ALMA View of the Galactic Center Minispiral: 
Ionized Gas Flows around Sagittarius A*

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Received 2016 August 30; revised 2017 May 5; accepted 2017 May 9; published 2017 June 19

Abstract

We have observed the “Galactic center minispiral (GCMS)” in the H42α recombination line as a part of the first large-scale mosaic observation in the Sagittarius A complex using Atacama Millimeter/submillimeter Array (ALMA). We revealed the kinematics of the ionized gas streamers of the GCMS. We found that the ionized gas streamers of the Northern Arm (NA) and Eastern Arm (EA) in their outer regions somewhat deviate from the Keplerian orbits that were derived previously from the trajectories in the inner regions. In addition, we found that the streamer corresponding to the Bar of the GCMS has a Keplerian orbit with an eccentricity of e ~ 0.8, which is independent from the Keplerian orbits of the other streamers of the GCMS. We estimated the LTE electron temperature and electron density in the ionized gas streamers. We confirmed the previously claimed tendency that the electron temperatures increase toward Sgr A*. We found that the electron density in the NA and EA also increases with approaching Sgr A* without the lateral expansion of the gas streamers. This suggests that there is some external pressure around the GCMS. The ambient ionized gas may cause the confinement and/or the perturbation of the orbits. There is a good positional correlation between the protostar candidates detected by JVLA at 34 GHz and the ionized gas streamer, the Northeastern Arm, newly found by our H42α recombination line observation. This suggests that the candidates had formed in the streamer and they were brought to near Sgr A* as the streamer falls.

Key words: accretion, accretion disks – Galaxy: center – Galaxy: kinematics and dynamics – stars: formation

Supporting material: data behind figure, figure set

1. Introduction

Sagittarius A* (Sgr A*) is a compact source from radio to X-ray wavelengths associated with the Galactic center supermassive black hole (GCBH), which is very close to the dynamical center of the Milky Way (Reid et al. 2003) and has a mass of ~4 × 10⁶M☉ (e.g., Ghez et al. 2008; Gillessen et al. 2009). A bundle of the ionized gas streams located within 2 pc of Sgr A* was identified as the “Galactic center minispiral (GCMS)” using the Karl G. Jansky Very Large Array (JVLA) and IR telescopes (e.g., Lacy et al. 1980; Ekers et al. 1983; Lo & Claussen 1983; Scoville et al. 2003). The kinematic structure of the GCMS has been studied mainly by these telescopes (e.g., Serabyn & Lacy 1985; Serabyn et al. 1988; Lacy et al. 1991b; Roberts et al. 1996; Zhao et al. 2009, 2010). The stretched appearance and kinematics of the GCMS suggest the models in which the streamers are tentative structures with Keplerian orbits around Sgr A* (e.g., Serabyn et al. 1988; Zhao et al. 2009, 2010). There are still alternate models to explain these properties (e.g., one-armed spiral; Lacy et al. 1991b; Irons et al. 2012). The tidal force of Sgr A* must have a serious effect on the interstellar medium (ISM) in the vicinity of Sgr A*, i.e., the GCMS (e.g., Lacy et al. 1982). Furthermore, the strong Lyman continuum radiation from the OB and WR stars in the Central cluster ionizes the ISM rapidly in the region (e.g., Genzel et al. 1996; Paumard et al. 2006). A recent dust observation of the GCMS with ALMA suggested that there is a possible scenario for the formation of the Central cluster: a star-forming molecular cloud is falling from a region somewhat far from Sgr A* and supplies young stars and the ISM to the vicinity of Sgr A* (e.g., Tsuboi et al. 2016). However, it is not clearly demonstrated how the gas is fed to Sgr A* because the innermost part of the ionized gas has very weak intensity and complicated structures.

We present new observational results on the ionized gas streams in the vicinity of Sgr A* based on the observation of the H42α recombination line using the Atacama Large Millimeter/submillimeter Array (ALMA). The distance of the Galactic center is assumed to be 8 kpc in this paper.

2. Observation and Data Reduction

We have observed the GCMS in the H42α recombination line (85.6848 GHz) as a part of the ALMA Cy.1 observation (2012.1.00080.S; PI: M.Tsuboi), which is an ionized gas tracer. The entire ALMA observation consists of a 137-pointing mosaic of the 12 m array and a 52-pointing mosaic of the 7 m array (ACA), covering a 330" × 330" area including the “Galactic center 50 km s⁻¹ molecular cloud” and the GCMS in CS J = 2 − 1 (97.980953 GHz), SiO ν = 0 J = 2 − 1 (86.846995 GHz), H¹²CO* J = 1 − 0 (86.754288 GHz), and H42α emission lines. The molecular cloud encompasses the most conspicuous star-forming region in the vicinity of Sgr A*.
full results in another paper. We have detected the recombination line in the GCMS and the Sgr A East H II region, and we concentrate on the GCMS in the H42α recombination line in this paper. The data of the recombination line have angular resolutions of 2′.48 × 1′.86, PA = 89′.3 and 1′.87 × 1′.37, PA = 84′.0 using “natural weighting” and “Briggs weighting (R = 0.5)” as u-v sampling, respectively. The frequency channel width is 244 kHz. The velocity resolution is 1.7 km s⁻¹ (488 kHz). J0006–0623, J1517–2422, J1717–3342, J1733–1304, J1743–3058, J1744–3116, and J2148+0657 were used as phase calibrators. The flux density scale was determined using Titan, Neptune, and Mars. Because the observation has a large time span of 19 months, the absolute flux density accuracy may be as large as 15%. The calibration and imaging of the data were done by CASA (McMullin et al. 2007). The continuum emission of the GCMS and Sgr A* was subtracted from the spectral data using the CASA task UVCONTSUB (fitorder = 1). Although the flux density of Sgr A* at 100 GHz varied in the range of 1–2 Jy, the residual emission seen at the position of Sgr A* in the channel maps is as small as 5–10 mJy beam⁻¹ (see Figures 2 and 3). This suggests that the contamination from the continuum emission of the GCMS is at most ∼1%.

