Letter

Galactic center mini-spiral by ALMA: Possible origin of the central cluster

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Received 2016 January 20; Accepted 2016 March 3

Abstract

We present continuum images of the “Galactic center mini-spiral” in the 100, 250, and 340 GHz bands with analysis of the Cy.0 data acquired from the Atacama Large Millimeter/submillimeter Array (ALMA) archive. Good u-v coverage of the data and the “self-calibration” method give us the opportunity to obtain dynamic ranges of over $2 \times 10^4$ in the resultant maps of the 250 and 340 GHz bands. In particular, the image of the 340 GHz band has high dynamic ranges unprecedented in sub-millimeter waves. The angular resolutions attained are $1\arcsec.57 \times 1\arcsec.33$ in the 100 GHz band, $0\arcsec.63 \times 0\arcsec.53$ in the 250 GHz band, and $0\arcsec.44 \times 0\arcsec.38$ in the 340 GHz band, respectively. The continuum images clearly depict the “mini-spiral,” which is an ionized gas stream in the vicinity of Sgr A*.

We found a tight correlation between the dust emission peaks and the OB/WR stars in the northern arm of the “mini-spiral.” The core mass function of the dust cores identified by the clumpfind algorithm would obey the flat power-law $dN/dM \propto M^{-1.5\pm0.4}$ on the high-mass side. These support the scenario that the star-forming cloud has fallen into the immediate vicinity of Sgr A* for the origin of the central cluster.

Key words: Galaxy: center — ISM: dust — stars: formation

1 Introduction

The Galactic center region is the nucleus of the nearest spiral galaxy, the Milky Way. Sagittarius A* (Sgr A*) is a compact source from radio to X-ray located near the dynamical center of the Galaxy and is associated with the Galactic central supermassive black hole (GCBH). The mass of the GCBH is estimated to be $M_{\text{GCBH}} \simeq 4 \times 10^6 M_\odot$ from infrared (IR) astrometry observations (e.g., Ghez et al. 2008; Gillessen et al. 2009). The region surrounding Sgr A* is recognized to be a laboratory for peculiar phenomena, which will be found in the nuclei of normal galaxies by future telescopes. In the last two decades, young and highly luminous clusters have been found in the Central Molecular Zone (CMZ: Morris & Serabyn 1996) by IR observations.
These bright star clusters apart from the central cluster presumably formed in the cradle dense molecular clouds in the CMZ. However, the central cluster is a unique object in the Milky Way because the cluster is centered at Sgr A* and concentrated within $r \sim 0.5$ pc. The cluster contains $\lesssim 10^2$ OB and WR stars (e.g., Genzel et al. 1996). It may be difficult to make the central cluster in the way by which stars are usually formed in the Galactic disk region because of the following reasons. First, the tidal force of Sgr A* must have a serious effect on star formation since the minimum $H_2$ number density for stabilization toward the tidal shearing is $n(H_2) \gtrsim 3 \times 10^5$ cm$^{-3}$ at $r \sim 0.5$ pc (Christopher et al. 2005; Tsuboi et al. 2011). Second, the strong Lyman continuum radiation from the early type stars in the cluster ionizes rapidly the ISM in the region. The ionized ISM stream is identified as the “Galactic center mini-spiral” surrounding Sgr A* (Ekers et al. 1983; Lo & Claussen 1983), whose elongated appearance and kinematics indicate that it is a tentative structure. Therefore, it is still an open question how the central cluster has formed.

Two distinct scenarios for the formation of the central cluster have been proposed so far. One is current in situ star formation in the extreme environment of the vicinity of Sgr A*. The other is that a molecular cloud has fallen from a region somewhat far from Sgr A* to the vicinity of Sgr A* after star formation in the cloud started (e.g., Tsuboi et al. 2015b). Recently, a high-resolution observation (0.088′′ x 0.046′′) within 30″ of Sgr A* at 34 GHz with JVLA (Jansky Very Large Array) detected many sources with bow-shock appearance (Yusef-Zadeh et al. 2015a). The authors explained them as ionized outer envelopes of newly forming low mass stars. If so, this may be circumstantial evidence of in situ star formation near Sgr A*. However, the elapsed time for falling from $r \sim 10$ pc to the vicinity of Sgr A* in the second scenario is $10^4$ yr, comparable to the ages of protostars in the Galactic disk region. The low mass stars may remain as protostars if the low mass star formation in the falling cloud is as slow as that in the Galactic disk region. Consequently, the JVLA-detected sources do not necessarily support the first scenario of current in situ star formation near Sgr A* (see also Paumard et al. 2006).

