A Detailed Observational Study of Molecular Loops 1 and 2 in the Galactic Center

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Abstract

Fukui et al. (2006, Science, 314, 106) discovered two huge molecular loops in the galactic center located at \((l, b)\) \(\simeq (355°–359°, 0°–2°)\) in a large velocity range of \(-180–40\) km s\(^{-1}\). Following the discovery, we present detailed observational properties of the two loops based on NANTEN \(^{12}\)CO \((J = 1–0)\) and \(^{13}\)CO \((J = 1–0)\) datasets at 10 pc resolution, including a complete set of velocity channel distributions and comparisons with H\(_1\) and dust emissions as well as with the other broad molecular features. We have found new features on smaller scales in the loops, including helical distributions in the loop tops and vertical spurs. The loops have counterparts of the H\(_1\) gas, indicating that the loops include atomic gas. The IRAS far-infrared emission is also associated with the loops, and was used to derive an \(X\)-factor of \(0.7 \pm 0.1\) \(\times 10^{20}\) cm\(^{-2}\) (K km s\(^{-1}\))^\(-1\) to convert the \(^{12}\)CO intensity into the total molecular hydrogen column density. From the \(^{12}\)CO, \(^{13}\)CO, H\(_1\), and dust datasets we estimated the total mass of loops 1 and 2 to be \(\sim 1.4 \times 10^6 M_\odot\) and \(\sim 1.9 \times 10^6 M_\odot\), respectively, where the H\(_1\) mass corresponds to \(\sim 10%–20%\) of the total mass and the total kinetic energy of the two loops is \(\sim 10^{52}\) erg. An analysis of the kinematics of the loops yields that the loops are rotating at \(\sim 47\) km s\(^{-1}\) and expanding at \(\sim 141\) km s\(^{-1}\) at a radius of \(\sim 670\) pc from the center. Fukui et al. (2006) presented a model that the loops are created by magnetic flotation due to the Parker instability with an estimated magnetic field strength of \(\sim 150\) \(\mu\)G. We present comparisons with the recent numerical simulations of the magnetized nuclear disk by Machida et al. (2009, PASJ, 61, 411) and Takahashi et al. (2009, PASJ, 61, 957), and show that the theoretical results are in good agreement with the observations. The helical distributions also suggest that some magnetic instability plays a role similarly to the solar helical features.

Key words: ISM: clouds — ISM: magnetic fields — magnetic loops — radio lines: ISM

1. Introduction

The evolution of molecular gas may be significantly different in the central region of a grand-design galaxy from that in the disk because the strong gravitational field by high stellar density makes the pressure much higher in the central region than in the disk. It is important to understand the distributions and physical conditions of molecular gas in the galactic center and their astronomical implications in our continuing efforts to elucidate galactic evolution.

Previous studies of the galactic center show that most of the molecular gas is concentrated in the inner 300 pc, which is called the “Central Molecular Zone” (hereafter CMZ, e.g., Morris & Serabyn 1996). The CMZ including Sgr A and Sgr B2 molecular clouds has been a region intensively studied (e.g., Scoville et al. 1975; Fukui et al. 1977; Güsten & Henkel 1983). The molecular gas in the CMZ is characterized by high temperatures, \(\sim 30–300\) K, as derived by observations in CO, NH\(_3\), H\(_2\), H\(^3\)\(_2\) lines (Martin et al. 2004; Hüttemeister et al. 1993; Rodríguez-Fernández et al. 2001; Oka et al. 2005; Nagai et al. 2007), and by violent motions of \(1 \sigma \sim 50\) km s\(^{-1}\) (e.g., Morris & Serabyn 1996; Güsten & Philipp 2004). The origin of these two characteristics has not been understood well during the last few decades, whereas a few mechanisms to drive gas motion including the stellar bar potential and supernova explosions have been discussed (e.g., Binney et al. 1991; Liszt 2006; Oka et al. 2007). The galactic center is also characterized by a strong magnetic field. Radio Arc and the non-thermal filaments (Yusef-Zadeh et al. 1984, 2004), and perhaps the infrared double helix (Morris et al. 2006), strongly suggest the existence of quite unique magnetic field structures in the galactic center with the field strength being as large as 1 mG. Most recently, Crocker et al. (2010) summarized previous observations of radio synchrotron emission in a frequency range of 1.4–10 GHz, and derived the galactic center field to be at least \(\sim 50\) \(\mu\)G on 400 pc scales. There are also unusually broad molecular features with weaker intensities outside the CMZ up to nearly 1 kpc from the center, e.g.,
Clump 1 \((l, b \approx 355\degree, 0\degree)\), Clump 2 \((l, b \approx 3\degree, 0\degree)\), and \(l = 5\degree 5\) complex \((l, b \approx 5\degree, 0\degree)\) (Bania 1977; Stark & Bania 1986; Liszt 2006), whereas these features have not received much attention so far.

Fukui et al. (2006, hereafter Paper I) discovered two molecular loops toward \((l, b) \approx (355\degree–359\degree, 0\degree–2\degree)\) by analyzing the \(^{12}\)CO \((J = 1–0)\) NANTEN galactic plane survey dataset, and named them loops 1 and 2. These loops are distributed in a negative \(V_{\text{LSR}}\) and named them loops 1 and 2. These loops are distributed in a negative \(V_{\text{LSR}}\) and have heights of \(\sim 2\) kpc from the galactic plane, which correspond to \(\sim 300\) pc at the distance to the galactic center, 8.5 kpc. The loops are characterized by two bright foot points in CO emission on each side; the foot points show large velocity dispersions of \(\sim 50–100\) km s\(^{-1}\). In addition, Science Online Material (SOM) of Paper I showed that Clump 2 and the \(l = 5\degree 5\) complex are connected by an off-plane loop-like feature, and the authors suggested their similarity with loops 1 and 2. Subsequently, Fujishita et al. (2009, hereafter Paper II) discovered loop 3, which is located in the same direction with loops 1 and 2 in a positive velocity range of \(V_{\text{LSR}} \approx 20–200\) km s\(^{-1}\). Loop 3 shows a loop-like outer shape and similar height and length with loops 1 and 2, and has two foot points with broad velocity dispersions on their ends.

These three loops are interpreted by magnetic flotation caused by the Parker instability (Parker 1966) in Papers I and II, where loops 1 and 2 offer the first observational evidence for Parker’s model of cloud formation on the galactic scale. The Parker instability was numerically studied by Matsumoto et al. (1988), and it was shown that the foot point is a natural outcome of the falling motion of gas along the floated field lines, and that the foot point often causes shocks. Most recently, Torii et al. (2010) presented a detailed analysis of the foot points between loops 1 and 2 by using multi-\(J\) CO transitions at 1–4 pc resolutions, and derived a kinetic temperature as high as \(30–100\) K, or more. The high temperature was interpreted as being due to shock heating in the foot point by the authors. In addition, they revealed that the foot point exhibits a characteristic U-shape, and interpreted the shape in terms of the magnetic flotation picture.

Paper I, a Letter, described limited observational properties of loops 1 and 2. After the subsequent work reviewed above, it remains important to present observational details of loops 1 and 2 in order to pursue their physical properties of the loops. We present here a full account of loops 1 and 2 from the \(^{12}\)CO and \(^{13}\)CO datasets of the NANTEN galactic plane survey, along with comparisons with H\(_{\text{II}}\) dust, and the other outstanding molecular features. Section 2 describes the \(^{12}\)CO \((J = 1–0)\) and \(^{13}\)CO \((J = 1–0)\) datasets. Detailed observational properties of the two loops are presented in section 3. Sections 4, 5, and 6 show comparisons, mass estimates, and a kinematical and morphological model, respectively. Section 7 presents discussion and section 8 summarizes the paper.

### 2. NANTEN Datasets

The \(^{12}\)CO \((J = 1–0)\) dataset at 115 GHz and the \(^{13}\)CO \((J = 1–0)\) dataset at 110 GHz obtained by using the NANTEN 4m mm telescope in Chile toward the galactic center were used in this study. Basic parameters of the observations are summarized in Table 1.