3. Channel Maps and Position–Velocity Diagrams

Figure 1 shows an ALMA view of the GCMS at 100 GHz (Tsaboi et al. 2016) for a finding chart of the substructures of the GCMS. The continuum emission in the figure is expected to be mainly originated from the ionized gas through the f-f emission mechanism except for Sgr A* itself. In this paper we use the traditional nomenclature of the substructures, which has been used since 1980 (features with white labels). Because the features with red labels have no customarily used names, they are newly named in the following section Northeastern Arm and Horizontal Arm.

Figure 2 shows the channel maps of the GCMS shown in Figure 1 in the H42α recombination line (pseudocolor). This data cube is cut from the large-area mosaic data mentioned in the previous section. The velocity coverage of the figure is from $V_{LSR} = -480$ to +400 km s⁻¹. The velocity width of each panel is 20 km s⁻¹. This is comparable to the thermal velocity width of the ionized hydrogen gas, $\Delta V = \sqrt{8 \ln 2 R T/m_\text{H}} \sim 21$ km s⁻¹ at $T_e = 1 \times 10^4$ K. The central velocity of each panel is indicated in the upper right corner. The contours in the figure show the continuum emission of the GCMS at 100 GHz for comparison (Tsaboi et al. 2016). All the component figures (45 images) are available in the online journal. The H42α recombination line data cube is available as the data behind the figure. The data used to create this figure are available.

(Complete figure set (45 images) is available.)
panels of $V_{\text{LSR}} = -200$ to $-180 \text{ km s}^{-1}$ and $\sim 30''$ southeast of Sgr A* in the panel of $V_{\text{LSR}} = -220 \text{ km s}^{-1}$. These emissions are probably contaminations of the $^{29}\text{SiO} \nu = 0 \ J = 1 - 0$ emission line (85.759188 GHz) because they have no continuum counterparts, while the counterparts in the CS and SiO emission lines are prominent (Tsuboi et al. 2017). On the other hand, the He$^{42}\alpha$ recombination line (85.7233 GHz) is not detected in the channel maps. The nondetection shows that the number ratio of He$^+$ to H$^+$ is less than $N(\text{He}^+)/N(\text{H}^+) \lesssim 0.1$.

Figure 3 shows the enlarged channel maps of the vicinity of Sgr A* in the H$^{42}\alpha$ recombination line (pseudocolor) to clarify the kinematics of the innermost part of the ionized gas streamers. The angular resolution is $1''9 \times 1''3 (\text{PA} = 84^\circ)$ using “Briggs weighting ($R = 0.5$),” which is shown in the lower left corner of each panel as a red filled oval. The contours in the figure show the continuum emission of the GCMS at 100 GHz for comparison (Tsuboi et al. 2016). “A,” “B,” “C,” and “D” in the figure indicate the Northern Arm, the Bar, the Eastern Arm, and the Western Arc, respectively.

Figure 3 shows the enlarged channel maps of the vicinity of Sgr A* in the H$^{42}\alpha$ recombination line (pseudocolor) to clarify the kinematics of the innermost part of the ionized gas streamers. The angular resolution is $1''9 \times 1''3 (\text{PA} = 84^\circ)$ using “Briggs weighting ($R = 0.5$).” The sensitivity is $\sim 0.7 \text{ mJy beam}^{-1}$ for a 20 km s$^{-1}$ channel. In addition, we see a faint component at the position of Sgr A* in Figures 2 and 3. This is probably the residual emission in the continuum subtraction process mentioned in the previous section, although
Figure 3. (Continued.)
there is a possibility that this is the H42α emission surrounding Sgr A*. Figure 4 shows the position–velocity diagrams along the substructures of the GCMS in the H42α recombination line. The integration area is shown as a rectangle in the guide map (contours). The angular offset is measured along the long side. The velocity bin width of each panel is 10 km s$^{-1}$.

### 3.1. The Northern Arm

The Northern Arm (NA) is the most prominent continuum substructure of the GCMS (see Figure 1). The ionized gas streamer corresponding to the NA is detected in the channel maps with the velocity range from $V_{\text{LSR}} \sim -300$ to $+160$ km s$^{-1}$ (see Figures 2 and 4(a)). The most negative velocity component of the NA is seen in the channel maps with the velocity range of $V_{\text{LSR}} \sim -300$ to $-220$ km s$^{-1}$ (see “A” in Figure 3 and a local peak in Figure 4(a)). This component is located around $\alpha \sim 17^h45^m39^s$, $\delta \sim -29^\circ00'32''$ and appears to be associated with IRS 2L. The component has been identified in previous observations (e.g., Zhao et al. 2009, 2010). In the velocity range of $V_{\text{LSR}} \sim -300$ to $-180$ km s$^{-1}$, the intensity peak position of the component shifts to the southeast as the velocity goes to positive. Then the peak position with $V_{\text{LSR}} \sim -180$ to $+160$ km s$^{-1}$ shifts to the north along the NA...
with increasing velocity. The ionized gas streamer is clearly identified as a curved ridge in the position–velocity diagrams along the NA (Figure 4(a)), which is connecting the north end with $V_{\text{LSR}} \sim +100 \text{ km s}^{-1}$ and the southwest end with $V_{\text{LSR}} \sim -300 \text{ km s}^{-1}$. The ionized gas streamer is also identified as a slightly curved ridge with a large velocity gradient in the position–velocity diagram along the Bar (Figure 4(b)). In addition, an extended component with the velocity range from $V_{\text{LSR}} \sim +40$ to $V_{\text{LSR}} \sim +140 \text{ km s}^{-1}$ is also seen in the whole of the NA (see Figure 2).