Detailed observations of the surviving molecular gas or partially ionized gas are necessary to understand the star formation in the vicinity of Sgr A*. Recently, SiO(5–4) emission line observations detected several spots of molecular gas around Sgr A*. However, the association between the spots and IR-detected stars is not clear (Yusef-Zadeh et al. 2013, 2015b). We analyze the ALMA Cy.0 data of the region to examine the dust emission from the molecular cloud at a high resolution of less than 1″. In this way, we can trace the molecular cloud before it is completely destroyed by the UV continuum radiation. Throughout this paper, we adopt 8.5 kpc as the distance to the Galactic center. Then, 1″ corresponds to about 0.04 pc at that distance.

### 2 Data analysis and results

We analyze the Cy.0 data of the Sgr A* region in the 100, 250, and 340 GHz bands as acquired from the ALMA archive (ADS/JAO.ALMA#2011.0.00887.S). Nineteen 12 m antennas were available. In addition, the epoch, 2012 May 18, was suitable for imaging observation because Sgr A* was in a relatively quiet phase (Brinkerink et al. 2015). Since the original observation aimed for the measurement of the time variation of Sgr A*, the time span of the observation is longer than 7 hr (from 03:30:47 UT to 10:52:16 UT). Each frequency band has four spectral windows. The band width of the spectral window is 1.875 GHz. The fields of view (FOVs) are centered at Sgr A*, $\alpha_{2000,0} = 17^h45^m40^s04, \delta_{2000,0} = -28^\circ00'28.10'$. NRAO 530 and J1924–292 were used as phase calibrators. The flux density scale was determined using Titan and Neptune.

Further data calibration and imaging of the archival data were done by classic VLBA AIPS (NRAO) using the “self-calibration” method. First we removed residual fringe rates and delays of the raw visibility by the task FRING, which was found to be quite effective. Second, the residual complex gain errors of the data were minimized using the “self-calibration” method with the task CALIB. The good u-v coverage and “self-calibration” method give us the opportunity of obtaining a high dynamic range in the resultant maps.

Figure 1 shows the intensity map of the 100 GHz band. Here, we combined the four spectral window maps of $f_c = 93, 95, 105, \text{ and } 107$ GHz in the 100 GHz band to improve the sensitivity. The figure size is $100'' \times 100''$. The resultant Full Width at Half Maximum (FWHM) beam is $1.57'' \times 1.33''$ (PA = 74°), which corresponds to 0.065 pc x 0.055 pc at the Galactic center. The diameter of the FOV is $D_{\text{FOV}} = 60''$ or 2.5 pc. This means that the sensitivity of the map decreases to 50% at the edge of the FOV, which is caused by the beam pattern of the element antenna. The correction for the primary beam attenuation is not applied to the map. Features with spatial scales larger than 38° or 1.6 pc were resolved out. The RMS noise level is $S_n = 0.33$ mJy beam$^{-1}$ (4-ch-combined) at the map center. The flux density of Sgr A* is $S_*= 2.35 \pm 0.19$ Jy at 100 GHz. The error includes the calibration error. The “mini-spiral” is clearly seen in this map, which has the “eastern arm,” the “northern arm,” the “bar,” and the “western arc” as substructures. Moreover, the “mini-cavity” is identified on the bar. Because the continuum emission at 100 GHz...
The correction for the attenuation of the primary beam is not applied to the map. The resultant FWHM beam at 340 GHz is 0′′44 × 0′′38 (PA = −89′′), which corresponds to 0.018 pc × 0.016 pc. Features with spatial scales larger than 1′′, or 0.46 pc, were resolved out. The RMS noise level at the map center is $S_n = 0.15 \text{ mJy beam}^{-1}$ at 340 GHz. The dynamic range in the resultant map reaches 2.3 × $10^4$, which is unprecedented at that frequency. The flux density of Sgr A* is $S_b = 3.44 ± 0.51 \text{ Jy}$ at 340 GHz.