#### 2.1. \(^{12}\)CO

Observations were carried out during the period from 1999 March to 2001 September. The half-power beamwidth (HPBW) was 2.6 at 115 GHz. NANTEN was equipped with a 4 K cryogenically cooled Nb superconductor-insulator-superconductor (SIS) mixer receiver (Ogawa et al. 1990). The typical system temperature was \(\sim 280\) K in the single-side band, including the atmosphere toward the zenith. The spectrometer was an acousto–optical spectrometer (AOS) with 2048 channels. The frequency band-width and resolution were 250 MHz and 250 kHz, which correspond to a velocity coverage of \(650\) km s\(^{-1}\) and a velocity resolution of \(0.65\) km s\(^{-1}\), respectively, at 115 GHz. The absolute intensity calibration from the observed antenna temperature was done by observing \(\rho\)-Oph East \((R.A. (B1950.0) = 16\degree29\arcmin20.9\arcsec, \delta = 24\degree22\arcmin13\arcsec)\) every 2 hours, the absolute temperature of which was assumed to be 15 K. The telescope pointing was maintained within 20\" by observing planets at radio wavelengths in addition to optical observations of stars with a CCD camera equipped with the telescope. The observed region was 200 square degrees toward \((l, b) \approx (350\degree–10\degree, -5\degree–5\degree)\) by using the position-switching mode with a 4\" grid spacing, which corresponds to \(\sim 10\) pc at 8.5 kpc. In total, 54000 positions were observed. Typical rms (root mean square) noise fluctuations of 0.36 K were achieved at a velocity resolution of 0.65 km s\(^{-1}\).

#### 2.2. \(^{13}\)CO

The \(^{13}\)CO \((J = 1–0)\) dataset toward the galactic center region was taken with the same instrument as the \(^{13}\)CO \((J = 1–0)\) observations in 2003 October. The half-power beam width (HPBW) was 2.7 at 110 GHz. The same receiver and spectrometer with \(^{12}\)CO \((J = 1–0)\) were used. The typical system temperature was \(\sim 100\) K in the single-side band, and the velocity coverage and the velocity resolution were \(620\) km s\(^{-1}\) and 0.62 km s\(^{-1}\), respectively, at 110 GHz. An absolute intensity calibration was carried out by observing \(\rho\)-Oph East

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**Table 1. Summary of the observations.**

| Transition  | Frequency (GHz) | Beam size (') | Grid (') | Observing region \(l (')\) | Total observed points | Mean rms (K) |
|-------------|----------------|--------------|---------|--------------------------|----------------------|-------------|
| \(^{12}\)CO \((J = 1–0)\) | 115.27120 | 2.6 | 4 | 350–10 | 45000 | 0.3 |
| \(^{13}\)CO \((J = 1–0)\) | 110.20137 | 2.7 | 2 | 354–8 | 25200 | 0.2 |
The fits file of loops 1 and 2 in 12CO($J = 1\rightarrow 0$) can be taken from (http://www.a.phys.nagoya-u.ac.jp/~torii/loop/eg).

1. RA (B1950.0), Dec (B1950.0) = $16^h29^m20^s9$, $-24^d22'13''$ every 2 hours. We assumed that the absolute radiation temperature of $\rho$-Oph East was 10 K. The observed region was toward $(l, b) \simeq (354^\circ-8^\circ, -1^\circ-1^\circ)$ with the position-switching mode at a grid spacing of 2'. In total, 25200 positions were observed. Typical rms noise fluctuations were 0.20 K at a velocity resolution of 0.62 km s$^{-1}$.

3. CO Distributions of Loops 1 and 2

Figure 1 shows the large-scale distribution of the 12CO intensity in an area of $(l, b) \simeq (350^\circ-10^\circ, -5^\circ-5^\circ)$ in $V_{\mathrm{LSR}} \simeq -300-300$ km s$^{-1}$. Figure 1a (upper) shows the distribution of the total 12CO integrated intensity. In figure 1a, most of the emission along the galactic plane is the 3-kpc expanding arm, and the CMZ is dominant in $l \simeq 359^\circ-1^\circ$. The locations of loops 1 and 2 and loop 3 toward $l \simeq 355^\circ-359^\circ$ are shown by two boxes with broken lines in figure 1a and figure 1b (lower). In figure 1b, the longitude-velocity diagram, the molecular gas in the galactic center region is seen as broad features whose velocity extents are a few tens of km s$^{-1}$ or more. The narrow features near 0 km s$^{-1}$ are clouds outside the galactic center, and the 3-kpc arm is seen as a narrow feature at $\sim -50$ km s$^{-1}$ toward $l \simeq 0^\circ$ with a velocity gradient of $\sim 8$ km s$^{-1}$ deg$^{-1}$.

Figure 2 shows the integrated intensity distributions for the negative and positive velocity ranges. Figures 2a and 2b show the distributions in the negative velocity range in the $l-b$ plane and $V-b$ plane, respectively, and loops 1 and 2 are indicated in figure 2a. Figures 2c and 2d show the distributions in the positive velocity range in the $l-b$ plane and $V-b$ plane, respectively, and loop 3 is indicated in figure 2c.

Figure 3 shows close-up images of 12CO and 13CO for loops 1 and 2 for two velocity ranges, from $-180$ to $-90$ km s$^{-1}$ and from $-90$ to $-40$ km s$^{-1}$, in an area of $l \simeq 355^\circ-359^\circ$ and $b \simeq 0^\circ-2^\circ$, shown by a rectangle in figure 2a. Figures 3a–3d are for loop 1; Figures 3a and 3b are the $l-b$ diagrams of 12CO and 13CO, and figures 3c and 3d are the $l-V$ diagrams of 12CO and 13CO. Figures 3e–3h are for loop 2; Figures 3e and 3f are the $l-b$ diagrams of 12CO and 13CO and figures 3g and 3h are the $l-V$ diagrams of 12CO and 13CO.

Figure 3a shows that loop 1 is a remarkable filamentary feature of $\sim 30$ pc width and $\sim 300$ pc projected length, being elevated from the plane by $\sim 200$ pc. It shows a bright spot at $(l, b) \simeq (356^\circ, 1^\circ)$, which has strong intensity gradients toward the plane, and also toward the east. We also recognize a less-enhanced peak toward $(l, b) \simeq (357^\circ4^\prime, 0^\circ8')$. We shall call these two peaks “foot points” following Paper I. Figure 3c shows that these two foot points have enhanced velocity extents of $\sim 50$ km s$^{-1}$ or more. The $^{13}$CO emission is significant only toward the foot point at $(l, b) \simeq (356^\circ, 1^\circ)$, while the observations do not cover the region above $b = 1^\circ$.

Figure 3e shows that loop 2 is an outstanding feature with a width of $\sim 30$ pc and a length of $\sim 400$ pc and is elevated by $\sim 300$ pc from the plane. A feature at $b \simeq 1^\circ4$ extending toward the center is part of loop 1. Loop 2 shows two bright spots with enhanced velocity extents of $\sim 60$ km s$^{-1}$ toward $(l, b) \simeq (355^\circ4^\prime, 0^\circ8')$ and $(356^\circ1^\prime, 0^\circ8')$. The $^{13}$CO emission is detected toward these two spots (figures 3c, 3d) although the coverage is limited to $b$ less than $\sim 1^\circ$. We shall call these two spots “foot points” of loop 2 (Paper I).

Figure 4 shows typical 12CO and 13CO line profiles toward loops 1 and 2. The shapes of these profiles are not Gaussian but triangle. We note that the profiles toward the foot points show asymmetry with a strong skew. The velocity span is as large as 40 km s$^{-1}$ toward the loop top, and becomes even larger as 100 km s$^{-1}$ toward the foot points.

Figures 5 and 6 show the distributions of the intensity-weighted averaged velocity and the $1\sigma$ velocity dispersion in the loops, respectively, where the velocity range is from $-190$ km s$^{-1}$ to $-30$ km s$^{-1}$ averaged with a single Gaussian function of a 10’ FWHM. The larger beam size was taken in order to suppress any small-scale irregularities. We confirmed the velocity gradients in Paper I and roughly estimated the gradients to be $\sim 0.2$ km s$^{-1}$ pc$^{-1}$ and $\sim 0.35$ km s$^{-1}$ pc$^{-1}$ along loops 1 and 2, respectively. We also found that the velocity dispersion in the foot points is significantly larger than that in the rest of the loops.