There are some components apparently connecting with the NA in the channel maps. A curved component appears abruptly around the north end of the NA in the panels of $V_{\text{LSR}} \sim -20$ to $0 \text{ km s}^{-1}$ of Figure 2. The ionized gas component probably corresponds to IRS 8. This component is seen as a narrow velocity width component with $V_{\text{LSR}} \sim -20$ to $0 \text{ km s}^{-1}$ at $20^\circ-30^\circ$ angular offsets in the position–velocity diagram along the NA (see Figure 4(a)). The component should not be physically associated with the ridge of the NA because it is isolated from the NA in the position–velocity diagram. Another ionized gas streamer crosses the NA around $\alpha \sim 17^\mathrm{h} 45^\mathrm{m} 40^\mathrm{s}, \delta \sim -29^\circ 00' 11''$ at nearly a right angle and is called “Horizontal Arm (HA)” hereafter. The peak position of this streamer moves to the east as the velocity increases from $V_{\text{LSR}} \sim -40$ to $+100 \text{ km s}^{-1}$. The HA is also identified as a component with a velocity width of $\Delta V \gtrsim 100 \text{ km s}^{-1}$ at $\sim 20^\circ$ angular offset in Figure 4(a). The component has been identified in previous observations (e.g., Zhao et al. 2009, 2010).

3.2. The Bar

The ionized gas streamers seen toward the Bar have two distinct velocity structures, which are shown in the position–velocity diagram along the Bar (see Figure 4(b)). The first one has an elongated S-shaped structure (curved dashed line) in the position–velocity diagram, which has large velocity width features at both velocity ends. This structure is also seen as an inclined linear feature in the position–velocity diagram along the NA (see Figure 4(a)). The second one has a curved ridge with a large velocity gradient, which is prominent around the angular offset of $\sim 0''$ from Sgr A* in the velocity range of $V_{\text{LSR}} \sim -300$ to $60 \text{ km s}^{-1}$. This component is identified as the NA mentioned in the previous subsection. Then the first component is the ionized gas streamer corresponding to the Bar itself. This component is also identified in the channel maps (“B” in Figure 3).

The negative velocity end of the component appears at $\alpha \sim 17^\mathrm{h} 45^\mathrm{m} 39^\mathrm{s} 6, \delta \sim -29^\circ 00' 26''$ in the panel of $V_{\text{LSR}} = -240 \text{ km s}^{-1}$. The intensity peak of the component stays around the continuum peak, $\alpha \sim 17^\mathrm{h} 45^\mathrm{m} 39^\mathrm{s} 6, \delta \sim -29^\circ 00' 27''$ (see Figure 1), although it slightly shifts southwest as the velocity goes to positive in the panels of $V_{\text{LSR}} = -240$ to $-100 \text{ km s}^{-1}$. Next, the peak shifts to the southeast along the Bar as the velocity increases from $V_{\text{LSR}} = -80$ to $+120 \text{ km s}^{-1}$. The component stays around the same position in the velocity range from $V_{\text{LSR}} = +120$ to $+220 \text{ km s}^{-1}$ and may not mingle with the Eastern Arm (EA). In the panels of $V_{\text{LSR}} = +220$ to $+340 \text{ km s}^{-1}$, a compact component is seen around $\alpha \sim 17^\mathrm{h} 45^\mathrm{m} 40^\mathrm{s} 3, \delta \sim -29^\circ 00' 34''$, i.e., at the southeast edge of the minicavity. This is presumably the positive velocity end of the Bar. The kinematics of the Bar is discussed in Section 4.

3.3. The Eastern Arm

The EA is also a conspicuous continuum substructure of the GCMS (see Figure 1). The ionized gas streamer corresponding to the EA has complicated velocity structures. The negative velocity end of the streamer appears as an elongated component apparently connecting to the Bar in the panel of $V_{\text{LSR}} = 80 \text{ km s}^{-1}$ in Figure 2. The component extends along the EA in the panels of $80 - 140 \text{ km s}^{-1}$ and reaches at least up to $\alpha \sim 17^\mathrm{h} 45^\mathrm{m} 39^\mathrm{s} 5, \delta \sim -28^\circ 59' 36''$. The peak of the component seems to shift to the west as the velocity goes to positive in the panels of $160 - 200 \text{ km s}^{-1}$. The velocity structure is seen as an inclined linear ridge in the position–velocity diagram along the EA (see Figure 4(c)), of which velocity increases from $V_{\text{LSR}} \sim 80 \text{ km s}^{-1}$ at the north end to $V_{\text{LSR}} \sim 200 \text{ km s}^{-1}$ at the south end. The velocity width increases around the south end. We also see the feature in the position–velocity diagram along the Bar (see Figure 4(b)). The EA apparently overlaps with the Bar in the diagrams, but this is presumably a coincidence in the line of sight.

Another ionized gas streamer is seen $7''$ north of the EA (see Figure 1) and is called “Northeastern Arm (NEA)” hereafter. The NEA is also identified in the panels of $V_{\text{LSR}} = 60 - 160 \text{ km s}^{-1}$ (see Figure 2). The NEA appears to cross the EA at its north end around $\alpha \sim 17^\mathrm{h} 45^\mathrm{m} 41^\mathrm{s} 9, \delta \sim -29^\circ 00' 20'' 5$ (see Figure 1). The negative velocity end of the NEA appears as a curved extension to $\sim 10''$ northeast of the crossing point in the panel of $V_{\text{LSR}} = 60 \text{ km s}^{-1}$. The velocity component tends to shift to the southwest along the NEA with increasing velocity. The positive velocity end of the ionized gas is seen as an elongated source between the NA and the EA in the panel of $V_{\text{LSR}} = 160 \text{ km s}^{-1}$. However, the inner part of the NEA does not appear to reach to the vicinity of Sgr A*. The southwest end corresponds to the group of half-shell-like sources found by JVLA at 34 GHz (Yusef-Zadeh et al. 2015), which is discussed in Section 4.

