INTERSTELLAR MEDIUM PROCESSING IN THE INNER 20 pc IN GALACTIC CENTER

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ABSTRACT

We present the Submillimeter Array 157 pointing mosaic in 0.86 mm dust continuum emission with 5″1 × 4″2 angular resolution, and the National Radio Astronomy Observatory Green Bank 100 m Telescope (GBT) observations of the CS/C34S/13CS 1–0 and SiO 1–0 emission with ∼20″ × 18″ angular resolution. The dust continuum image marginally resolves at least several tens of 10–102 M⊙ dense clumps in the 5′ field including the circumnuclear disk (CND) and the exterior gas streamers. There is very good agreement between the high resolution dust continuum map of the CND and all previous molecular line observations. As the dust emission is the most reliable optically thin tracer of the mass, free from most chemical and excitation effects, we demonstrate the reality of the abundant localized structures within the CND, and their connection to external gas structures. From the spectral line data, the velocity dispersions of the dense clumps and their parent molecular clouds are 10–20 times higher than their virial velocity dispersions. This supports the idea that the CND and its immediate environment may not be stationary or stable structures. Some of the dense gas clumps are associated with 22 GHz water masers and 36.2 GHz and 44.1 GHz CH3OH masers. However, we do not find clumps that are bound by the gravity of the enclosed molecular gas. Hence, the CH3OH or H2O maser emission may be due to strong (proto)stellar feedback, which may be dispersing some of the gas clumps.

Key words: Galaxy: center – Galaxy: kinematics and dynamics – Galaxy: structure – ISM: clouds – stars: formation – techniques: interferometric

Online-only material: color figures

1. INTRODUCTION

The Galactic center (see Morris & Serabyn 1996; Mezger et al. 1996 for reviews) is a fertile ground for studying the interplay between the supermassive black hole (SMBH; see Genzel et al. 1997; Ghez et al. 2005) and the surrounding interstellar medium (ISM). The overall dynamics, the clumpiness, and the local kinematics may provide clues as to how the SMBH is fed by the ISM, how the circumnuclear gas streams evolve, and how the molecular cores and the young massive-stellar objects (Krabbe et al. 1991; Launhardt et al. 2002; Pfuhl et al. 2011; Lu et al. 2013; Do et al. 2013, etc.) form and migrate in the Galactic center. Previous molecular line observations indicated that the warm and turbulent gas clouds or streamers in the central ∼20 pc in the Galactic center (Ho et al. 1991; Okumura et al. 1991; Coil & Ho 1999, 2000; McGary et al. 2001; Herrnstein & Ho 2002, 2005; Oka et al. 2011) are well connected with the 2–4 pc circumnuclear disk (CND; Güsten et al. 1987a; Jackson et al. 1993; Marshall et al. 1995; Christopher et al. 2005; Montero-Castaño et al. 2009; Liu et al. 2012; Martín et al. 2012) surrounding the central black hole. These gas structures are the most extreme environments for high-mass star formation in the Milky Way (Morris 1993 and references therein).

The thermal dust continuum emission is the least biased by the chemical abundances and the excitation conditions. Hence, it is the most reliable tracer for demonstrating the reality and significance of the individual gas clouds or streamers, as well as their internal structures. The IRAM 30 m and the JCMT single-dish telescope observations of the millimeter and the submillimeter continuum emission have been presented by Zyka & Mezger (1988), Mezger et al. (1989), Dent et al. (1993), Lis & Carlstrom (1994), Pierce-Price et al. (2000), and García-Marín et al. (2011). In this work, we report the first wide-field interferometric mosaic observations (157 pointings, ∼5′ × 5′ field of view) of the 0.86 mm dust continuum emission using the Submillimeter Array (SMA8; Ho et al. 2004). The improved angular resolution of ∼5″ permits the detection of 0.1–0.2 parsec scale gas clumps, which can be the candidates of high-mass star-forming cores. In addition, we compare the dust continuum image with the HCO+ 4–3 line image simultaneously obtained with the SMA. We also compare these maps with the National Radio Astronomy Observatory (NRAO9) Robert C. Byrd Green Bank Telescope (GBT) observations of the CS/C34S/13CS 1–0 lines and the SiO 1–0 lines. This allows us to examine the gravitational stabilities of the dense structures and the possible existence of shock fronts (e.g., Kaufmann et al. 2013).