In order to show more details of the velocity distributions, we present a series of velocity channel distributions every 10 km s$^{-1}$ as 18 panels in figure 7. We identified the foot points of loops 1 and 2 toward $l \simeq 355^\circ$, $357^\circ$, and $359^\circ$ at $b \simeq 0^\circ8'$. We found two new features in these panels; i.e., a vertical feature toward $(l, b) \simeq (356^\circ, 1^\circ4-1^\circ6)$ in $V_{\mathrm{LSR}}$ from $-120$ to $-90$ km s$^{-1}$ between loops 1 and 2 and a vertical protrusion toward $(l, b) \simeq (355^\circ4^\prime, 1^\circ8-2^\circ0')$ above the western foot point of loop 2. One of these features, which we tentatively called “spurs”, between loops 1 and 2 seems to be separated from loop 2 in its vertical direction.

In addition, we note that three regions show peculiar distributions that are not part of simple loops, as shown in figures 8, 9, and 10. We hereafter call these features in figures 8 and 9 helical distributions.

Figure 8 shows the details of the top of loop 1 every 4 km s$^{-1}$ from $-129$ to $-107$ km s$^{-1}$. The panels from $-121$ to $-113$ km s$^{-1}$ show S-shaped distributions in the range of $l \simeq 357^\circ0'-357^\circ4'$, and those from $-115$ to $-113$ km s$^{-1}$ also show a similar feature in $(l, b) \simeq (356^\circ8'-357^\circ3', 0^\circ9')$.

Figure 9 shows the top of loop 2 every 4 km s$^{-1}$ from $-86$ to $-66$ km s$^{-1}$. A peculiar peaked shape is found from $(l, b) \simeq (356^\circ8'-357^\circ3', 1^\circ8'-2^\circ1')$.

Figure 10 shows the area south of the foot point of loop 2. The panels from $-50$ to $-42$ km s$^{-1}$ show a vertical feature at $l \simeq 355^\circ6$, and the panels from $-44$ to $-36$ km s$^{-1}$ indicate a bridge-like feature that connects this vertical feature and the local intensity peak at $(l, b) \simeq (355^\circ7'-355^\circ2', 1^\circ1')$ in the panel from $-44$ to $-40$ km s$^{-1}$. In addition, the panel from $-34$ to $-30$ km s$^{-1}$ shows another vertical feature in $(l, b) \simeq (355^\circ2', 1^\circ4'-1^\circ8')$.

To summarize the section, we note that the results in Paper I are basically confirmed in velocity channel distributions and that new features, including spurs above the foot points and helical distributions in the loop tops, were found.
Fig. 1. Integrated intensity distributions of the galactic center in $^{12}$CO$(J = 1-0)$ obtained by NANTEN. Dotted boxes in the figures show the regions where loops are located. Solid boxes show other broad line features; Clumps 1 and 2 and $l = 57.5$ complex. (a: upper) Longitude–latitude distributions. The integration range in velocity is from $-300$ to $300$ km s$^{-1}$. Contours are plotted at 10, 20, 60, 100, 220, 340 K km s$^{-1}$ in black and 460, 820, 1180, 1540, 1900, 2260, 2620 K km s$^{-1}$ in white. (b: lower) Longitude–velocity distribution. The velocity resolution was smoothed to 3 km s$^{-1}$. The integrated range in galactic latitude is from $-2^\circ$ to $2^\circ$. Contours are plotted every 6 K from 0.25 K (black) and then every 1.2 K from 10 K the one.
Fig. 2. (a, b) Integrated intensity distributions of the galactic center for the negative velocity range. Dotted boxes show the region where loops 1 and 2 are located. (a) Velocity integrated intensity distributions. The integration range in velocity is from $-300$ to $-20$ km s$^{-1}$. Contours are plotted at 10, 20, 60, 100, 220, 340 K km s$^{-1}$ in black and 460, 820, 1180, 1540, 1900 K km s$^{-1}$ in white. (b) Velocity–latitude distributions. The velocity resolution was smoothed to 3 km s$^{-1}$. Integration range in galactic longitude is from 10$^\circ$ to 10$^\circ$. Contours are plotted every 1.6 K from 0.8 K (black) and then every 3.2 K from 6th one (white). (c, d) Integrated intensity distributions of the galactic center for positive velocity range. Dotted boxes show the region where loop 3 is located. (c) Velocity integrated intensity distributions. Integration range in velocity is from 20 to 300 km s$^{-1}$. Contours are plotted at the same levels of figure (a). (d) Velocity–latitude distributions. The velocity resolution was smoothed to 3 km s$^{-1}$. Contours are plotted at the same levels of figure (b).

4. Comparisons with the Other Broad CO Features, H$\text{I}$, and Dust

4.1. The Other Broad CO Features

There are a few CO features that have similar characteristics with loops 1 and 2 in the inner 1 kpc of the galactic center: a loop-like shape with two foot points of broad velocity widths at both ends of the loop. Paper II reported the discovery of another molecular loop, loop 3, as observed in the CO $J = 1-0$ transition. Loop 3 is distributed in the same direction with loops 1 and 2 in a positive velocity range of $V_{\text{LSR}}$ 20–200 km s$^{-1}$ (figure 2c). Loop 3 shows a dome-like feature with broad foot points at both ends; its inside is filled with CO emission. The size and velocity spans of loop 3 are fairly similar to those of loops 1 and 2; Paper II showed that the foot points of loop 3 seem to be still undeveloped because the mass of the foot points is significantly smaller than in the loop top, as compared with loops 1 and 2 (table 2, see also table 4 of Paper II). It was suggested in Paper II that loop 3 is in an earlier evolutionary stage than loops 1 and 2, because most of the floated gas in loop 3 still remains above the foot points. Paper II also showed that loop 3 is associated with H$\text{I}$ having a similar distribution and kinematics.

There are two outstanding CO clumps, known as Clump 2 and the $l = 5.5$ complex at $l \approx 3^\circ$ and $l \approx 5^\circ$, these clumps have very broad velocity widths of $\sim 100$–150 km s$^{-1}$ (Bania 1977; Stark & Bania 1986; Boyce & Cohen 1994; Bitran et al. 1997; Liszt 2006). The NANTEN CO survey revealed a bridge-like feature connecting these two clumps in ($l$, $b$) $(3^\circ - 4^\circ$, $0^\circ - 1^\circ$) and $V_{\text{LSR}} \approx 30$–100 km s$^{-1}$ (in SOM of Paper I) at 10 pc resolution. This bridge-like feature is seen in the $^{12}$CO images at 20 pc resolution in Bitran et al. (1997) (e.g., their figure 5), but these authors gave no discussion on this feature. The feature was also discussed by Liszt (2008) as an inward flow from the outside of the galactic center, but the authors did not discuss the loop interpretation by Fukui et al. (2006). Boyce and Cohen (1994) detected the bridge-like feature in OH absorption and named it Clump 4 and Filament B but did not discuss the nature of the feature. The other previous studies cover only lower latitudes below the connecting feature.