3.4. The Western Arc

Figure 2 shows that the intensity peak goes to north along the Western Arc (WA) with increasing velocity from $V_{\text{LSR}} = -140$ to $40 \text{ km s}^{-1}$. The component of the WA with $V_{\text{LSR}} = -20$ to $20 \text{ km s}^{-1}$ appears to cross the Bar. Figure 4(d) shows the position–velocity diagram along the WA. The WA is seen as an inclined linear feature crosses the point of $0 \text{ km s}^{-1}$ and $0''$ offset in the diagram. This linear feature suggests that the WA is a part of a nearly circular orbiting ring (e.g., Zhao et al. 2009). The Bar is also seen as a linear feature with a high-velocity gradient at the angular offset of $\sim 0''$ from Sgr A* in the diagram. Because both components cross at nearly a right angle in the diagram, the WA would not be physically associated with the Bar.

4. Discussion

4.1. Kinematics of the Northern Arm and the Eastern Arm

Figure 5 shows the position–velocity diagram along galactic longitude in the H42α recombination line. This is the finding chart of the ionized gas streamers discussed in the following. The diagram shows the mutual relations among the velocity structures of the gas streamers. A model that the ionized gas streamers of the GCMS are in elliptical Keplerian orbits has been advocated to explain the
observed kinematics and structures of the GCMS (e.g., Zhao et al. 2009). The ionized gas should not be bounded by self-gravity in the GCMS, as well as in the H II regions of the Galactic disk. When the ionized gas in the GCMS moves along its Keplerian orbit, the ionized gas can expand up to $D \sim 1$ pc within one orbital period, which is comparable to the semimajor axis of the orbit of $\sim 1$ pc, because the typical thermal velocity and typical orbital period are $\sim 10$ km s$^{-1}$ and $\sim 10^4$ yr, respectively. This corresponds to the angular diameter of $D \sim 20''$. However, the observed morphology of the ionized gas appears as a single trajectory at least within the scope of this observation. Although the width of the ionized gas is wider than that of the dust ridge in the GCMS (Tsuboi et al. 2017), there would be no sign of such rapid expansion on the ionized gas streamers (see Figures 1 and 2). Some external pressure is necessary in order to prevent the expansion of the ionized gas. The electron density of ambient ionized gas can be estimated from the observations by single-dish radio telescopes that detected the extended emission (e.g., Mezger & Wink 1986; Tsuboi et al. 1988). The electron temperature is assumed to be $T_e = 1 \times 10^4$ K here because it has been reported to be $T_e \sim (5-13) \times 10^3$ K in the region (Mezger & Wink 1986). The ambiguity of the electron temperature results in an error of at most $\pm 10\%$ in the electron density because the electron density has a small dependence on the electron temperature (see Equation (2)). The average ambient electron density within 0.5 pc is derived to be $n_e \sim 2 \times 10^3$ cm$^{-3}$ from the continuum flux density at 91 GHz subtracting the GCMS and Sgr A* ($S_{\nu, \text{amb}} = 3.8$ Jy beam$^{-1}$ (20$''$); see Equation (1) of Tsuboi et al. 1988). The electron density of the NA by our ALMA

Figure 5. Finding chart of the ionized gas streamers on the position–velocity diagram along galactic longitude in the H42α recombination line.
The typical uncertainty is estimated to be as large as 30% of the derived value.

On the other hand, such ambient ionized gas may also affect somewhat the Keplerian orbital motion by ram pressure because the orbital velocity is as large as \( \sim 100 \text{ km s}^{-1} \). Here we estimate the ram pressure of a gas globe with a radius of \( R \sim 0.1 \text{ pc} \) at a distance of \( r \sim 0.5 \text{ pc} \) from Sgr A*, and we compare this with the gravity by Sgr A*. The perturbation by ram pressure is estimated to be \( f_{\text{ram}} = n_e (\text{ambient}) m_p v^2 \pi R^2 \sim 1 \times 10^{20} \text{ g cm}^{-2} \). On the other hand, the gravity by Sgr A* is estimated to be \( f_g = GM \rho / 3 \pi R^3 \sim 4 \times 10^{30} \text{ g cm}^{-2} \) assuming that the density is \( n_e (\text{GCMS}) \sim 1 \times 10^4 \text{ cm}^{-3} \). The deceleration effect on the Keplerian orbital velocity is a few percent of the gravity at this distance. If this is the case, the deceleration effect would increase as the ionized gas streamer approaches periastron, and the semimajor axis by fitting to the inner part of the trajectory would be smaller than that by fitting to the outer part.

Figure 6 shows the comparison between the ionized gas distribution of \( V_{\text{LSR}} = 70-90 \text{ km s}^{-1} \) and the trajectories of the elliptical Keplerian orbits for the NA and EA+Bar that were proposed by Zhao et al. (2009). The correspondence between the ionized gas distribution and the proposed trajectory is very good in the EA. The northern half trajectory of the EA found by our observation also shows a clear correspondence.

![Figure 6](image_url)

Figure 6. Comparison between the H42\( \alpha \) recombination line intensity of the velocity range from \( V_{\text{LSR}} = 70 \) to \( 90 \text{ km s}^{-1} \) (pseudocolor) and the trajectories of the elliptical Keplerian orbits for the NA and the EA and Bar, which were proposed by Zhao et al. (2009) (white dashed ovals).

Although the EA is seen to connect with the Bar in the continuum emission map and the integrated intensity map of the H42\( \alpha \) recombination line (see Figures 1 and 10), the
velocity structures of the EA and the Bar do not smoothly connect with each other in the position–velocity diagram (see Figure 5). Then the ionized gas distribution in the Bar does not fit the trajectory well. The kinematics of the Bar is discussed later. Meanwhile, although the ionized gas distribution fits the proposed trajectory in the inner part of the NA, the distribution appears to extend to the north beyond the proposed trajectory for the NA. The extension would be understood as the northernmost part of the NA in the original orbit that was not perturbed by the ambient gas.

