THE FOSSIL NUCLEAR OUTFLOW IN THE CENTRAL 30 pc OF THE GALACTIC CENTER

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ABSTRACT

We report a new 1 pc (30") resolution CS(J = 2 − 1) line map of the central 30 pc of the Galactic center (GC), made with the Nobeyama 45 m telescope. We revisit our previous study of an extraplanar feature called the polar arc (PA), which is a molecular cloud located above SgrA*, with a velocity gradient perpendicular to the galactic plane. We find that the PA can be traced back to the galactic disk. This provides clues to the launching point of the PA, roughly 6 × 106 years ago. Implications of the dynamical timescale of the PA might be related to the Galactic center lobe at parsec scale. Our results suggest that, in the central 30 pc of the GC, the feedback from past explosions could alter the orbital path of molecular gas down to the central tenth of a parsec. In the follow-up work of our new CS(J = 2 − 1) map, we also find that, near systemic velocity, the molecular gas shows an extraplanar hourglass-shaped feature (HG-feature) with a size of ~13 pc. The latitude-velocity diagrams show that the eastern edge of the HG-feature is associated with an expanding bubble B1, ~7 pc away from SgrA*. The dynamical timescale of this bubble is ~3 × 106 years. This bubble is interacting with the 50 km s−1 cloud. Part of the molecular gas from the 50 km s−1 cloud was swept away by the bubble to b = −0.2. The western edge of the HG-feature seems to be molecular gas entrained from the 20 km s−1 cloud toward the north of the galactic disk. Our results suggest a fossil explosion in the central 30 pc of the GC, a few 106 years ago.

Key words: Galaxy: center – Galaxy: structure – ISM: molecules – radio lines: ISM – techniques: image processing

Supporting material: extended figure

1. INTRODUCTION

Because our Galactic center (GC) is the nearest nucleus of a galaxy (d = 8.5 kpc) (Reid 1993; Ghez et al. 2008; Reid et al. 2014), it is the best target for study of detailed structures and dynamics in a circumnuclear environment at sub-pc scale, which, using ground-based telescopes, cannot be easily done in external galaxies. However, observations of the GC suffer from our edge-on vantage point. Optical and near-infrared (IR) emissions suffer from large amounts of extinction. The V-band extinction (AV) varies from 20 to 50 mag, with a median value of 31.1 mag (Scoville et al. 2003). Dust is transparent at radio wavelengths. However, at millimeter wavelengths, the more abundant molecular lines (e.g., CO, J = 1 − 0) become optically thick and suffer from foreground absorption or self-absorption in a direction toward the GC (Guesten et al. 1987; Wright et al. 2001; Christopher et al. 2005). High-excitation molecular lines and high-density tracers are less affected by the foreground/ambient cold gas (Jackson et al. 1993; Tsuboi et al. 1999; McGary et al. 2001; Herrnstein & Ho 2002, 2005; McGary & Ho 2002; Montero-Castaño et al. 2009).

Fruitful studies have already been carried out with low-excitation molecular lines and low angular resolutions (e.g., Scoville 1972; Burton & Liszt 1983, 1992; Bally et al. 1987, 1988). Our focus is on the complex activities and physical conditions in the nuclear region probed by the dense molecular gas. We have conducted wide-field single-dish observations of the central 30 pc of the GC, with multiple transitions of the CS molecule (Hsieh et al. 2015, hereafter paper I). In paper I, we report a new feature called the connecting ridge (CR) that was detected with the CS(J = 4 − 3) line. The CR has a velocity gradient perpendicular to the disk rotation. It is physically associated with the extraplanar polar arc (PA) (Bally et al. 1988; Henshaw et al. 2016). The PA extends from north of the SgrA* region at a 40° angle and shows a large velocity gradient from (l, b, VLSR) = (0°, 0.05, 70 km s−1) to (0°2, 0.25, 140 km s−1). Below VLSR of 70 km s−1, the PA lies close to the galactic plane and becomes confused with the molecular clouds in the SgrA* region. In paper I, we find that the kinematic and spatial structures connect the Galactic disk, the CR, and the PA. These results suggest that the molecular gas might be lifted out of the galactic plane. Thus, we propose the idea of a molecular outflow in the central 30 pc of the GC and suggest that the PA is pushed away, possibly by the energy of 8–80 supernovae explosions. The importance of galactic outflows is that they may be the primary mechanism to recycle metals and deposit them into the intergalactic medium (Veilleux et al. 2005). In starburst galaxies, vast amounts of stellar winds from massive stars, as well as supernovae explosions, generate a huge amount of energy and high pressure to create high-velocity galactic winds, which interact with and sweep up the ambient gas. Our GC is the nearest nucleus, and, therefore, it is the best target to resolve the structure, kinematics, and physical conditions of nuclear outflows. The presence of atomic and molecular gas allows us to measure the outflow of neutral material, its impact, and the transfer of energy and momentum to the surrounding interstellar medium (ISM). In this paper, we...
2. OBSERVATIONS AND DATA REDUCTION