The two clumps show elongation vertical to the galactic plane with sizes of around 75 pc times 135 pc (Clump 2) and
Fig. 3. (a–d) Integrated intensity distributions of loop 1 in $^{12}$CO ($J = 1–0$) and $^{13}$CO ($J = 1–0$). (a) Longitude–latitude distributions of loop 1 in $^{12}$CO ($J = 1–0$). The integration range in velocity is from $-180$ to $-90$ km s$^{-1}$. Contours are plotted every 10 K km s$^{-1}$ (black line) from 7.0 K km s$^{-1}$ (3σ) and every 20 K km s$^{-1}$ (white line) from the 6th one. (b) Longitude–latitude distributions in $^{13}$CO ($J = 1–0$). The integration range is the same in the figure (a). Contours are plotted every 4 K km s$^{-1}$ from 3.5 K km s$^{-1}$. (c) Longitude–velocity distributions of loop 1 in $^{12}$CO ($J = 1–0$). The velocity resolution was smoothed to 2.0 km s$^{-1}$. The integration range in the galactic latitude is shown by the solid lines in the figure (a). Contours are plotted every 0.12 K from the lowest one of 0.20 K. An approximate position of the 3 kpc arm is indicated by a dotted line. (d) Longitude–velocity distributions of loop 2 in $^{13}$CO ($J = 1–0$). The velocity was smoothed to 2.0 km s$^{-1}$. The integration range is the same as figure (c). Contours are plotted every 0.05 K from 0.035 K.
Fig. 3. (e–h) Integrated intensity distributions of loop 2 in $^{12}$CO ($J = 1–0$) and $^{13}$CO ($J = 1–0$). (e) Longitude–latitude distributions of loops 1 and 2 in $^{12}$CO ($J = 1–0$). The integration range in velocity is from $-90$ to $-40$ km s$^{-1}$. Contours are plotted every 10 K km s$^{-1}$ (black line) from $7.0$ K km s$^{-1}$ (3σ) and every 20 K km s$^{-1}$ (white line) from the 6th one. (f) Longitude–latitude distributions in $^{13}$CO ($J = 1–0$). The integration range is the same in the figure (e). Contours are plotted every 4 K km s$^{-1}$ from 4 K km s$^{-1}$. (g) Longitude–velocity distributions of loop 2 in $^{12}$CO ($J = 1–0$). The velocity resolution was smoothed to 2.0 km s$^{-1}$. The integration range in the galactic latitude is from about 0° to 2.5°. Contours are plotted every 0.12 K from the lowest one of 0.20 K. (h) Longitude–velocity distributions of loop 2 in $^{13}$CO ($J = 1–0$). The velocity resolution was smoothed to 2.0 km s$^{-1}$. The integration range is the same as the figure (g). Contours are plotted every 0.05 K from 0.035 K.
around 50 pc times 100 pc (the \(l = 5\,5\) complex), respectively, and such vertical elongation is similar to the foot points of loops 1 and 2. Their sizes are a few-times larger than those of the foot points of loops 1 and 2. As derived later in section 5, the molecular masses of the foot points of loops 1 and 2 are of the order of \((1–6) \times 10^5 M\odot\), several times smaller than those of Clump 2 and the \(l = 5\,5\) complex having \((2–6) \times 10^6 M\odot\) (table 2, Bania 1977; Stark & Bania 1986). The two clumps, therefore, share a similar observed property in their shape and velocity span with the foot points of loops 1 and 2, whereas their masses are \(\sim 10\)-times larger than the foot points of loops 1 and 2. The larger mass of the two clumps suggests that they are in a later evolutionary stage by a similar argument for loop 3 (Paper II) and/or that they have higher gas density due to their proximity to the CMZ.

4.2. H I

Figure 11 shows a comparison between \(^{12}\)CO and H I, where the H I data were taken with the Parkes 64 m telescope having a 16\(') beam (McClure-Griffiths et al. 2005). Figures 11a and 11c are for loop 1 and figures 11b and 11d for loop 2 in the \(l-b\) and \(l-V\) diagrams. Although there are strong emissions from the foreground disk component (\(V_{\text{LSR}} \approx -50-0\) km s\(^{-1}\)) and the 3-kpc arm (\(V_{\text{LSR}} \approx -100-50\) km s\(^{-1}\)) in figures 11c and 11d, H I toward loop 1 shows a clear similarity to the CO distributions (figure 11a). Both foot points of loop 1 are bright in CO as well as in H I. On the other hand, H I of the entire loop 2 is not so clearly recognized as loop 1 due to contamination, whereas the western half of loop 2 in \((l, b) \approx (355\,5-356\,5, 1\,2-2\,5)\) is recognized in H I (figure 11b). In figure 11d we clearly find these emissions in \(l \approx 355\,3\) and \(V_{\text{LSR}} \approx -70-50\) km s\(^{-1}\) and in \(l \approx 356\,0-357\,4\) and \(V_{\text{LSR}} \approx -170-100\) km s\(^{-1}\). The inside of loop 1 shows weak H I emission (figure 11a), whereas the outside of loops 1 and 2 shows little H I emission. In figure 12a, loop 1 is seen from \(V_{\text{LSR}} \approx -150-100\) km s\(^{-1}\) as a tilted feature in \(b \approx 0\,6-1\,0\) and H I is associated with this CO feature (figure 12b). The \(^{12}\)CO features in \(b \approx 0\,8-2\,0\) and \(V_{\text{LSR}} \approx -100-40\) km s\(^{-1}\) correspond to part of loops 1 and 2, whereas their H I counterparts are not clearly separated from the 3-kpc arm peaked at \(V_{\text{LSR}} \approx -60\) km s\(^{-1}\).

To summarize, loop 1 and the upper part of loop 2 show H I counterparts as in case of loop 3 (Paper II), although the H I counterpart of the lower part of loop 2 is not clearly identified due to the heavy contamination.

4.3. Dust

In order to test if the loops in CO and H I are seen in the dust emission, we have compared dust emission obtained...
Fig. 5. Average velocity distributions of loops 1 and 2 in $^{12}$CO ($J = 1\rightarrow 0$). Contours in the figures are plotted at 5.2 km s$^{-1}$ (bold contours) and 45.2 km s$^{-1}$ (dashed line).
Fig. 6. Distributions of $1\sigma$ velocity dispersion of loops 1 and 2 in $^{12}$CO ($J = 1$–0). Contours in the figures are plotted at 5.2 K km s$^{-1}$ (bold contours) and 45.2 K km s$^{-1}$ (dashed line).
Fig. 7. Velocity channel distributions of loops 1 and 2 in $^{12}$CO ($J = 1-0$) integrated every 10 km s$^{-1}$. Contours are plotted every 4.8 K km s$^{-1}$ (black contours) from 3.6 K km s$^{-1}$ and every 9.6 K km s$^{-1}$ (white contours) from 32.4 K km s$^{-1}$.
Fig. 7. (Continued)
Fig. 7. (Continued)
Fig. 8. Integrated intensity distributions of the helical distribution in loop 1. (a: upper) Velocity integrated intensity distributions in $^{12}$CO ($J = 1$–$0$). The integration range is from $-129$ to $-107$ km s$^{-1}$. Contours are plotted every 2 K km s$^{-1}$ from 2.6 K km s$^{-1}$. A black box indicates the region shown in figures (b: lower). (b) Velocity channel distributions of the helical feature integrated over 4 km s$^{-1}$ with intervals of 2 km s$^{-1}$. Contours are plotted every 0.8 K km s$^{-1}$ from 1.6 K km s$^{-1}$. Dotted lines show the fitting result shown in table 4 (in p. 1331).
Fig. 9. Integrated intensity distributions of the helical distribution in loop 2. (a: upper) Velocity integrated intensity distributions in $^{12}$CO ($J = 1-0$). The integration range is from $-86$ to $-66$ km s$^{-1}$. Contours are plotted every 2 K km s$^{-1}$ from 2.6 K km s$^{-1}$. A black box indicates the region shown in figures (b: lower). (b) Velocity channel distributions of the helical feature integrated over 4 km s$^{-1}$ with intervals of 2 km s$^{-1}$. Contours are plotted every 0.8 K km s$^{-1}$ from 1.6 K km s$^{-1}$. A dotted line shows the fitting result shown in table 4.
Fig. 10. Integrated intensity distributions of the helical distribution in loop 2. (a: upper) Velocity integrated intensity distributions in $^{12}$CO ($J = 1–0$). The integration range is from $-44$ to $-34$ km s$^{-1}$. Contours are plotted every 2.4 K km s$^{-1}$ from 2.6 K km s$^{-1}$. A black box indicates the region shown in figures (b: lower). (b) Velocity channel distributions of the helical feature integrated over 4 km s$^{-1}$ with intervals of 2 km s$^{-1}$. Contours are plotted every 1.2 K km s$^{-1}$ from 1.6 K km s$^{-1}$.
Table 2. Comparison between the loops and loop candidates.*

| No. | Name          | $l, b$  | $V_{LSR}$ (km s$^{-1}$) | Size (pc × pc) | $M$ (10$^3 M_\odot$) | $\lambda$ (pc) | $H$ (pc) | $M_{tot}$ (10$^3 M_\odot$) | $M_{fp}$ (10$^3 M_\odot$) |
|-----|---------------|---------|-------------------------|----------------|------------------|-------------|----------|-----------------------------|--------------------------|
| 1   | loop 1W†      | 356.20, 0.87† | -130– -40†             | 85 × 100†      | 6.3†            | 180        | 150– 180 | 11.5                         | 0.35                     |
|     | loop 1E       | 357.40, 0.73 | -180–120               | 40 × 50         | 0.9             | 110        | 240–310 | 15.7                         |                         |
| 2   | loop 2W       | 355.37, 0.80 | -90– -40               | 30 × 45         | 2.2             | 420        | 30–210  | 55.4                         | 0.16                     |
|     | loop 2E†      | 356.20, 0.87† | -130– -40†             | 85 × 100†      | 6.3†            | 350        | 60–160  | 117.5                        |                         |
| 3   | loop 3W       | 355.50, 0.70 | 45–100                  | 65 × 75         | 6.0             | 350        | 60–160  | 117.5                        |                         |
|     | loop 3E       | 358.34, 0.80 | 70–110                  | 90 × 100        | 2.6             | 350        | 60–160  | 117.5                        |                         |
|     | Clump 2       | 3.10, 0.17   | 30–180                  | 75 × 135        | 63.3            | 350        | 60–160  | 117.5                        |                         |
|     | l = 5.5 complex | 5.47, -0.30  | 30–170                  | 50 × 100        | 19.2            | 350        | 60–160  | 117.5                        |                         |