An alternate model that the NA and WA form a one-armed spiral structure in a nearly circular orbit also has been proposed, which is based on the observations in the [Ne II] emission line (e.g., Lacy et al. 1991a; Irons et al. 2012). In this model, the ionized gas of the NA and WA does not flow along the features, but flows at a large angle to them. In addition, the NA and WA should connect with each other around $\alpha = 17^h 45^m 40^s$, $\delta = -29^\circ 00' 08''$ (see Figure 1 in Irons et al. 2012). However, the NA appears to extend north beyond the connecting point in the H42$\alpha$ recombination line (see Figure 5). Note that the northern extension of the NA is identified even in the integrated intensity map in the [Ne II] emission line (see Figure 1 in Lacy et al. 1991a). Moreover, the velocity structures of the NA and the WA do not smoothly connect with each other in the position–velocity diagram. The velocity structure of the HA apparently bridges the gap between the WA and the middle of the NA (see also Figure 4(a)).

4.2. Kinematics of the Bar

Two distinct models have been proposed to explain the kinematics and structures of the Bar. One model is that the Bar is understood as components in the elliptical Keplerian orbit including the EA (e.g., Zhao et al. 2009). However, some discrepancies between the model and the observed kinematics have been indicated (e.g., Irons et al. 2012). Another model is that the Bar is understood as components in a Keplerian orbit not including the other streamers, which is nearly edge-on (Liszt 2003). The model is based on the observation of the radio recombination line H92$\alpha$ (Roberts et al. 1993, 1996), which covered the $V_{\text{LSR}}$ range of $-200$ to $+200\text{ km s}^{-1}$, narrower than that in our observation.

Our observation supports the latter model. In Figure 4, component B shifts along the minor axis of the elongated Bar structure with increasing velocity from $V_{\text{LSR}} = -240$ to $-80\text{ km s}^{-1}$. Such positional shift cannot be understood as a part of the previously proposed Keplerian orbit for the EA+Bar. On the other hand, this positional shift can be explained by an independent Keplerian orbit with high eccentricity based on our observation. Component B approaches Sgr A* along the major axis of the elongated Bar structure with increasing velocity from $V_{\text{LSR}} = 200$ to $340\text{ km s}^{-1}$.

Figure 7 shows the relation between the S-shaped ridge that appeared on the position–velocity diagram along the Bar (see also Figure 4(b)) and the Keplerian trajectory in the Bar, which is derived in the following part. The top panel is the integrated intensity map of the H42$\alpha$ recombination line, and the bottom panel is the position–velocity diagram along the Bar. The kinematic characteristics on the position–velocity diagram suggest that the S-shaped ridge is a part of a component with a nearly Keplerian orbit around the GCBH, of which the major axis should be nearly parallel to the line of sight. Position–velocity diagrams of Keplerian orbits with high eccentricity are calculated in the Appendix. As shown in Figure 12 in the Appendix, the kinematic characteristics seen in the figure are reproduced only in the case of $PA = 0^\circ$. Because the ionized gas streamer cannot be confined simply to a single orbit by the perturbation mentioned in the previous subsection and the gas distribution is not homogeneous, it is not easy to derive the orbital parameters accurately from the characteristics of the streamer on the position–velocity diagram. However, the orbit probably has a high eccentricity. The curves with $e = 0.8$ seem to well reproduce the observed position–velocity curve of the Bar. The dashed line in the bottom panel shows the orbit with $e = 0.8$ and $i = 80^\circ$ (please see the following paragraph) at $PA = 0^\circ$.

The semimajor axis of the orbit is expected to be $b = a\sqrt{1 - e^2} \approx 0.3$ pc from the angular extent on the position–velocity diagram, $\theta \approx \pm8^\circ$. The semimajor axis and period of the orbit are $a \sim 0.5$ pc and $P \sim 1.7 \times 10^4$ yr, respectively. Assuming the GCBH mass of $M_{\text{GC}} \sim 4 \times 10^6 M_\odot$, the maximum radial velocity is estimated to be $V_{\text{max}} = \sqrt{\frac{GM}{a(1 - e^2)}} = 304\text{ km s}^{-1}$. The radial velocities at the maximum angular offsets are estimated to be $\mp \sqrt{\frac{GM}{a}} \sim \mp 180\text{ km s}^{-1}$. These are actually seen on the position–velocity diagram. Comparing the calculated maximum velocity with the maximum velocity observed on the position–velocity diagram, the angle between the line of sight and the normal of the orbital plane, that is, the inclination angle, is as large as $i = 80^\circ$. The semimajor axis and the inclination angle estimate that the projected angular extent along the semimajor axis is $\lesssim 5^\circ$. 

![Figure 7. Top panel: integrated intensity map of the H42$\alpha$ recombination line.](image-url)
The expected orbit with $i = 80^\circ$ is shown as an oval on the integrated intensity map (see the top panel of Figure 7).

Component B moves along the orbit in the velocity range from $V_{\text{LSR}} = -80$ to $80$ km s$^{-1}$ (see Figure 3). The component should be located at the opposite side of Sgr A$^*$ on the orbit, i.e., around the apoastron. The periastron distance from the GCBH and the orbiting velocity at the periastron are estimated to be $\alpha(1 - e) \sim 0.1$ pc and $V_{\text{orbit}} = \sqrt{\frac{GM}{1 + e}} \sim 550$ km s$^{-1}$, respectively. The periastron is probably located within the Bondi accretion radius of Sgr A$^*$, $R_A \sim 0.2$ pc, which is derived from X-ray observations by Chandra (Wang et al. 2013).