The central molecular zone (CMZ) of the Milky Way was observed in the CS(\(J = 2 - 1\)) (97.98093 GHz) line with the 45 m telescope of the Nobeyama Radio Observatory (NRO)\(^5\) in 2012 May. The FWHM of the beam size at this frequency was \(\sim 17''\). We used the 25 elements of the focal plane receiver (BEam Array Receiver System: BEARS) (Sunada et al. 2000) to observe the central 108' \times 27' (\(l \times b\)) area of the CMZ in On-the-Fly (OTF) mapping mode (Sawada et al. 2008) with position-switching. As the backend spectrometer, we used digital auto-correlators with a bandwidth of 512 MHz with a spectral resolution of 500 kHz with 1024 channels. The total bandwidth was \(\sim 1740\) km s\(^{-1}\); with a resolution of 1.3 km s\(^{-1}\) in the raw data.

The mapping area was arranged into four sub-regions, each covering 27' \times 27'. We sampled an emission-free reference (OFF) position at \((l, b) = (1^\circ, -0^\circ7)\) for every two 35 s on-source scans along each sub-region. The sampling interval along the scan rows was 5'1, and the separation between the scan rows was 7'5, which corresponds to roughly 1/3 and 1/2 of the beam, respectively. We scanned along the \(l\) and \(b\) directions in order to minimize scanning artifacts with the basket-weave method (Emerson & Graeve 1988). These artifacts likely originate from pointing errors, time variations of the system temperature \(T_{\text{sys}}\), insufficient sampling grids, and the non-uniform beam separations of the BEARS elements (Sawada et al. 2008).

The pointing of the antenna was corrected by measuring the SiO maser VX Sgr every hour with the SIS receiver S40 in the 40 GHz band. The double side band (DSB) \(T_{\text{sys}}\) varied from 300 to 700 K during our observations. We used the standard chopper wheel method to calibrate the output signal into the antenna temperature \(T_A\), which was corrected for atmospheric attenuation. Because the original \(T_{\text{sys}}\) measured by BEARS were DSB \(T_{\text{sys}}\), we needed to measure the relative gains of the two sidebands. We used the single beam receiver S100, equipped with a single side band (SSB) filter to observe a calibrator. Every beam of BEARS was then scaled to convert from \(T_A^{\text{DSB}}\) to \(T_A^{\text{SSB}}\). The main beam efficiency \(\eta_{\text{MB}}\) was \(\sim 43\%\). In the maps presented here, we are using the \(T_A^{\text{SSB}}\) scale.

We used the NOSTAR package (Sawada et al. 2008) to reduce our OTF data. The baselines were subtracted with linear or higher-order polynomial functions, and bad scans were flagged. During the observations, one of the receivers (A09) had abnormally high \(T_{\text{sys}}\). Therefore, the data of A09 were flagged, and we only used 24 receivers. The resulting gridding size of the map is 7'5, with an effective final resolution of 21' with Bessel–Gaussian convolution and an rms noise of 0.1 K \((T_A)\) at a velocity resolution of 2.5 km s\(^{-1}\). In this paper, we present the CS(\(J = 2 - 1\)) line data for the central 30' (70 pc) region of the Milky Way. Complete CS(\(J = 2 - 1\)) data for the CMZ will be presented in another paper.

\(^5\) Nobeyama Radio Observatory is a branch of the National Astronomical Observatory of Japan, National Institutes of Natural Sciences.