* Column (1): loop number. (2): Name of foot point. (3): Position of peak integrated intensity. (4): Velocity range. (5): Size of foot point (longitude × latitude). (6): Molecular mass of foot point. We used the X-factor of 0.7 $10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ derived in the text. (7): Projected length between the two foot points. (8): Height of loop top from $b = 0^\circ$. (9): Total molecular mass in loop (including foot point and loop top). (10): Mass ratio between $M_{tot}$ and foot point masses, $M_{fp}$.
† Loop 1W and loop 2E are treated together because it is difficult to estimate separately.

Fig. 11. Integrated intensity distributions of H I and $^{12}$CO ($J = 1–0$) emission. Color images and dashed contours indicate H I emission. Solid contours indicate $^{12}$CO ($J = 1–0$) emission. Dotted lines in figures 11c and 11d show the 3-kpc arm and foreground disk components. (a) Longitude–latitude distributions. The integration velocity range is from -180 to -90 km s$^{-1}$. H I: Contours are plotted at 42 K km s$^{-1}$. $^{12}$CO ($J = 1–0$): Contours are plotted every 4.8 K km s$^{-1}$ from 3.6 K km s$^{-1}$ and every 9.6 K km s$^{-1}$ from 6th one. (b) Longitude–latitude distributions of loop 2. Integration velocity range is from -90 to -40 km s$^{-1}$. Contours are plotted at the same levels in figure (a). (c) Longitude–velocity distributions. The integration range in latitude is shown in figure (a) by solid lines. H I: Contours are plotted at 0.42 K. $^{12}$CO ($J = 1–0$): Contours are plotted every 0.2 K from 0.12 K. (d) Longitude–velocity distributions of loop 2. Contours are plotted at the same levels of figure (c).
Fig. 12. (a) Velocity–latitude distributions of loops 1 and 2 in $^{12}$CO ($J = 1–0$) integrated from 355° to 358° in galactic longitude. Contours are plotted every 0.2 K from 0.2 K (black) and every 0.4 K from the 9th one (white). (b) Velocity–latitude distributions of loops 1 and 2 in $^1$H and CO integrated from 355° to 358° in galactic longitude. Color image and dotted contours indicate H I emission. Solid contours indicate $^{12}$CO ($J = 1–0$) emission. H I: Contours are plotted at 0.4 K. $^{12}$CO ($J = 1–0$): Contours are plotted at the same levels of figure (a).

with IRAS at 60 and 100 μm (Miville-Duchênes & Lagache 2005), where we did not use shorter wavelength data because of possible contamination by the zodiacal light. Figures 13a and 13b show comparisons between the total integrated intensity of $^{12}$CO from −300 to 300 km s$^{-1}$, including loops 1, 2, and 3, and IRAS 60 μm and 100 μm emissions, respectively. We find that the enhanced CO emission above $b = 1°$ in a range of $l \simeq 355^\circ–358^\circ$ shows a good coincidence with the dust emissions; the hole of the CO emission around ($l, b$) = (356°5, 1°2–2°0) is recognized well, particularly at 100 μm. We note, however, that the correlation is not seen due to heavy contamination by the foreground disk emission. Figure 14 shows four panels of CO in different velocity intervals, and suggests that both loops 1 and 3 contribute significantly to the main dust emission at $b$ above $\sim 1°$ and $l \simeq 355^\circ–358^\circ$; e.g., the western half of loop 2 at ($l, b$) $\simeq (355^\circ3, 1^\circ2–2^\circ0)$ shows a clear counterpart in the IRAS emission (figure 14b). There is another CO feature from the foreground in the same region toward ($l, b$) $\simeq (355^\circ3, 1^\circ2–2^\circ0)$ (figure 14c), and both loop 2 and the foreground feature possibly contribute to the dust emission here, whereas the peak of the foreground CO emission around ($l, b$) $\simeq (359^\circ2, 1^\circ7$) shows an offset from the IRAS emission above, suggesting that loop 2 mainly contributes to the dust emission. Figures 15a and 15b, a comparison between IRAS and the H I, where the IRAS emission is convolved to the same beam size with H I, shows that the dust emissions have similar high-$b$ distribution, as in figure 13. We use the convolved data in the following analysis in section 5.

5. Mass Estimates

Estimating molecular mass in the galactic center is important in terms of energetics. It is, however, not appropriate to use the virial theorem, if the magnetic flotation (Paper I) is working and if, accordingly, the gas dynamics is far from the dynamical equilibrium. In Paper I the authors estimated a lower limit for the total molecular mass in loops 1 and 2 with $^{13}$CO because $^{12}$CO observations are confined to $b \leq 1°$. Here, we attempt to derive a more accurate value of the total masses of loops 1, 2, and 3 by comparing the $^{12}$CO integrated intensity and the molecular column density derived from both dust emission and H I emission. We use a velocity range from −300 to 300 km s$^{-1}$ for calculating $^{12}$CO integrated intensity. We estimate the total hydrogen column densities by including helium atoms of 10% of total hydrogen atoms.

We used the following relationship to convert the dust emission into the total column density of hydrogen atoms including both of H I and H$_2$, $N$(H I)$_{dust}$, by assuming the gas-to-dust mass ratio, $R_{gd}$, to be

$$N$(H I)$_{dust} = \frac{4}{3} \left( \frac{\alpha_\rho}{Q_{100}} \right) \frac{\tau_{100} R_{gd}}{1.4 m_H} \text{cm}^{-2}, \tag{1}$$

where $\alpha$ is the grain radius in cm, $\rho$ is the grain density in g cm$^{-3}$, $Q_{100}$ is the grain emissivity at 100 μm, and 1.4 $m_H$ is the atomic hydrogen mass (g) multiplied by a factor for presence of helium. We used an average value for ($\alpha_\rho/Q_{100}$) of $[0.3 \times (10 \times \lambda)^\beta]^{-1}$ at wavelength $\lambda$ for a mixture of graphite and silicate grains (e.g., Agladze et al. 1996). The optical depth at wavelength $\lambda$, $\tau_\lambda$, is represented as
Fig. 13. (a, b) CO integrated intensity distributions superposed on IRAS 60 μm (a) and 100 μm (b). The integration range of CO is from −300 to 300 km s\(^{-1}\). Contours are plotted every 15 K km s\(^{-1}\) from 7 K km s\(^{-1}\) and every 30 K km s\(^{-1}\) from the 5th one. (c) CO integrated intensity distributions without IRAS emission. The contour levels are the same as in figures (a) and (b).

\[
T_{\text{dust}} = \frac{f_{60}}{f_{100}} \left( \frac{60}{100} \right)^{-3\beta} \left\{ \frac{\exp[hc/(\lambda_{60}k_bT_{\text{dust}})] - 1}{\exp[hc/(\lambda_{100}k_bT_{\text{dust}})] - 1} \right\} \frac{\Omega_{60}}{\Omega_{100}}.
\]

where \( f_{60} \) (Jy str\(^{-1}\)) is the flux density at \( \lambda = 60 \) μm, and \( f_{100} \) (Jy str\(^{-1}\)) is the flux density at \( \lambda = 100 \) μm. We estimated the dust temperature, \( T_{\text{dust}} \), by comparing flux densities of 60 μm and 100 μm at each observed point with the following equation:

\[
W(\text{HI})_{\text{HI}} = 1.82 \times 10^{18} \times W(\text{HI}) = 1.82 \times 10^{18} \int T_R^* dV \text{ (cm}^2\text{)},
\]

where \( W(\text{HI}) \) is HI integrated intensity and \( T_R^* \) is the HI radiation temperature (K).