The new observations are described in Section 2. The results are presented in Section 3. We compare our observations with the previous observations of OH, CH3OH, and H2O masers in

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Figure 1. The SMA+JCMT 0.86 mm continuum image with a free–free model subtracted (color and contour). The angular resolution of this image is $\theta_{\text{maj}} \times \theta_{\text{min}} = 5''.1 \times 4''.2$. Contour spacings are 3$\sigma$ starting at 3$\sigma$ ($\sigma = 24$ mJy beam$^{-1}$). Yellow crosses are the 1720 MHz OH masers taken from Sjouwerman & Pihlström (2008), Yellow triangles are the compact, either thermal or low-gain masing 1612 MHz OH line sources discussed in Pihlström et al. (2008); see also Sjouwerman et al. 1998). Pink diamonds are the 36.2 GHz Class I CH$_3$OH masers reported in Sjouwerman et al. (2010). Yellow diamonds are the 44.1 GHz Class I CH$_3$OH masers reported in Pihlström et al. (2011). White Crosses and diamonds are the 22 GHz water masers and the 44.1 GHz CH$_3$OH masers reported in Yusef-Zadeh et al. (2008). Note the symbol size is not representative to the spatial uncertainty. For our convenience in discussion, we mark the peaks above the 45$\sigma$ significance level besides the Northeast Lobe and Southwest Lobe as JCMT-1, 2, 3 (see Appendix A). The regions associated with CH$_3$OH masers are labeled by A–H.

Section 4. A discussion of the non uniformity of the CND based on the 0.86 mm dust continuum image is given in Section 4.4. A brief summary of our results is given in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Submillimeter Continuum Emission

2.1.1. SMA Observations

We made mosaic observations toward the Galactic center using the SMA, in its compact and subcompact array configurations. These observations covered the frequency range of 354.1–358.1 GHz in the upper sideband, and 342.1–346.1 GHz in the lower sideband. Details of the subcompact array observations, and the pointing centers of the observations, can be found in Liu et al. (2012). The compact array observations were made in two observing runs, on 2012 May 7 and 2012 May 20, with six and seven available antennas, respectively. The system temperatures $T_{\text{sys}}$ during these two runs were $\sim$180–400 K. We observed two phase calibrators, 1733-130 and 1924-292, every $\sim$15 minutes during all observations. The amplitude and passband calibrators were Titan and 3C 279 on May 7, Neptune and 3C 279 on May 20. The target loops iterated over 157 pointing centers, with five 5 s integrations at each pointing center. Each of the 157 pointings was visited more than three times in each observing run (i.e., on source time $>$3 hr in total in each run). The minimum and maximum projected baselines in our SMA observations are $\sim$7.0 k$\lambda$ and $\sim$82 k$\lambda$. All SMA data were calibrated using the MIR IDL software package (Qi 2003). We used the MIRIAD (Sault et al. 1995) task UVAVER to average all line-free channel data and reconstruct the 0.86 mm continuum band data. The short spacing data were complemented by combining the archival JCMT SCUBA image (Appendices A and B). The zeroth order free–free continuum emission model was constructed based on the archival Very Large Array (VLA) 7 mm observation data, and was subtracted from the combined SMA+JCMT 0.86 mm continuum image (Appendix C). The simultaneously observed HCO$^+$ 4–3 line was regrided to 2.1 km s$^{-1}$ velocity channels for an adequate sensitivity, and will be presented for the purpose of discussing the virial condition. The detailed studies of the submillimeter line data are deferred.
2.2. GBT Observations

We observed the CS 1–0 (48.99095 GHz) and the C34S 1–0 (48.20692 GHz) transitions using the NRAO GBT on 2011 November 4 and 7. We observed the 13CS 1–0 (46.24754 GHz) and the SiO 1–0 (43.42376 GHz) transitions on 2011 November 7 and 9. The field of view of the SiO and 13CS observations is slightly offset toward the west to better recover the western gas streamers. The angular resolution of the GBT is 763′/′/ν, where ν is the observing frequency in GHz. The bright point source 1733-130 was observed in the beginning of each session for antenna surface (i.e., by Out of Focus Holography) and pointing calibrations. A line-free reference position R.A.: 17h43m43s.444, decl.: −29°59′32″.27 was integrated for 30 s before and after the target observations in each block for off-source calibration data.