3. THE CENTRAL 30 PC OF THE MILKY WAY

3.1. CS(\(J = 2 - 1\)) Line Map

In Figure 1, we show the CS(\(J = 2 - 1\)) and CS(\(J = 1 - 0\)) (Tsuboi et al. 1999) integrated intensities. We overlay the...
CS$(J = 2 - 1)$ channel maps on the VLA archival 20 cm radio continuum emission in Figure 2. The noise levels of these two data sets are comparable. The integrated intensity maps of both transitions are smoothed to $30''$ ($\sim 1$ pc) for comparison. In general, the structures are consistent in both transitions, but the new CS$(J = 2 - 1)$ line map reveals more details and extended emission than the CS$(J = 1 - 0)$ line. This is due to the high excitation properties of the GC (e.g., Morris & Serabyn 1996). Two molecular clouds, called the 20 km s$^{-1}$ cloud (hereafter 20 MC) and 50 km s$^{-1}$ cloud (hereafter 50 MC), are well-studied in the GC (e.g., Guesten et al. 1981; Tsuboi et al. 2009; Liu et al. 2012). These two clouds are part of the CMZ (e.g., Morris & Serabyn 1996). The 50 MC is known to interact with the SNR SgrA East (e.g., Serabyn et al. 1992), and the 20 MC is feeding the circumnuclear disk (CND) (e.g., Ho et al. 1985), which is a ring-like feature between the 20/50 MC (e.g., Harris et al. 1985; Guesten et al. 1987; Mezger et al. 1989; Jackson et al. 1993; Wright et al. 2001; Herrnstein & Ho 2002, 2005; Christopher et al. 2005; Montero-Castaño et al. 2009; Amo-Baladrón et al. 2011; Etxaluze et al. 2011; Martín...
et al. 2012; Requena-Torres et al. 2012; Lau et al. 2013; Mills et al. 2013). The CND shows a fast rotation from −120 to 120 km s\(^{-1}\). It is known to have a high excitation state and is, thus, more clearly seen in CS\((J = 2 - 1)\) than in CS\((J = 1 - 0)\) (e.g., McGary et al. 2001; McGary & Ho 2002; Montero-Castaño et al. 2009). The PA (Bally et al. 1988) is a high-velocity cloud with velocities up to \(\pm 100\) km s\(^{-1}\). It shows a high gas density (Tsuboi et al. 1999), but its origin is not clear. In paper I, we reported that the PA appears to be physically connected to the galactic disk and it may originate from there. The PA is also the molecular counterpart of the eastern spur of the Galactic center lobe (GCL) (e.g., Sofue 1996). The CS\((J = 2 - 1)\) line emission located at the base of the PA appears both at the negative velocity of \(-50\) km s\(^{-1}\) and at the positive velocities of \(60\)–\(80\) km s\(^{-1}\). This double-peak feature is called the molecular loop (ML) in paper I.

In Figure 2, we note that the CS\((J = 2 - 1)\) emission seems to have an interesting spatial association with the 20 cm radio continuum. In particular, the molecular gas around \(-20\) km s\(^{-1}\) to 20 km s\(^{-1}\) shows an hourglass-shaped feature (hereafter HG-feature), with a northwest–southeast orientation perpendicular to the galactic disk, with the openings or cavities that surround the radio halo (Pedlar et al. 1989; Zhao et al. 2014). In the negative galactic plane, the 20/50 MC seem to surround the southern radio halo. Above SgrA*, there is also some molecular gas that coincides with the filaments inside the radio lobe. We compare this with the previous CS\((J = 1 - 0)\) line map (Tsuboi et al. 1999). To avoid any possible contamination from the 20/50 MC, we show, in Figure 3, the intensity map integrated for\(\pm 10\) km s\(^{-1}\) based on higher-resolution channel maps (2.5 km s\(^{-1}\) resolution). We overlay the CS line maps on the 20 cm continuum map to show more clearly the HG-feature structures. In general, CS\((J = 2 - 1)\) and CS\((J = 1 - 0)\) have a similar morphology. With a comparable sensitivity, our new CS\((J = 2 - 1)\) line emission shows a more extended structure than CS\((J = 1 - 0)\).