We shall take into account that the CO emission integrated in the whole velocity range consists of that in the galactic center, \( W(\text{CO})_{\text{gc}} \), and that from the fore- and backgrounds, \( W(\text{CO})_{\text{disk}} \). We denote the X-factor in the galactic center, \( X_{\text{gc}} \), by assuming that loops 1, 2, and 3 at ~1 kpc from the center have the same X-factor and \( X_0 = 2.0 \times 10^{20} \text{cm}^{-2} \text{(K km s}^{-1}\text{)}^{-1} \) as the typical value in the disk (e.g., Strong et al. 1988; Hunter et al. 1997; Dame et al. 2001). \( W(\text{CO}) \) is calculated for a velocity range −300–300 km s\(^{-1}\) and \( W(\text{CO})_{\text{gc}} = W(\text{CO}) - W(\text{CO})_{\text{disk}} \). A comparison between \( W(\text{CO})_{\text{gc}} \) and \( N(\text{H}_2) \) in the galactic center is shown in figure 17b, where the latter is
Fig. 14. CO integrated intensity distributions superposed on 100 μm. (a) Loop 1: The integration range is from −180 to −90 km s\(^{-1}\). (b) Loop 2: The integration range is from −90 to −40 km s\(^{-1}\). (c) The galactic disk and local components: The integration range is from −40 to 30 km s\(^{-1}\). (d) Loop 3: The integration range is from 30 to 200 km s\(^{-1}\). Contours in all the figures are plotted every 15 K km s\(^{-1}\) from 7 K km s\(^{-1}\) and every 30 K km s\(^{-1}\) from 5th one.

expressed as

\[
[N(H_2) \text{ in the galactic center}] = W(CO)_{\text{gc}} \times X_{\text{gc}} \tag{5}
\]

\[
= [N(H_2)_{\text{dust}} - N(H_2)_{\text{HII}}]/2 - W(CO)_{\text{disk}} \times X_0. \tag{6}
\]

We chose the tops of the loops shown by the two boxes in figure 15 for this comparison because these regions are not significantly contaminated by the foreground emission, and we can clearly distinguish between the disk components and the loops there (figure 16). Finally, we chose the velocity range of the disk components from −30 to 15 km s\(^{-1}\) (gray area in figure 16) and calculate \(W(CO)_{\text{gc}}\) and \(W(CO)_{\text{disk}}\). We note here that the contribution of ionized hydrogen is negligibly small because the dust content in the H\textsc{ii} regions should become much less than in H\textsc{i} gas due to ultraviolet photons. This is consistent with that the 60 μm and 100 μm emissions are from cold dust grains with dust temperature of \(\sim 20–30\) K. We did not take into account the possible contribution of the unknown component that is not detected either in H\textsc{i} or CO, suggested from the γ rays (Grenier et al. 2005).

We have here two parameters in the fitting, i.e., \(\beta\) and \(R_{\text{gd}}\). In order to simplify the procedure we first fix \(\beta\) to be 2.0, since this index is relatively well established from previous observations (e.g., Draine & Lee 1984). The value of \(R_{\text{gd}}\) is known to be around 100 in the general ISM but can vary depending on the dust fraction in the gas. We made plots of \(W(CO)_{\text{gc}}\) and \(N(H_2)\) in the galactic center from equation (6) for \(R_{\text{gd}}\) from 90 to 290 (figure 17a) and found that the value of the intercept in \(N(H_2)\), the \(N(H_2)\) for \(W(CO)_{\text{gc}} = 0.0\) K km s\(^{-1}\), varies from \(\sim 20 \times 10^{20}\) cm\(^{-2}\) to \(20 \times 10^{20}\) cm\(^{-2}\) in the above range of \(R_{\text{gd}}\). We adopt \(R_{\text{gd}}\) so that the intercept becomes zero, as is the case if the dust is either in the neutral H\textsc{i} or H\textsc{ii} gas. The best-fit result is shown by the solid regression in figure 17b. The \(X\)-factor and \(R_{\text{gd}}\) were estimated to be \(0.7 (\pm 0.1) \times 10^{20}\) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\) and 248 (± 10), respectively. Here we include \(\sim 10\%\) error in the 60 μm intensity, \(\sim 14\%\) error in the 100 μm intensity (Miville-Deschênes & Lagache 2005) and \(\sim 10\%\)
Fig. 15. H I integrated intensity distributions superposed on IRAS 60 μm (a) and 100 μm (b). The integration range of H I is from −300 to 300 km s⁻¹. Contours are plotted every 300 K km s⁻¹ from 100 K km s⁻¹. Black boxes show the regions where we used for mass estimates shown in figure 17.

Fig. 16. Longitude–velocity distributions of the tops of the loops (b ≳ 1.2–2.0). Black boxes show the regions shown in figure 15. Filled gray areas show foreground emission, the extent of which in velocity is from −30 km s⁻¹ to 15 km s⁻¹.

error of the CO integrated intensity. The derived X-factor 0.7 (±0.1) × 10²⁰ cm⁻² (K km s⁻¹)⁻¹ agrees well with an X-factor of 0.8 × 10²⁰ cm⁻² (K km s⁻¹)⁻¹, estimated in the inner Galaxy by comparing the IRAS and gas emission by Bloemen, Deul, and Thaddeus (1990), who used the IRAS, CO, and H I emissions by adopting a model for dust emissivities as a function of the distance from the galactic center. If we use an X₀ of 1.6 × 10²⁰ cm⁻² (K km s⁻¹)⁻¹ (Hunter et al. 1997) for the calculations, R₀ and Xgc are derived to be 220 and 0.6 × 10²⁰ cm⁻² (K km s⁻¹)⁻¹, respectively, fairly similar to the above Xgc. The total molecular masses in loops 1, 2, and 3 are estimated to be ~1.2 × 10⁶ M⊙, ~1.6 × 10⁶ M⊙, and ~5.5 × 10⁶ M⊙ with the present X-factor as given in table 2.

Next, we estimate the molecular mass of the loops with 13CO because there is an uncertainty for mass estimation with optically thick 12CO. We shall extrapolate the mass at b ≳ 1° by comparing W(CO) and the molecular column density estimated from 13CO. The optical depth of 13CO, , was calculated using

$$\tau(13\text{CO}) = -\ln\left(1 - \frac{T_{\text{R}}(13\text{CO})}{5.29 \times [J(T_{\text{ex}}) - 0.164]}\right), \quad (7)$$

where $T_{\text{R}}(13\text{CO})$ and $T_{\text{ex}}$ are the peak radiation temperature (K) and the excitation temperature (K) of 13CO, respectively. $J(T)$ is defined as $J(T) = 1/[\exp(5.29/T) - 1]$. 13CO column density $N(13\text{CO})$ (cm⁻²) was estimated from

$$N(13\text{CO}) = 2.42 \times 10^{14} \frac{\tau(13\text{CO}) \Delta V T_{\text{ex}}}{1 - \exp(-5.29/T_{\text{ex}})} \text{ (cm}^{-2}), \quad (8)$$

where ΔV is the linewidth in km s⁻¹ of 13CO. $N(13\text{CO})$ is calculated for each position which matches the observed position in 12CO. In this study, we assumed $T_{\text{ex}}$ of 40 K and two abundance ratio from 13CO to H₂, [H₂]/[13CO], of 5 × 10⁵ (Dickman 1978) and 1 × 10⁶ (Lis & Goldsmith 1989). A comparison between $W(CO)$ and $N(H_2)$ is shown in figure 18. The conversion functions for loops 1 and 2 and
loop 3 are estimated as $N(\text{H}_2) = [1.1 (\pm 0.2) \times 10^{20} \ W(\text{CO}) - 4.1 (\pm 3.0) \times 10^{21}] \ (\text{cm}^{-2})$ and $N(\text{H}_2) = [1.6 (\pm 0.3) \times 10^{20} \ W(\text{CO}) - 1.1 (\pm 0.5) \times 10^{21}] \ (\text{cm}^{-2})$, respectively. If we use $[\text{H}_2]/[^{13}\text{CO}]$ of $1 \times 10^6$, derived $N(\text{H}_2)$ is doubled. We then calculated the total molecular masses of loops 1, 2, and 3 including $b \geq 1'0$ to be $\sim (0.8-1.6) \times 10^6 M_{\odot}$, $\sim (1.5-3.0) \times 10^6 M_{\odot}$ and $\sim (6.0-12.0) \times 10^6 M_{\odot}$, respectively, consistent with the molecular mass estimated for the present $X$-factor. Here, negative solutions of $N(\text{H}_2)$ are neglected.