### 4.3. High-velocity Component of the Galactic Center Minispiral

Figure 8 shows a magnified map of the vicinity of Sgr A$^*$ in the H42$\alpha$ recombination line. The velocity range is from $V_{\text{LSR}} = -390$ to $-370$ km s$^{-1}$. A faint component with extremely negative velocity is identified at $\alpha \sim 17^h 45^m 40.0^s$, $\delta \sim -29^\circ 00' 30.8''$, which corresponds to $\sim 2.8'$ ($\sim 0.11$ pc) south—southwest of Sgr A$. The IR counterpart of the faint component has been identified in SINFONI observations (Steiner et al. 2013). Note that another faint component seen at the position of Sgr A$^*$ is probably a residual in the continuum subtraction process by CASA.

Assuming a circular Keplerian orbit around Sgr A$^*$, the orbital velocity is estimated to be $V_{\text{orbit}} = \sqrt{\frac{GM}{\alpha}} \sin i$. Because the observed radial velocity is consistent with the orbital velocity estimated for a circular Keplerian orbit with $i \sim 90^\circ$, $V_{\text{orbit}} \sim 395$ km s$^{-1}$, the physical distance from the GCBH of the component should be close to the projected distance. The entire orbit is located within the Bondi accretion radius. On the other hand, the observed radial velocity is also consistent with a freefall velocity ($\sim 550 \sin i$ km s$^{-1}$) from $r = 3$ pc, i.e., the outer end of the GCMS, to the observed position with $i \sim 45^\circ$. This component might be an inner tip of a streamer approaching the GCBH. This will be instantly disrupted by strong tidal shear of the GCBH, and a part of the fragments will begin freefall to it (e.g., Saitoh et al. 2014).

### 4.4. Relation between the Western Arc and the Circumnuclear Disk

Figure 9(a) shows the comparison between the position—velocity diagrams of the WA in the H42$\alpha$ recombination line and the circumnuclear disk (CND) in the CS $J = 2 - 1$ emission line (contours; Tsuboi et al. 2017). There is a molecular gas component with $V_{\text{LSR}} = -100$ to $0$ km s$^{-1}$ of the CND that is along the outer boundary of the WA (see Figure 9(b); e.g., Christopher et al. 2005; Montero-Castaño et al. 2009; Martín et al. 2012; Lau et al. 2013). The molecular gas component with the negative angular offset and negative velocity is located on the just positive velocity side of the ionized gas component of the WA in the position—velocity diagram.

Figure 9(b) shows the relation between the WA in the H42$\alpha$ recombination line (pseudocolor) and the CND in the CS $J = 2 - 1$ emission line (white contours; Tsuboi et al. 2017) in the velocity range of $V_{\text{LSR}} = -105$ to $-5$ km s$^{-1}$. This molecular gas component is located just outside the western periphery of the WA (e.g., Christopher et al. 2005; Montero-Castaño et al. 2009; Martín et al. 2012). Thus, it is plausible that the ionized gas component is physically associated with the molecular gas component with negative velocity. Moreover, the overall motion of the ionized and molecular gas is nearly circular rotation around Sgr A$^*$ with a velocity of $\sim 100$ km s$^{-1}$.

Meanwhile there is another molecular gas component of the CND in the velocity range from $V_{\text{LSR}} = 60$ to $110$ km s$^{-1}$ (see Figure 9(a)). Figure 9(c) shows the molecular gas component of the CND (red contours; Tsuboi et al. 2017) overlaid on the H42$\alpha$ recombination line (pseudocolor) with the velocity range of $V_{\text{LSR}} = 45$ to $145$ km s$^{-1}$. The component has no ionized gas counterpart with the same velocity, although it is located just outside along the western periphery of the WA traced by the millimeter-wave continuum emission (see also Figure 1). It has long been advocated that the CND is a rotating torus-like molecular gas around Sgr A$^*$ (e.g., Güsten et al. 1987). However, the existence of the components being out of the rotation law indicates that the CND has more complicated structures. The relation between the ionized gas and molecular gas components will be discussed in detail with ALMA molecular line data in another paper.

### 4.5. Electron Temperature and Electron Density in the Galactic Center Minispiral

#### 4.5.1. Electron Temperature

Figure 10 shows the integrated intensity map of the H42$\alpha$ recombination line. The velocity range is from $V_{\text{LSR}} = -400$ to $-320$ km s$^{-1}$. The contours in the figure show the continuum flux density at 100 GHz for comparison (Tsuboi et al. 2016). The LTE electron temperature, $T_e^*$, in the substructures of the GCMS is estimated from the line—continuum flux density ratio shown in Figure 10. $S_{\text{line}}/S_{\text{cont}}$, and the observed FWHM velocity width, $\Delta V_{\text{FWHM}}$, assuming that the line and continuum emissions are optically thin. The well-known formula of the
LTE electron temperature is given by

\[
T_e^* \,[\text{K}] = \left[ \frac{6.985 \times 10^3 \left( \frac{\nu}{\text{GHz}} \right)^{1.1} \left( \frac{N(\text{He}^+)}{N(\text{H}^+)} \right) \int S_{\text{line}} \left( \frac{dV}{\text{km s}^{-1}} \right)}{a(\nu, T_e^*)} \right]^{\frac{1}{2.8}}.
\]  

The correction factor, \(a(\nu, T_e^*)\), for \(\nu = 86 \text{ GHz}\) and \(T_e^* = 4 \times 10^3-1.5 \times 10^4 \text{ K}\) is 0.822–0.942 (Mezger & Henderson 1967). We assume that the number ratio of He\(^+\) to H\(^+\) is \(N(\text{He}^+)/N(\text{H}^+) = 0.09\), a typical value for the Orion \(\text{H II}\) region (e.g., Rubin et al. 1998). This is consistent with the nondetection of the He4\(2\alpha\) recombination line mentioned in Section 2. The LTE electron temperature is obtained by iteratively solving the formula for \(T_e^*\).