In Figure 4, we display the color-composite map of the 20 cm (Yusef-Zadeh et al. 2004) and the MSX E-band 21 μm map (Simpson et al. 1999, 2007; Price et al. 2001). We compare the CS\((J = 2 - 1)\) line emission with the dust (21 μm) and the emission from free electrons (20 cm). The map shows that low-velocity gas roughly surrounds the infrared/radio features. The 21 μm emission shows a prominent GC bubble (Simpson et al. 2007) (GC bubble, or arc bubble in Ponti et al. 2015) near the SgrA radio halo/arc. The northern part of the GC bubble has a radio feature known as the “radio arc” (e.g., Yusef-Zadeh et al. 1984; Serabyn & Guesten 1987; Lang et al. 1999). The GC bubble could be produced by starbursts that occurred in the past (Sofue 2003; Simpson et al. 2007). Our CS\((J = 2 - 1)\) line map spatially coincides with the infrared/radio features. The HG-feature seems to surround the warm dust and the free-electron emission.

In summary, our new high-resolution/excitation CS\((J = 2 - 1)\) line map suggests that motions in the central 30 pc are not simply rotation but are also associated with structures in the vertical direction of the galactic plane. In the following, we will revisit the association of the known features with the HG-feature and the PA.

3.2. Latitude–Velocity Diagrams

Latitude–velocity diagrams (\(b–v\) diagram) of the CS line data are presented to investigate the extraplanar kinematics. Figure 5 specifies the range for the \(b–v\) diagrams. The \(b–v\) diagrams are presented for both CS\((J = 2 - 1)\) and CS\((J = 1 - 0)\) data at a resolution of \(30''\) × \(5\) km s\(^{-1}\) (Figures 6–8). In order to improve their signal-to-noise ratios, the \(b–v\) diagrams are averaged every \(2'/6\) in longitude (\(\Delta\ell\)) for individual sub-regions (A–E). The gaps between regions are \(30''\), which corresponds to the convolved beam size. As shown in Figure 5, regions A and B present the eastern edge of the HG-feature. Region C covers SgrA* and the CND. Regions D and E cover the western edge of the HG-feature. From a visual inspection, there are several apparent features in the \(b–v\) diagrams. In the top panel of Figure 6, we also present the \(b–v\) diagram averaged over the entire HG-feature (from \(l = 0''70\) to \(l = -0''18\)) (Regions A–E). In the following, we briefly
The 50 MC appears in the regions A–C (Figures 6 and 7). Tsuibo et al. (2009) discussed the expanding properties of the central 50 MC (Region B). An SNR candidate is located in the expanding shell in the 50 MC (Tsuibo et al. 2009). The 20 MC appears in the regions D and E. (Figure 8). An SNR candidate, G359.92–0.09 (wisp; Ho et al. 1985, l = 359°89, b = -0°086), in the GC region was studied by the ASCA and the Chandra telescopes (Senda et al. 2003). The interaction of the wisp and the 20 MC was also investigated by Ho et al. (1985) and Coil & Ho (2000).

2. *The CND:* the CND appears in the regions C and D (Figures 7 and 8) in CS( J = 2 – 1). As shown in the channel maps, it has high velocities of up to ±120 km s⁻¹, and a steep velocity gradient as compared to the galactic disk. The CND is known to have high excitation (Montero-Castaño et al. 2009; Mills et al. 2013). This explains why the CND appears more significant in CS(J = 2 – 1) than in CS(J = 1 – 0).

3. *The High-Velocity Compact Cloud (HVCC) CO 0.02–0.02:* in region B, there is a high-velocity clump (b = -0°015; v ~ 90 km s⁻¹) with a broad linewidth ≥100 km s⁻¹ and with sizes of ~3–4 pc. This is one of the HVCCs studied by Oka et al. (1999, 2008) (CO 0.02–0.02). This HVCC is located in the “finger-like” ridge that connects to the CND. This HVCC was suggested to be impacted by the SN explosions resulting in an unusually high density and temperature (Oka et al. 1999, 2008, 2011).