The atomic mass of loop 1 was estimated to be $\sim 2.4 \times 10^5 M_{\odot}$, including the mass of $\sim 0.7 \times 10^5 M_{\odot}$ inside of the loop, $(l, b) \simeq (356'5-357'2, 0'^6-1'0)$, and that of loop 2 was estimated to be $\sim 2.5 \times 10^5 M_{\odot}$ for $(l, b) \simeq (355'0-356'0, 1'2-2'5)$, by using equation (4). The loop 2 HI mass is a lower limit since the lower half is not included. Then, the total gas mass of loops 1 and 2 are estimated to be $\sim 1.4 \times 10^6 M_{\odot}$ and $\sim 1.9 \times 10^6 M_{\odot}$, respectively. We also estimated the mass of the foot points to be $1'6 \times 10^5 M_{\odot}$ for each. If we assume a uniform velocity dispersion of 20 km s$^{-1}$ in the loops, the total kinetic energy of each loop amounts to $\sim (1-6) \times 10^{52}$ erg.
6. Geometry and Kinematics of the Loops

Paper II derived the geometrical and kinematic properties of loop 3 by assuming a constant radius. We shall here estimate the geometrical and kinematical parameters of loops 1 and 2, such as the radius, rotation, and radial velocities following Paper II with small modifications.

First, we estimate the geometrical parameters of the loops. For simplicity we assume that the two loops have the same radius, physical length, and shape and subtend the same angle with respect to the center. By considering triangles, the corners of which are the galactic center, the Sun, and a foot point of loops (the left foot point of loop 1: \( l_0 \approx 357.5 \), the right foot point of loop 1 and the left foot point of loop 2: \( l_1 \approx 356.0 \), and the right foot point of loop 2: \( l_2 \approx 355.5 \)), we can derive simultaneous equations by applying the sine theorem to the three triangles:

\[
R = \frac{R_0 \sin l_0}{\sin (\theta_0 + l_0)},
\]

\[
R = \frac{R_0 \sin l_1}{\sin (\theta_0 + \theta + l_1)},
\]

\[
R = \frac{R_0 \sin l_2}{\sin (\theta_0 + 2\theta + l_2)}.
\]

where \( R \) is the radius, \( R_0 \) is the distance to the galactic center, 8.5 kpc, \( \theta \) is the angles subtended by the arcs between the foot points at the galactic center and \( \theta_0 \) is an offset. A schematic view of these parameters is shown in figure 19. We then solved the equations and derived \( R, \theta_0, \) and \( \theta \) to be \( \approx 670 \) pc, \( \approx 27.5 \), and \( \approx 31^\circ \), respectively. Therefore, the location of the left end of loop 1 is at \( \theta_0 \approx 27.5 \), the right end of loop 1 and the left end of loop 2 is at \( \theta_0 + \theta \approx 58.5 \), and the right end of loop 2 is at \( \theta_0 + 2\theta \approx 89.5 \). The projected length to the disk of each loop, \( L \), is 360 pc.

Next, we estimated the kinematical parameters of the loops. It is uncertain if the loops have radial motions. Some other features like the expanding molecular ring (EMR) are supposed to be expanding (Sawada et al. 2001; Morris & Serabyn 1996). We for simplicity assumed that the loops are rotating and expanding from the center although the expansion is not yet confirmed in loops 1 and 2. All of the molecular gas of loops 1 and 2 has negative velocities. The velocity with respect to the LSR, \( V_{LSR} \), is then expressed as follows:

\[
V_{LSR} = V_{\text{exp}} - \frac{R_0}{R} \sin l - V_{\text{rot}} \left( 1 - \frac{R_0^2}{R^2} \sin^2 l \right)^{1/2} - V_{\text{sun}} \sin l,
\]

where \( V_{\text{rot}} \) is the rotational velocity of the disk, \( V_{\text{exp}} \) is the expansion velocity, and \( V_{\text{sun}} \) is the rotation velocity of the LSR about the center \( \approx 200 \) km s\(^{-1}\). We estimated that \( V_{\text{exp}} \) to be \( \approx 141 \) km s\(^{-1}\) and \( V_{\text{rot}} \) to be \( \approx 47 \) km s\(^{-1}\). These parameters are listed in table 3 for the three loops, and figure 19 shows a schematic face-on view of these loops. The radius of loops 1 and 2 is somewhat smaller than that of loop 3.

7. Discussion

We here discuss the loops along the line of the Parker instability following Paper I, and do not repeat the discussion on the other possibilities, including supershells (Papers I and II).

7.1. Magnetic Flotation Theory and Its Application to the Loops

Parker (1966) presented pioneering work on the Parker instability in order to explain cloud formation in the foot point of a magnetic loop in the Galaxy. Horiuchi et al. (1988) and Matsumoto et al. (1988) made detailed studies of the Parker instability analytically with a linear analysis, and numerically included nonlinearity. Their results indicate that the fundamental parameters are the Alfvén speed, \( V_A = B/\sqrt{4\pi \rho} \), and the pressure scale height, \( H \), where \( B \) is the magnetic field, and \( \rho \) is the gas density. The height and length of a loop is given as a few-times \( H \) and several-times \( H \), respectively. A typical timescale is given by the ratio \( H/V_A \). A reasonable scenario is that the differential rotation in the nuclear disk creates toroidal magnetic field where the molecular gas is frozen-in to the field lines; the molecular gas in the disk is ionized at an ionization degree of \( \approx 10^{-7} \) by cosmic ray protons and the ionization degree is high enough for the frozen-in condition (e.g., Güsten & Philipp 2004). Indirect arguments on the arching...
filaments suggest that the field strength is as large as ~1 mG (Yusef-Zadeh & Morris 1987), ~1000-times larger than the typical field strength of ~μG in the disk, whereas the field strength may be much less in lower density regions (LaRosa et al. 2006). The magneto-hydrodynamics (MHD) describes well the gas disk. The mG field is a natural outcome of the gravitational potential in the central few 100 pc, which is more than a few 10 times deeper than in the disk. An outstanding observational property of a magnetic floatation loop is that the falling down gas often becomes supersonic and forms shock fronts at both ends of the loop, where the gas density and velocity dispersion become enhanced (Matsumoto et al. 1988). These compressed regions appear as foot points of enhanced density. This supersonic motion and heating indicate that magnetic floatation may explain the origin of the high temperature and violent motion in the galactic center (Paper I).

Three molecular loops, loops 1, 2, and 3, were discovered in the galactic center, and an interpretation was presented that they are created by the Parker instability in the magnetized nuclear disk with a field strength of ~150 μG (Papers I, II). The three loops show sizes consistent with the theoretical predictions for a scale height of ~100 pc in the central several 100 pc. They also show foot points on their both ends, and the gas in the foot points appears to be heated and compressed by the shock fronts. For a strong field of 100 μG and gas density of 100 cm⁻³, the Alfvén speed is a few 10 km s⁻¹ and the flotation time scale becomes a few Myrs for a 100 pc scale height. An LVG analysis of the CO J = 1–0, 3–2, and 4–3 transitions indicates that the typical gas temperature is about ~30–50 K or more in the foot points of loops 1 and 2, whereas no stellar heat source is found there (Torii et al. 2010). These are reasonable properties of the foot points in the magnetic flotation. We note that another remarkable aspect of the loops is the spur, a vertical upward flow of gas above the foot point reaching a height more than the loop height. The present velocity channel distributions show evidence for such a spur in two places, offering additional pieces of evidence that support the magnetic flotation picture.

Generally, it is easier for lower density gas to be lifted up rather than for dense molecular gas by magnetic floatation, and it might seem odd that the dense molecular gas rises rather than for dense molecular gas by magnetic floatation, although it is actually observed in the sun. We also note that the ambient H I gas is perhaps being converted into H₂ during flotation. The shock compression by the rising loop in the upper part may lead to form molecular gas along the loop which is initially atomic. It is likely that the loop is surrounded by H I gas, and that the motion of the flotation at Vₐ inevitably causes shocks in the front side. This can lead to form H₂ in the shock-compressed layer along the loop. The time scale of H₂ formation is given as 10³/n(H) yr, where n(H) is the number density of H I gas in cm⁻³ (Spitzer 1978), and is estimated to be ~10 Myr for n(H) of 100 cm⁻³. This time scale is consistent with the present ratio H₂/Vₐ.