We used the GBTIDL software package (Marganian et al. 2006) to calibrate the GBT data. We note that the CS isotopologue targets observations in each block for off-source calibration data. We used the Astronomical Image Processing System (AIPS) software package to perform imaging. We smoothed the final CS and C34S image to an rms noise levels in each 24 kHz (∼0.15 km s⁻¹) at 48.99 GHz) spectral channel are ∼0.5 K for the CS and C34S observations, and are ∼0.14 K for the 13CS and SiO observations.

3. RESULTS

We present the observing results in this section. Our nomenclature follows Christopher et al. (2005), Amo-Baladrón et al. (2011), and Liu et al. (2012).

We also compare our results with the VLA observations of the 1612 MHz OH masers (Pihlström et al. 2008; see also Sjouwerman et al. 1998), the VLA observations of the 1720 MHz OH masers (Sjouwerman & Pihlström 2008), the GBT and VLA observations of the 44.1 GHz Class I CH3OH masers (Yusef-Zadeh et al. 2008), the JVLA observations of the 44.1 GHz Class I CH3OH masers (Pihlström et al. 2011), the JVLA observations of the 36.2 GHz Class I CH3OH masers (Sjouwerman et al. 2010), and the GBT observations of the 22 GHz H2O masers (Yusef-Zadeh et al. 2008).

3.1. Continuum Emission

Figure 1 shows the high angular resolution SMA+JCMT 0.86 mm continuum image. A model of the free–free emission has been subtracted (see Appendix C). The 0.86 mm continuum image recovers the detailed gas structures in the CND including the Northeast Lobe, the Northeast Extension, the Southwest Lobe, the Southern Extension, and the W-2,3,4 Streamers that connect to the CND from the west. It addition, it presents the detailed structures embedded in the Northern Ridge, and the Southern Ridge, the 50 km s⁻¹ cloud, the Molecular Ridge, the 20 km s⁻¹ cloud. A southern dust ridge which appears to connect JCMT-1 to JCMT-2 (see Figure 1) in the archival JCMT SCUBA 0.44 mm (678 GHz) continuum image published by Pierce-Price et al. (2000; Project ID: M98AU64) is also resolved in our SMA+JCMT image (see Figure 2). The spatial location of this southern dust ridge coincides with the Southern Arc reported by the previous observations of the CS 1–0 line emission (Liu et al. 2012).

Excluding the central point source, the 0.86 mm flux of the CND is approximately 68 Jy in a distribution that closely follows that of the inner 5 pc of the CND. At least a few tens of dense molecular gas clumps are marginally resolved. Higher angular resolution observations may resolve more blended dense clumps in this field. The precise number of clumps is not important for this discussion. The main conclusion is the impression of a very clumpy structure. The most significant dense clumps are found in the protrusion connecting to the Southwest Lobe. Clusters of very dense clumps are also resolved toward the peaks of the JCMT SCUBA 0.86 mm image (e.g., JCMT-1,2,3 and the peaks in the Northern Ridge; see Appendix A).