As shown in Figures 2 and 3, there are multivelocity components on the line of sight at many positions of the GCMS, and thus it is difficult to derive the electron temperature at such positions. We select the positions where one velocity component is stronger than the other ones by a factor of 4 or more except for the connecting points among the ionized gas streamers. The derived electron temperatures are also shown in Figure 9 (numbers in yellow). These electron temperatures are consistent with typical values in the \(\text{H II}\) regions in the Galaxy. The typical uncertainty is estimated to be as large as 15% of the derived value. These electron temperatures are summarized in Table 1.

The electron temperatures estimated in the NA are in the range of \(T_e^* = (6.4-14.0) \times 10^3 \text{ K}\). The electron temperature of the component at \(\alpha = 17^\text{h}45^\text{m}39.8^\text{s} \delta = -29^\circ 00'33''\) reaches the maximum value of \(T_e^* = (14.0 \pm 2.1) \times 10^3 \text{ K}\). The electron temperature in the NA probably increases as it approaches Sgr A\(^*\). The tendency is consistent with that estimated from previous
The electron temperatures at the west and east ends of the Bar are estimated to be $T_e^w = 7.3 \times 10^3$ and $7.6 \times 10^3$ K, respectively. At the east end of the Bar, the spectrum is contaminated with the component that belongs to the EA. Because the electron temperature in the EA is as low as $T_e^e \sim 6 \times 10^3$ K as mentioned above, the estimated electron temperature should be fairly lower than the true electron temperatures of the Bar.

4.5.2. Electron Density

The electron density, $n_e$, in the substructures of the GCMS is estimated from the continuum brightness temperature, $T_B = 1.22 \times 10^{10} \left( \frac{B_\alpha \times B_\text{arcsec}}{\text{Jy beam}^{-1}} \right)^{-1} \nu^{-2} \Delta v_{\text{cont}}$, and the electron temperature, $T_e$, shown in Figure 10 and the path length of the ionized gas, $L$, assuming that the continuum emission is optically thin. The well-known formula of the electron density is given by

$$n_e [\text{cm}^{-3}] = \left[ \frac{T_B 4.35 \left( \frac{\nu}{\text{GHz}} \right)^{2.1}}{8.235 \times 10^{-2} \alpha (\nu, T) \frac{L}{pc}} \right]^{0.5} \tag{2}$$

(Altenhoff et al. 1960; Mezger & Henderson 1967). We also assumed here that the $L$ is equal to the observed width of the boundary (see Figures 1 and 2) and $n_e$ is constant over the path.

The derived electron densities are also shown in Figure 10 (numbers in red). Although these electron densities are somewhat lower than those toward IRS sources in previous observations (Zhao et al. 2010), these are consistent with typical values in the H II regions in the Galaxy. The typical uncertainty is estimated to be as large as 30% of the derived value. These electron densities are also summarized in Table 1.

The electron density in the NA appears to increase from $n_e = 7 \times 10^3$ cm$^{-3}$ to $n_e = 13 \times 10^3$ cm$^{-3}$ with approaching Sgr A*. Although a similar tendency is probably seen in the EA, it is not clear in the WA. As mentioned previously, the electron temperature also increases with approaching Sgr A*. 

JVLA and SMA observations (Zhao et al. 2010). Because the ionization is originated by UV emission from the Central cluster around Sgr A*, the tendency of the electron temperature may be caused by approaching Sgr A* along the Keplerian orbit (Zhao et al. 2009). On the other hand, the electron temperatures estimated in the EA are lower than those in the NA. They are in the range of $T_e^w = (5.3-6.0) \times 10^3$ K. Although they are fairly monotonous, the highest electron temperature in the EA seems to be also located nearest to Sgr A* on the Keplerian orbit.

The electron temperatures estimated in the WA are in the range of $T_e^w = (3.7-8.3) \times 10^3$ K. The electron temperatures in the southern half of the WA may be higher than those in the northern half, and the tendency is different from those seen in the NA and EA. However, note that the highest value in the southernmost part of the WA has the largest uncertainty because the line intensity at the position is very weak, as shown in Figure 10.

4.5.2. Electron Density

The electron density, $n_e$, in the substructures of the GCMS is estimated from the continuum brightness temperature, $T_B = 1.22 \times 10^{10} \left( \frac{B_\alpha \times B_\text{arcsec}}{\text{Jy beam}^{-1}} \right)^{-1} \nu^{-2} \Delta v_{\text{cont}}$, and the electron temperature, $T_e$, shown in Figure 10 and the path length of the ionized gas, $L$, assuming that the continuum emission is optically thin. The well-known formula of the electron density is given by

$$n_e [\text{cm}^{-3}] = \left[ \frac{T_B 4.35 \left( \frac{\nu}{\text{GHz}} \right)^{2.1}}{8.235 \times 10^{-2} \alpha (\nu, T) \frac{L}{pc}} \right]^{0.5} \tag{2}$$

(Altenhoff et al. 1960; Mezger & Henderson 1967). We also assumed here that the $L$ is equal to the observed width of the boundary (see Figures 1 and 2) and $n_e$ is constant over the path.

The derived electron densities are also shown in Figure 10 (numbers in red). Although these electron densities are somewhat lower than those toward IRS sources in previous observations (Zhao et al. 2010), these are consistent with typical values in the H II regions in the Galaxy. The typical uncertainty is estimated to be as large as 30% of the derived value. These electron densities are also summarized in Table 1.

The electron density in the NA appears to increase from $n_e = 7 \times 10^3$ cm$^{-3}$ to $n_e = 13 \times 10^3$ cm$^{-3}$ with approaching Sgr A*. Although a similar tendency is probably seen in the EA, it is not clear in the WA. As mentioned previously, the electron temperature also increases with approaching Sgr A*.

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(Altenhoff et al. 1960; Mezger & Henderson 1967). We also assumed here that the $L$ is equal to the observed width of the boundary (see Figures 1 and 2) and $n_e$ is constant over the path.