A global aspect of the loops on a kpc scale is also to be compared between theories and observations. Machida et al. (2009) carried out three-dimensional global numerical simulations of the nuclear gas disk and showed that the magneto-rotational instability coupled with the Parker instability works to create many loops over a 2 kpc-radius nuclear disk, where the axially symmetric Miyamoto–Nagai potential (Miyamoto & Nagai 1975) was adopted as the stellar gravitational field. Machida et al. (2009) have shown that a one-armed non-axisymmetric density pattern of m = 1 mode is developed in the nuclear disk. In half of the azimuthal area of the nuclear disk having lower density, the magnetic pressure tends to become stronger compared with the gas pressure, and prominent magnetic loops are formed preferentially on this side of the disk, rather than in the other half having higher density. Such predicted asymmetry of the global distribution of the loops generally seems to be consistent with the observations that about three-fourths of the dense molecular gas, the CMZ, is distributed in the positive galactic longitude and that three loops are distributed in the negative galactic longitude. We note that Clump 2 and the l = 5°5 complex are located outside the CMZ where the surface gas density is lower than in the CMZ, but is yet higher than in the negative longitude side where loops 1–3 are distributed. This is consistent with the global simulations.

The bar-like gravitational potential is considered to be a viable mechanism to explain the radial motions of the gas in the central few 100 pc of the Galaxy (Binney et al. 1991, see also Liszt 2006). In order to incorporate the effects of the bar-like potential, it is required to develop a model that adopts the bar potential instead of the Miyamoto–Nagai potential in the global simulations of the magnetized gas disk. It is naturally expected that magnetic floatation loops are also created in such calculations because the basic physics remains the same in connection with the Parker instability.

7.2 Comparisons with the Solar Phenomena

The present study revealed helical distributions of the loops. On the solar surface we find similar helical distributions which may be explained by MHD instabilities. Figures 8 and 9 reveal that loops 1 and 2 have helical distributions that change within a small velocity interval of ~4 km s⁻¹. We shall compare these distributions with solar loops and theoretical calculations of magneto-hydrodynamics and discuss formation mechanisms of the helical distributions.

First, we attempted to estimate the amplitude and wavelengths of the helix by applying sinusoidal and elliptical functions, as follows;
where \( l_c \) and \( b_c \) are the central position of an ellipse, \( X \) and \( Y \) are the semi-major and semi-minor axes of the ellipse, \( A \) is the wave amplitude, \( k \) is the wave number in the ellipse, \( \Theta \) is defined as \( \Theta = \arctan(Y/(l - l_c)/X(b - b_c)) \) and \( \Delta \Theta \) is an offset of \( \Theta \). As a result we find the parameters in table 4 show reasonable fits to the observations, as shown in figures 8 and 9. The wavelengths of helix in loops 1 and 2 are estimated to be \( \sim 0.28 \) (41 pc)–\( 0.42 \) (62 pc) and \( \sim 0.28 \) (41 pc), and the amplitudes are estimated to be \( \sim 0.2 \) (29 pc)–\( 0.34 \) (50 pc) and \( \sim 0.26 \) (38 pc), respectively.

Next we compare the above results with the solar phenomena. It has been known that solar prominences show helical distributions (e.g., Matsumoto et al. 1998). The formations of prominences are discussed under the following two ideas: (1) Magnetic flux tubes having helical shapes originally rise up, and (2) Magnetic reconnection in the corona forms a helical shape. Recent Hinode observations show evidence for (1) (Okamoto et al. 2008) and we shall discuss possibility of formation of the distorted field in the disk. One possible candidate along this line is the shear effect. A gas disk rotating differentially drives the magneto–rotational instability (MRI: Balbus & Hawley 1991) due to the shear motion. MRI drives magnetic turbulence inside the disk (e.g., Hawley et al. 1995; Matsumoto & Tajima 1995), and distorted fields are formed.

Another possibility including (2) is discussed by Shibata and Matsumoto (1991). They suggested that floating loops driven by the Parker instability could be affected by the Coriolis force, and the loops are twisted. Then, the twisted fields are accumulated in the foot points of the loops by falling motion of gas.

In addition, Matsumoto et al. (1998) showed that distorted magnetic field lines become unstable against the kink instability form a helical shape while they rise. Hood and Priest (1981) give a condition of the kink instability as the number of turns in the helical distributions in a loop where \( \Phi > 2.5 \). Observed helical distributions in loops 1 and 2 are estimated to be \( \sim 3\pi \) and \( \sim 5\pi \), respectively, satisfying the requirement.

The present findings of the helical distributions in loops 1 and 2 offer support for that the magnetic floatation is a viable idea to explain these features, and that more detailed numerical simulations are desirable in this direction.

8. Summary

We have presented a detailed study of molecular loops 1 and 2 in the galactic center based on the NANTEN \(^{12}\)CO and \(^{13}\)CO (J = 1–0) dataset. The main conclusions are summarized below:

(1) A full account of the \(^{12}\)CO dataset at 10 pc resolution obtained with the NANTEN 4 m telescope is presented mainly in velocity channel distributions every 10 km s\(^{-1}\) from \(-180\) to 20 km s\(^{-1}\) for an area (\( l, b \)) \( \simeq (355.0\text{'}–359.0\text{'} , -1.0\text{'}–2.5\text{'} ) \). For part of the area, the \(^{13}\)CO distribution is also presented. We newly identified helical distributions in the tops of loops 1 and 2, an unusual small loop-like feature in the western foot point of loop 2 and two spurs above the foot points.

(2) We compared the foot points of loops 1 and 2 with the known two broad molecular features Clump 2 and the \( l = 5^\circ 5 \) complex and found that they share common properties; the elongation vertical to the plane with a size of \( \sim 30 \) pc \( \times \) 100 pc and large velocity spans of \( 50–150 \) km s\(^{-1}\), suggesting that they may be of a similar origin. Most of them have \( \sim 10^{3}–10^{6} \) \( M_{\odot} \), whereas Clump 2 is the most massive one of \( \sim 10^{6} \) \( M_{\odot} \).

(3) A comparison with the HI emission indicates that loops 1 and 2 have atomic components, while the atomic component in the lower part of loop 2 is not seen due to heavy contamination by the foreground features. The mass fraction of the atomic component is \( 10\%–20\% \) of the molecular component, indicating that the atomic gas is a minor component in the loops.

(4) A comparison with the dust emission at 60 \( \mu \)m and 100 \( \mu \)m shows that loops 1, 2, and 3 are associated with the dust features at \( b \) higher than 1\( ^\circ \), whereas the association is not clear at \( b \) lower than 1\( ^\circ \) due to the contamination. Based on the good correlation among CO, HI, and dust, we derived an \( X \)-factor for the central kpc to convert the \(^{12}\)CO intensity to molecular hydrogen column density to be \( 0.7(\pm 0.1) \times 10^{20} \) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\).

(5) The total mass of loops 1 and 2 are estimated to be \( \sim (1.4–1.9) \times 10^{6} \) \( M_{\odot} \). The total kinetic energy of loops 1 and 2 are estimated to be \( \sim 10^{52} \) erg for the observed velocity dispersions.

(6) By assuming that the two loops are of the same size at radius \( R \) from the center, we estimated the geometrical and kinematical properties of the loops; the projected length of a loop, \( L \), the angle subtended by a loop, \( \theta \), and the rotation and expansion velocities, \( V_{\text{rot}} \) and \( V_{\text{exp}} \). The results are as follow:

\[ R \approx 670 \text{pc}, L \approx 360 \text{pc}, \theta \approx 31^\circ, V_{\text{rot}} \approx 47 \text{km s}^{-1}, \text{and } V_{\text{exp}} \approx 141 \text{km s}^{-1}. \]

(7) Recent theoretical work both in global 3-dimensional and local 2-dimensional on magneto flotation loops (Machida et al. 2009; Takahashi et al. 2009) were compared with the observations, and we confirmed that the theoretical results are consistent with the observational properties of the two loops.

The helical distributions in the loop tops were compared with...
similar solar features, and we found that the basic parameters of a helical distribution can be explained in terms of magnetic effects.

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