The northern arm, the western half of the eastern arm, and the bar are clearly seen in both the figures at 250 and 340 GHz. The mini-cavity is clearly identified around $\Delta \alpha = −1.5, \Delta \delta = −2.0$ (cf. figure 6 in Zhao et al. 2009). While the eastern half of the eastern arm is reasonably in the FOV at 250 GHz, it is outside the FOV at 340 GHz. The western arc is outside both FOVs. The northern arm seems to have a helical appearance in both figures (cf. figure 22 in Zhao et al. 2009). Moreover, we find many smaller components in both the figures that have statistical significance of $>5 \sigma$. Because the data in the two bands have different UV coverage, these small objects are real substructures rather than artifacts caused by the side lobes. However, these are not associated with the SiO sources detected by ALMA (Yusef-Zadeh et al. 2013, 2015b).

### 3 Discussion

The continuum emission at 340 GHz can be considered as the dust thermal emission for the following reason. The widths of the northern arm at 250 and 340 GHz seem to be narrower than at 100 GHz. In the latter, the northern arm has a "spine" structure and a relatively smooth envelope structure around it, while the northern arm at 250 and 340 GHz has only a "spine" structure (see figures 1 and 2). The beam-deconvolved widths at $\Delta \delta = 2.7$ are $\theta = 2′′03 ± 0.05$ at 340 GHz, although the width is $\theta = 1′′56 ± 0.02$ at 100 GHz. The beam sizes at the three bands are much smaller than the arm widths. In addition, the resolve-out limits at the three bands are much larger than the arm widths. Thus the difference between the widths is not caused by the beam size difference and/or the resolve-out limit difference. While the continuum emission at 100 GHz of the mini-spiral is thought to mainly come from ionized gas, the continuum emission at 340 GHz presumably comes from dust, although that at 250 GHz may be a mixture of free–free emission from ionized gas and dust emission. The observed "spine" structure presumably shows the dust ridge in the mini-spiral. On the other hand, the envelope structure probably shows the distribution of the ionized gas oozing from the ridge by strong UV radiation.

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Fig. 1. ALMA map in the 100 GHz band of the “mini-spiral” including Sgr A*. The four spectral windows of $f_c = 93, 95, 105,$ and 107 GHz are combined to improve the sensitivity. The diameter of the FOV is 60′′. The angular resolution is 1′′37 × 1′′33 at PA = 74′′, which is shown as an oval in the lower left corner. The RMS noise level is 0.33 mJy beam$^{-1}$, and the contour levels are 0.63, 1.3, 2.5, 5.0, 7.5, 10, 20, 30, 40, 50, 100, 200, 300, 400, 500, 1000, and 2000 mJy beam$^{-1}$. The flux density of Sgr A*$ is $S_b = 2.35 ± 0.19 \text{ Jy}$ at 100 GHz. The square shows the area covered by figure 2. (Color online)
To explore the relation between the dust ridge of the mini-spiral and the OB/WR stars of the central cluster (e.g., Genzel et al. 1996; Paumard et al. 2006; Zhao et al. 2009), we show the positions of the stars on the emission maps at 250 and 340 GHz in the left and right panels of figure 3, respectively. More than ten early type stars are located on the dust emission peaks in the northern arm and the bar. The “bow-shock” stars, which have shell-like envelopes, were found in recent IR observations (e.g., Sanchez-Bermudez et al. 2014). IRS1W, IRS2L, IRS5, IRS10W, IRS13EN, IRS13N, and IRS21 seem to lie along the northern arm and the bar. Moreover, they are located on the dust emission peaks or within 0.5″ of them, except for IRS3, which is out of the FOV at 340 GHz. Other early type stars, IRS16NE, IRS16SSW, IRS33E, IRS33N, IRS33NW, IRS34SW, Hel-N2, and AF, are also located on the dust emission peaks or within 0.5″ of them. In addition, the “famous” massive dense star cluster IRS13E is located on the center of the brightest dust condensation in the bar (e.g., Schödel et al. 2005). There seems to be tight correlation between the dust emission peaks and the OB/WR stars in the northern arm and the bar. On the other hand, the correlation between the eastern arm and the OB stars except for IRS9W is not clear because of the limitation of the FOV.