4. *The PA:* the PA represents a pair of arcs with positive and negative components above the galactic plane (green dashed lines, Figures 6–8) that extend down to b ≤ 0°23 and become confused with the galactic disk. A velocity gradient of ~5.5 km s⁻¹ pc⁻¹ is seen across the PA. The ML mentioned in Section (3.1) is located at the contact point of the PA and the galactic disk around b = 0°03. Velocities of the ML at the intensity peaks are ~60 km s⁻¹ and ~50 km s⁻¹. The ML and the PA appear from regions A to E, with a spatial length of ~34 pc. The ML seems to be part of the PA in the b–v diagrams based on their coherent locations and kinematics. The CS( J = 4 – 3) CR studied in paper I fills the gap between the positive-velocity knot of the ML and the galactic disk. In addition, the positive-velocity component is brighter than the negative-velocity component by a factor of ~1.5. The b–v diagrams of the PA and ML indicate an accelerating and expanding motion perpendicular to the galactic disk. Similar kinematic structures are seen in outflows from starburst galaxies (e.g., Walter et al. 2002; Tsai et al. 2009; Bolatto et al. 2013), but on kilo-pc scales. It is particularly important to note that all the emissions north of the galactic plane, with positive and negative velocities, converges in the b–v diagrams toward SgrA* in the nucleus of the galaxy in our high-resolution map.

5. *The Newly Found Bubble?:* in Figure 6, a low-level emission as indicated by the red ellipse in the southern galactic plane shows a half-curve feature with a central cavity (here, we call this feature B1). The newly found B1 appears in regions A–C, and seems to extend to the northern galactic plane marked by the blue ellipse, called B2 in Figure 6. The kinematics of B1 can be explained by an expanding bubble in the b–v diagrams. Above b = -0°1, B1 is blended with the 50 MC and

Figure 4. Color-composite image of 20 cm VLA map (blue) (Yusef-Zadeh et al. (2004), courtesy of Dr. Yusef-Zadeh) and archival MSX E-band (21 μm) map (red) (Price et al. 2001). The CS(J = 2 – 1) line contour maps integrated over ±10 km s⁻¹ are overlaid. The hourglass feature is marked with white small crosses and a dashed line box. SgrA* is marked as a large cyan cross. The ML and the 20 MC was also investigated by Ho et al. (1985) and Coil & Ho (2000).

Figure 5. Regions made for the latitude velocity diagrams are shown in the CS(J = 2 – 1) line map. Each region covers a width of 2.6° in longitude. The color map is identical to the one in Figure 1 and the contour image is identical to Figure 3. Regions A–E are marked. The central large red cross marks the position of SgrA*. Small black crosses mark the HG-feature. The spacing between regions corresponds to the convolved beam size of 30".

summarize the known/new features with our new wide-field data in this complicated region.

1. **The 20 MC and 50 MC:** in Figure 6, the 20/50 MC appear south of the galactic plane, from b = -0°102 to b = -0°14, with velocities from ~80 km s⁻¹ to ~30 km s⁻¹. These two molecular clouds are well-studied and known to be located in the galactic disk (e.g., Guesten et al. 1981; Serabyn et al. 1992; Coil & Ho 2000; McGary et al. 2001; Liu et al. 2012). The morphology of these two clouds is consistent in both CS lines.
−13 km s⁻¹ cloud. The structure inside the galactic disk is very complicated, and it is not clear how to identify the boundary of the northern side of either B1 or B2. For a visual inspection, the center and the radius of B1 are \((b, v) = (−0.098, 19 \text{ km s}⁻¹)\) and \((\Delta b, \Delta v) = (0.01, 40 \text{ km s}⁻¹)\), respectively. In regions A–C, some gas in the 50 MC shows a smooth connection to the B1 from 40 to 70 km s⁻¹. To avoid any contamination from the CND, we present intensity ratio maps by averaging regions A and B (Figure 9). We exclude ratios lower than 3σ, and hence, the emission in the southern galactic plane is discarded due to its low-level emission. High ratios \(\geq 3.5\)
appear in the HVCC CO 0.02–0.02 and in B2. At the contact point of the 50 MC and B1, the ratios are also $\gtrsim 3.5$. In general, the remaining disk emission has ratios lower than 2.