The derived electron densities are also shown in Figure 10 (numbers in red). Although these electron densities are somewhat lower than those toward IRS sources in previous observations (Zhao et al. 2010), these are consistent with typical values in the H II regions in the Galaxy. The typical uncertainty is estimated to be as large as 30% of the derived value. These electron densities are also summarized in Table 1.

The electron density in the NA appears to increase from $n_e = 7 \times 10^3$ cm$^{-3}$ to $n_e = 13 \times 10^3$ cm$^{-3}$ with approaching Sgr A*. Although a similar tendency is probably seen in the EA, it is not clear in the WA. As mentioned previously, the electron temperature also increases with approaching Sgr A*.
Then the thermal pressure, \( n_e k T_e \), of the ionized gas in the inner region of the NA becomes three times or more larger than those in the outer region. If there is no confinement by any external pressure as discussed previously, we cannot explain why the electron density and temperature increase without the lateral expansion of the gas streamers.

4.6. Protostar Candidates in the Galactic Center Minispiral

A millimeter-wave continuum observation with JVLA found several compact components near Sgr A*, which have ionized half-shell-like structures facing Sgr A*. These components could be protostar candidates with low mass; their surfaces facing Sgr A* are rapidly photoevaporated by strong Lyman continuum emitting from the Central cluster around Sgr A* (Yusef-Zadeh et al. 2015). However, the physical relation between these candidates of low-mass protostars and the ionized gas streamers of the GCMS has not been clarified yet.

The top panel of Figure 11 shows an integrated intensity map for the EA and NEA in the H42α recombination line from \( V_{\text{LSR}} = +130 \) to \(+150 \) km s\(^{-1}\) (see also Figure 1). The NEA component seen in the H42α recombination line is located at the southwestern tip of the NEA traced by the 100 GHz continuum. Moreover, the component seems to be accompanied by a faint component seen in the CS emission line (Tsuboi et al. 2017).

The bottom panel in Figure 11 shows the comparison between the ionized gas streamer and the photoevaporating low-mass protostar candidates. The black-and-white image shows the continuum emission at 34 GHz observed by JVLA (Yusef-Zadeh et al. 2015). The protostar candidates detected in
the 34 GHz continuum map are concentrated exclusively in the ionized gas streamer of the NEA traced by the H42α recombination line. This good positional correlation indicates that the protostar candidates are physically associated with the NEA.

As mentioned in the Introduction, the tidal force of Sgr A* and the strong Lyman continuum radiation from the Central cluster must suppress the star formation activity near Sgr A*. The positional correlation in Figure 11 suggests that the protostar candidates had formed in the NEA when it was located in the outer region and they were brought closer to Sgr A* as the streamer fell. If a star-forming molecular cloud falls from an outer region and supplies young stars to the vicinity of Sgr A*, the obstacles to the star formation activity near Sgr A* should be overcome.

5. Summary

We have observed the GCMS in the H42α recombination line as a part of the first large-scale mosaic observation in the Sgr A complex using the Atacama Millimeter/submillimeter Array (ALMA). We found that the ionized gas streamers of the NA and EA in their outer regions somewhat deviate from the Keplerian orbits that were derived previously from the trajectories in the inner regions. In addition, we found that the ionized gas streamer corresponding to the Bar has an independent Keplerian orbit with an eccentricity of $e \sim 0.8$. The periastron is probably located within the Bondi accretion radius of Sgr A*. We estimated the electron temperature and electron density in the ionized gas streamers. The electron temperatures are in the range of $T_e = (4-14) \times 10^3$ K. We confirmed the previously claimed tendency that the electron temperatures increase toward Sgr A*. We found that the electron density in the NEA and EA also increases with approaching Sgr A* without the lateral expansion of the streamers. This suggests that there is some external pressure around the GCMS. If the pressure is caused by the ambient ionized gas, the ambient gas may affect the orbits of the ionized gas streamers by ram pressure. There is a good positional correlation between the protostar candidates detected by JVLA as the streamer fell. If a star-forming molecular cloud falls from an outer region and supplies young stars to the vicinity of Sgr A*, the obstacles to the star formation activity near Sgr A* should be overcome.

Appendix

Position–Velocity Diagram of Keplerian Orbits with High Eccentricity

As is well known, the position of a test particle on a Keplerian elliptical orbit around a heavy mass, $M$, is shown by

$$x = a (\cos \alpha - e), \quad y = a \sqrt{1 - e^2} \sin \alpha,$$

where $a$, $e$, and $u$ are the semimajor axis, the eccentricity, and the eccentric anomaly, respectively. On the other hand, the orbital velocity components of the test particle are given by

$$V_x = -\frac{na \sin u}{1 - e \cos u}, \quad V_y = \frac{na \sqrt{1 - e^2} \cos u}{1 - e \cos u},$$

where $n$ is the mean motion, $n = \sqrt{\frac{GM}{a^3}}$. If $u$ is used as a parameter, the relations between $x$ and $V_y$ and between $y$ and $V_x$ are easily given. When the orbit is observed from a very far place, the relation is called the position–velocity diagram of the orbit. The direction of the line of sight is shown by position angle, PA, which is the angle between the line of sight and the major axis of the orbit. Then the position–velocity diagram is given by the following equations:

$$P = -x (0) \sin \alpha + y (0) \cos \alpha,$$

$$V = V_x (0) \cos \alpha + V_y (0) \sin \alpha PA.$$

Figure 6 shows the position–velocity diagrams of the Keplerian oval orbits with $e = 0.5–0.95$ on the various position angles of the line of sight. In the calculation, we assumed that $na = 1$. The relation between the line of sight and the elliptical orbit is shown in the lower left corner of each panel. The measured position–velocity diagram shown in Figure 4 is the convolution of the orbit motion shown in Figure 8 with the internal motions that are turbulent and thermal velocities for the case of ionized gas.

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