As the next step of the quantitative analysis of the dust emission, we searched for dust clumps in the 340 GHz continuum map using the `clumpfind` algorithm (Williams et al. 1994), and detected 18 clumps within the FOV at 340 GHz. To estimate the clump mass, \( M_c \), from the integrated intensity at 340 GHz, \( F_{340} \), we use the formula for optically thin thermal emission from dust, \( M_c = F_c d^2 / \kappa_c B_c (T_c) \), where \( \kappa_c \) is the dust mass absorption coefficient, \( \kappa_c = 0.1 \times (\nu/1200 \text{GHz})^\beta \) (Hildebrand 1983). We assume here a dust temperature of \( T_d = 20 \text{K} \) as a conservative value, \( \beta = 2 \), and a metallicity of \( Z/Z_\odot = 1 \). The most massive core is \( \sim 170 M_\odot \). When we get a new dust temperature of the clump, \( T_c \), the clump mass changes to \( [B_c (20)/B_c (T_c)] M_c \sim (20/T_c) M_c \) because \( b v / k T < 1 \).

Assuming a spherical dust particle, we estimate the mean number density using \( \bar{n} = M_c / \mu m_1 / (4\pi/3) r_c^3 \), where \( \mu \) is the mean molecular weight, \( \mu = 2.3 \) and \( r_c \) is the mean radius of the cores. The physical parameters of the clumps are shown in table 1. Figure 4 shows the dust clump mass function (CMF). The function on the high-mass side seems to obey a power law, which is usually used to depict the CMFs in the disk region of the Galaxy. The solid line in the figure shows the best-fit function for three massive data points, \( dN/dM \propto M^{-1.3 \pm 0.4} \). Recent IR observations suggested that the stars in the vicinity of Sgr A* have continuously formed with a top-heavy IMF (e.g., Maness et al. 2007). Although the slope of the mini-spiral CMF on the high-mass side is steeper than that of the expected top-heavy
IMF of the central cluster, the steeper CMF can change into the flat IMF by the tidal shear of Sgr A*. The mean gas number densities of the dust clumps are reasonably less than the minimum gas density required for stability against the tidal shear of Sgr A* (Tsuboi et al. 2015a). The proto- stars already formed in the cloud could finally grow to stars because the typical number density of the protostars is larger than the minimum gas density; on the other hand,
the remaining cloud gas will be ruined by the tidal shear. Consequently the IMF should become flatter than the CMF because the tidal destruction is more effective for lower mass cores.

Based on the observed tight correlation between the dust emission peaks and the OB/WR stars in the northern arm and the properties of the detected dust clumps, we would propose the following scenario as the origin of the central cluster: The stars, including massive stars, have formed in a molecular cloud located at a relatively large distance from Sgr A*. The massive star formation could be triggered by cloud–cloud collision because it can easily make high-mass stars (e.g., Tsuboi et al. 2015a). In addition, the cloud has lost a considerable amount of its angular momentum owing to the head-on collision. Consequently, the star-forming cloud has fallen into the immediate vicinity of Sgr A* with the time scale of ~10^5 yr, comparable to the expected growth time of massive stars by accretion (e.g., Krumholz et al. 2008). Now the falling cloud is being disrupted by the tidal shear of Sgr A* and the molecular gas in the cloud is ionized by the UV continuum from the OB stars of the central cluster. This is identified as the mini-spiral. Because the period of the circular orbit around Sgr A* is 0.2–2 × 10^4 yr at R = 0.1–0.5 pc (see table 1), the shearing motion would wind the mini-spiral around Sgr A* closely within ~10^4 yr. Although massive stars evolve quickly, low-mass stars should still be at the protostar stage. They may be the sources with bow-shock appearance observed by JVLA (Yusef-Zadeh et al. 2015a). Some of the massive stars formed in the cloud may be captured in the vicinity of Sgr A* and participate in the central cluster. The captured stars probably form a disk-like structure (cf. Saitoh et al. 2014). This is consistent with the observed disk-like distributions of the central cluster (e.g., Paumard et al. 2006).

Acknowledgement

We would like to acknowledge Dr. S. Nishiyama at Miyagi University of Education for useful discussions. This paper makes use of the following ALMA data: ADS/JAO.ALMA#2011.0.00887.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), NSC, and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ.

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