6. The Hourglass-Shaped (HG) Feature: we have identified the HG-feature in the low-velocity channels (Figure 2). Here, we investigate the kinematics of this structure in the $b-\nu$ diagrams. We are specifically examining the extraplanar nature of this feature. The low-velocity structure of the HG-feature is labeled as a yellow box in Figures 6–8, where the regions A/B and D/E trace the eastern and western edges, respectively. The eastern edge of the HG-feature (region A) corresponds to the blueshifted side of the B1. This side is not blended with the 50 MC and 20 MC, and hence can be seen as a half-shell feature. The western edge of the HG-feature (region D) shows a half-arc feature and seems to smoothly connect to the 20 MC out to the northern plane (western HG), with increasing velocity. The western HG is mostly located between $-10\,\text{km}\,\text{s}^{-1}$ and $10\,\text{km}\,\text{s}^{-1}$. We also present the intensity ratio map generated by averaging
regions D and E in Figure 9. The high-ratio (≥3) data concentrate on the western HG.

4. PA: GC MOLECULAR OUTFLOW?

In the $b$–$v$ diagrams, we find that the velocity of the PA is linearly increasing along the galactic latitude to more than 100 km s$^{-1}$. This can be interpreted as an expanding motion. Similar features caused by kpc-scale molecular outflows are seen in the nearby starburst galaxies, e.g., NGC 2146, NGC 3628, NGC 253, and M82 (García-Burillo et al. 2001; Walter et al. 2002; Tsai et al. 2009; Bolatto et al. 2013). These molecular outflows are suggested to be the late evolved stage of superbubbles (Yokoo et al. 1993), which are driven by intensive stellar winds and supernovae explosions (Veilleux et al. 2005). The velocities of the GC outflow are typical values of molecular outflows seen in external starburst galaxies (∼100 km s$^{-1}$ on average; Veilleux 2004), which are generally lower than the velocities of their ionized-gas outflows. With the implications of:

Figure 8. Top: $b$–$v$ diagrams of region D, which covers the western edge of the HG-feature. The region D is averaged over the longitude from $l = 359^\circ 92^\prime 359^\circ 87$. The contour levels are: CS($J = 2 \rightarrow 1$): 4%, 8%, 12%, 16%, 20%, 27%, 35%, 42%, 56%, and 70% of the peak, where the peak is 4.2 K; CS($J = 1 \rightarrow 0$): identical levels, but the peak is 2.6 K. The yellow rectangle marks the western side of the HG-feature. Bottom: $b$–$v$ diagrams of region E, which covers the western edge of the HG-feature. Region E is averaged over the longitude from $l = 359^\circ 86^\prime 0^\prime 18$. The contour levels are: CS($J = 2 \rightarrow 1$): 4%, 8%, 12%, 16%, 20%, 27%, 35%, 42%, 56%, and 70% of the peak, where the peak is 3.0 K; CS($J = 1 \rightarrow 0$): identical levels, but the peak is 1.8 K. The yellow rectangle marks the western side of the HG-feature.
extraplanar structures, and (2) expanding/accelerating motions, we suggest that the PA is associated with the molecular outflow. We then estimate the kinetic properties of the outflow by assuming a constant acceleration. For the positive-velocity ridge, we use a velocity of \(\sim 100 \text{ km s}^{-1}\) and a length of 34 pc (as shown in Figure 6), which then gives an acceleration \(a_{\text{pos}} = 0.5 \times (100 \text{ km s}^{-1})^2/(34 \text{ pc}) = 4.8 \times 10^{-12} \text{ km s}^{-2}\), and a dynamical timescale \(t_{\text{dyn}} = (100 \text{ km s}^{-1})/4.8 \times 10^{-12} \text{ km s}^{-2} = 6.7 \times 10^5 \text{ years}\). We note that this value is averaged over the structure. As shown in paper I, the PA belongs to the eastern protrusion of the GCL (see Figure 20 in paper I). The timescale of the PA is close to the dynamical timescale of the GCL (1 Myr) (Bland-Hawthorn & Cohen 2003). Implications of the extraplanar PA can be traced back to the disk region (the ML), providing clues of the launching point of the PA, and perhaps a link to the GCL at parsec scale. At kpc-scale, fossil imprints of past explosions in the GC were reported in (e.g., Bland-Hawthorn & Cohen 2003; Su et al. 2010; Crocker et al. 2011). For example, there is evidence that the GC experienced episodic starbursts a few Myr ago, producing more than 100 supernovae during the entire starburst (q.v. Tamblyn & Rieke 1993; Hartmann 1995; Ozernoy 1996; Sijoumer et al. 1998; Simpson et al. 1999; Carretti et al. 2013). Detailed modeling of the low-excitation, fine-structure line spectrum (Lutz 1999) suggests a starburst event about 7 Myr ago. It is also suggested that SgrA* went through a Seyfert phase in the recent past (q.v., Zubovas et al. 2011; Guo & Mathews 2012; Bland-Hawthorn et al. 2013). Guo & Mathews (2012) propose that the SgrA* jets, which inflated the Fermi bubble (Su et al. 2010), formed 1–3 Myr ago and persisted for 0.1–0.5 Myr. The total energy of the SgrA* jets is in the range of \(10^{55–57}\) erg. The ASCA 2–10 keV observations of the CMZ also provide evidence that SgrA* was 10^5 times more active in the past 10^7 years. The fluorescent X-ray radiation from cold iron atoms in the molecular clouds of the CMZ is possibly due to X-ray irradiation from SgrA* flares (q.v., Sunyaev et al. 1993; Koyama et al. 1996; Ponti et al. 2010). Bland-Hawthorn et al. (2013) also suggest that the H\(\alpha\) emission of the Magellanic Stream arose from an accretion flare of SgrA* 1–3 Myr ago. The required star-formation rate to produce the H\(\alpha\) emission of the Magellanic stream is at least two orders of magnitude larger than what can be generated by the star formation history of the GC. In this paper, we have confirmed that the PA originates from the galactic disk. Henshaw et al. (2016) also show that the PA seems to extend from Arm I (Sofue 1995), but with an offset in velocity. Our results suggest that, in the central 30 pc of the GC, feedback from past explosions could alter the orbital path of the molecular gas down to the central tenth of a parsec.

