.35 \leq b \leq 0.17\) as obtained with the Bell Telephone 7-m telescope by Bally et al.\(^{18}\)\(^{17}\) as obtained with the Bell Telephone 7-m telescope by Bally et al (1987). Contours are in unit of \(K T^*_A\) at levels \(0.1 \times (1, 2, 3, 4, 5, 6, 8, 12, 15, 20, 25)\).

(b) The same as Fig. 1a, but the local and foreground CO emissions have been subtracted by applying the “pressing method” (see the text for the procedure). Contour levels are same as in (a).

Fig. 2: The \((l, V_{\text{LSR}})\) diagrams averaged in 4’ b interval. Local/foreground emissions have been removed. ‘Rigid-rotation’ ridges (arms) are dominant in the disk at \(|b| < 10’\) (25 pc). Contours are in unit of \(K T^*_A\) at levels \(0.2 \times (1, 2, 3, \ldots, 9, 10, 12, 14, 16, 18, 20, 25, 30)\).

Fig. 3: Schematic sketch of the major ridges (arms) in the \((l, V_{\text{LSR}})\) diagrams.

Fig. 4: (a) Integrated intensity map in the whole velocity range at \(-250 \leq V_{\text{LSR}} \leq 250\) km s\(^{-1}\). This is almost the same as the map presented by Stark et al (1989), except that the local contribution has been subtracted. Contours are in unit of \(K\) km s\(^{-1}\) at levels \(25 \times (1, 2, 3, \ldots, 9, 10, 12, 14, 16, 18, 20, 25, 30)\).

(b) Same but in a grey-scale representation. For intensity scale, see (a). The bottom figure shows the same, but the scale in the latitude direction has been doubled. Galactic Center Arm (GCA) I runs as a long arc in the positive b side; GCA II runs in the negative b side.

Fig. 5: \((l, V_{\text{LSR}})\) diagrams corresponding to (a) Galactic Center Arms I and (b) II, which were used to obtain intensity maps of the Galactic Center Arms in Fig. 6. Contours are in unit of \(K T^*_A\) at levels \(0.2 \times (1, 2, 3, 4, 5, 6, 8, 10, 12, 15, 20, 25, 30, 35)\).

Fig. 6: Integrated intensity maps corresponding to (a) Galactic Center Arm I, and (b) Arm II as in Fig. 5. Contours are in unit of \(K\) km s\(^{-1}\) at levels \(12.5 \times (1, 2, 3, \ldots, 9, 10, 12, 14, 16, 18, 20, 25, 30)\). (c) Arms I+II. Contours are in unit of \(K\) km s\(^{-1}\) at levels \(25 \times \) (as above).

Fig. 7: Intensity variation across Galactic Center Arms I and II perpendicular to the galactic plane averaged at \(l = 0^\circ.24\) to \(-0^\circ.33\), where the arms are most clearly separated.

Fig. 8: (a) A velocity field as obtained by taking the first moment of the \((V_{\text{LSR}}, l, b)\) cube (intensity-weighted mean velocity field). Contour interval is 10 km s\(^{-1}\). Full-line contours are for positive velocity starting at 0 km s\(^{-1}\). Dashed contours are for negative velocity.

(b) Same as (a), but for the “disk component” with \(|V_{\text{LSR}}| < 100\) km s\(^{-1}\).

Fig. 9: Two-armed spiral model with a spiral infalling motion. Gas density distribution is shown by spiral-like contours as projected on the galactic plane. Calculated \((l, V_{\text{LSR}})\) diagram is shown by tilted X shaped contours. The scales are arbitrary.

(a) Two spiral arms with a pitch angle \(p = 10^\circ\) are assumed. The azimuthally averaged gas density has a hole at the center, corresponding to a ring distribution of gas on which two arms are superposed. In addition to a constant circular rotation, radial infall of velocity \(V_{\text{rot}} \sin p\) is superposed.

(b), (c) The same as (a), but the spiral arms are oval in shape whose major axis are inclined by \(\pm 30^\circ\) from the nodal line.
(d)-(f) The same as (a)-(c), respectively, but the density distribution along the arms has the maximum at the center and the pitch angle is taken larger: \( p = 20^\circ \).

Fig. 10: Possible deconvolution of the \((l, V)\) diagrams for Galactic Center Arms I and II into a spatial distribution as projected on the galactic plane. Contour interval is 0.25 starting at 0.1 in an arbitrary unit. Sgr A is assumed to be at the center.

Fig. 11: Superposition of the radio continuum emission at 10 GHz (contours: Handa et al 1987) on (a) \(^{13}\)CO, and (b) CS emission maps (grey scale). Contours are in unit of \( K T_B \) of 10 GHz continuum brightness at levels \( 0.1 \times (1, 2, 3, 4, 6, 8, 10, 15, 20, 25) \). For CO intensity scale, see Fig. 4.