5. EXTRAPLANAR FEATURES IN THE GC

The molecular feature B1 appearing below \(b = -0^\circ.1\) suggests an expanding bubble in the \(b-v\) diagrams. B1 has higher CS(\(J = 2 - 1\))/CS(\(J = 1 - 0\)) line ratios (\(\sim 3\)) than the ambient 20/50 MC, by a factor of 2. B1 also has a counterpart in SiO(\(J = 2 - 1\)) (Tsuboi et al. 2011), suggesting that the low-level emission of B1 is shocked. At \(v = -20\) to \(v = 60 \text{ km s}^{-1}\), B1 seems to interact with the 20/50 MC; these clouds curve around the entire southern part of the shell in the \(b-v\) diagrams (marked by the ellipse of B1). The northern boundary (\(b \geq -0^\circ.1\)) of B1 is not clear, due to the complicated structures inside the 20/50 MC. It is possible that B1 extends to the 20/50 MC, as hinted in the ratio map, marked as B2 (Figure 9). B2 has ratios higher than 3 and shows a shell-like feature in the 20/50 MC. In region A (Figure 6), above \(b = 0^\circ\), the “low-velocity” emission tracing the eastern edge of the HG-feature (yellow box) is hard to identify because of the confusion of the galactic disk. This “low-velocity” emission might also belong to the “high-velocity” part of B1, if we consider that B1 extends up to \(b = 0^\circ.05\). In this sense, the eastern edge of the HG-shaped feature might be part of B1. In any case, we estimate the lower limit of the kinetic parameters with B1. With an expanding velocity of \(\sim 40 \text{ km s}^{-1}\), the kinetic energy of the northern HG-feature is \(\frac{1}{2}M_{\text{shell}}V_{\text{shell}}^2\), which...
is on the order of $10^{59}$ erg with an $H_2$ mass of $1000 M_\odot$. The $H_2$ mass is adopted from a local thermal equilibrium (LTE) condition, with an excitation temperature of 20 K (paper I), a CS abundance of $5 \times 10^{-9}$ (Martín et al. 2008), and the measured brightness temperature from the CS$(J = 1 - 0)$ line. The shell kinetic energy could be different by a factor of 0.1–10 for different CS abundances and excitation temperatures. The expansion time of B1 is $3 \times 10^8$ years, with the above expansion velocity of 40 km s$^{-1}$ and a size of 13 pc. We note that the timescales of B1 and PA are similar. The timescale is larger than the age of SgrA East (a few $10^8$ year; e.g., Herrnstein & Ho 2005). However, we note that the current measured expansion velocity sets an upper limit on the age, because the expansion speed was most likely greater in the past. Nevertheless, the identification of these individual shells is not unique or certain. There is also the possibility that all of the features are related, that is they may be complexities on top of a general outflowing shell.

The western edge of the HG-feature (western-HG) is located in region D. There is a velocity continuation of the 20 MC above SgrA$^*$. This continuation traces the western edge of the HG-feature above the galactic plane from $(b, v) = (-0\degree03, -10$ km s$^{-1}$) to $(b, v) = (0\degree06, 30$ km s$^{-1}$). The velocity of this continuation is increasing out to the galactic latitude, and corresponds to the western-HG. Rather than a closed, expanding bubble, this feature seems to be entrained and swept into the HG-feature from the 20 MC, which shows a kinematic behavior similar to the PA. The ratios (≥4.5) of the western-HG are higher than those of the cold disk emission (≤2.5), which suggests a higher excitation state in the western-HG. However, the structures in this region are complicated, and it is difficult to identify structures in the $b - v$ diagrams. Moreover, the current results do not show evidence that the HG-feature is a physical bipolar feature because the western and eastern edges do not show a coherent shell expansion. The asymmetry of the structures in the $b - v$ diagrams might suggest that the outflow phenomenon must be greatly influenced by the asymmetric circumnuclear environment.

In the following, we discuss the physical association between the HG-feature and the radio halo/lobe. The bipolar radio lobe has counterparts in X-ray emissions (Maeda et al. 2002; Markoff 2010). Mixtures of the thermal S and Si emissions in the radio lobe suggest a thermal origin of the hot plasma (Park et al. 2004) heated by shocks from supernovae and massive stellar winds. The interaction of the hot plasma with the ambient dense cloud might also produce the observed neutral Fe line. It is unclear whether the hot plasma from the radio lobe in situ can entrain the molecular gas. We do a self-consistent check of whether the ionized gas of the bipolar radio-lobe is able to entrain the molecular gas from the disk clouds, assuming it is moving outward perpendicular to the GC. For the given emission measure of $2.7 \times 10^{5}$ pc cm$^{-6}$ and the source size of 4$''$ (Pedlar et al., 1989), we derive the electron density $n_e$ to be $7.8 \times 10^4$ cm$^{-3}$. The electron temperature is $T_e = 5000$ K, adapted from Pedlar et al. (1989). Therefore, we estimate the thermal ionized gas pressure to be $P_e/k = n_e T_e \sim 4 \times 10^8$ cm$^{-3}$ K. The thermal pressure of the molecular gas is derived from $P_m/k = n_{H_2} T_{kin}$, where $P_m/k$ is the gas thermal pressure, $n_{H_2}$ is the number density of the molecular gas, and $T_{kin}$ is the kinetic temperature. We assume $n_{H_2}$ is $10^5$ cm$^{-3}$ (the critical density of CS($J = 2 - 1$)), and a

**6. SUMMARY**

From our 1 pc resolution CS($J = 2 - 1$) line maps, we find that the molecular gas in the central 30 pc of the GC has a morphology that reflects recent explosions ($3 – 6 \times 10^5$ years ago). As a follow-up study of paper I, we revisit the idea that the PA is a molecular outflow launched from the galactic disk. The linearly increasing velocity of the PA suggests that it is moving out of the galactic disk. Near the systematic velocity, the molecular gas shows an HG-feature, which might be a mixture of multiple explosive events. The north-western edge of the HG-feature might trace the entrainment from the 20 MC, ranging from $b = -0\degree07$ to $b = 0\degree06$. The southern part of the eastern edge of the HG-feature suggests an expanding bubble (B1). The low-level emission of B1, south of the galactic plane, is shocked. These individual features might be complexities on top of a general outflowing shell.

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