In the present work, only the dense clumps located near the CH3OH masers, and additionally the dense clumps located in JCMT-1 and JCMT-2, are discussed (Figure 3). We do not attempt to systematically search for and analyze all dense clumps in the entire field because of the limited image quality and insufficient angular resolution for the CND (see Montero-Castaño et al. 2009 and Martín et al. 2012 for higher angular resolution spectral line images). To estimate the 0.86 mm fluxes of the selected clumps, we first fit ∼1 pc scale 2D Gaussian components to suppress the contribution of the ambient gas, and then fit 2D Gaussian components to the localized peaks. The 0.86 mm fluxes of the individual Gaussian components are summarized in Table 1, which provides a quantitative measure of how massive the sub-parsec scale gas over-densities may be. The uncertainties in background subtraction can give a few tens of percent of errors in fluxes. In addition, the overestimates of the background emission can lead to underestimates of the clump sizescale. The main purpose of this analysis is to estimate the virial velocity dispersions of these dense clumps (Section 4.3). In this sense,
the effects of overestimates of the background and underestimates of the clumps sizescale are competing. Gaussian components with minor axis FWHM smaller than one standard deviation of the SMA+JCMT Gaussian beam width, $5\prime/2/2.355 = 2\prime$, are not considered because we cannot estimate the physical deconvolved size scales. The Gaussian components that are located near the edge of the SMA+JCMT 0.86 mm continuum image are also not considered.

3.2. Molecular Emission

The SMA image of HCO$^+$ 4–3 is shown in Figure 4, over-plotted with the fitted 0.86 mm dense clumps (Section 3.1; Figure 3). The HCO$^+$ 4–3 line is a good tracer of the ring-like CND, and also the gas streamers connecting to the CND. The eastern part of the CND is relatively narrow and smooth compared to the western part. The CND may be undergoing dynamical evolution, or is composed of distinct streams of molecular gas (Jackson et al. 1993; Wright et al. 2001; see Section 4.4).

Toward the more extended 20 km s$^{-1}$ cloud, the Southern Arc, the Molecular Ridge, and the 50 km s$^{-1}$ cloud, the SMA observations are detecting strong missing flux (see Liu et al. 2012). In addition, the lower gas temperature in the extended cloud than in the CND also causes the weak detection or non-detection of the warm gas tracer HCO$^+$ 4–3 ($E_{up} = 43$ K). We therefore can only robustly image the HCO$^+$ 4–3 line toward
Figure 4. The velocity integrated HCO\(^+\) 4–3 image (\(\theta_{maj} \times \theta_{min} = 5.8 \times 4.1\)\(^{\prime}\)). The red ellipses show the fitted 0.86 mm clumps (see Figure 3). The blue star labels the location of Sgr A\(^*\).

(A color version of this figure is available in the online journal.)

a few fitted dense clumps. The detected HCO\(^+\) 4–3 spectra are presented in Figure 5. The velocity dispersions derived from the single component Gaussian fittings are summarized in Table 1. From Figures 3 and 5 we see that the brightest clump over the selected samples (Table 1), the JCMT-1\(n\), has a centroid velocity of \(-95\) km s\(^{-1}\). The JCMT-1\(n\) clump is likely to be embedded in the very blueshifted Southern Ridge, which shows strong SiO 2–1 emission in the earlier Nobeyama Millimetre Array observations (Sato & Tsuboi 2008, and also see Amo-Baladrón et al. 2011). However, the CS 1–0 line spectrum taken at JCMT-1\(n\) indicates that a \(v_{lsr} \sim 7\) km s\(^{-1}\) gas component is completely missed from the SMA observations of HCO\(^+\) 4–3 (ref. spectrum 10 in Liu et al. 2012). The virial velocity of JCMT-1\(n\) derived from the 0.86 mm dust continuum emission (Table 1) then should be considered as an upper limit when comparing with the HCO\(^+\) 4–3 velocity dispersion.

The more extended gas streamers are recovered by the GBT observations of the CS/C\(^{34}\)S/\(^{13}\)CS 1–0 lines and the SiO 1–0 line (Figure 6), which trace cooler gas (\(T_{up} = 2.1–2.3\) K). The SiO 1–0 emission appears to be correlated with the CS 1–0 emission. The flux ratio of these lines will be discussed in Section 4.1.

4. DISCUSSION

We discuss the inferred ISM properties based on the presented observations.

4.1. The Spectral Line Ratio

While the abundance of the CS molecule is only mildly enhanced in UV and shocked environments (Amo-Baladrón et al. 2011 and references therein), the abundance of the SiO molecule in shocked environments can be enhanced by up to a factor of 10\(^6\) with respect to the value in quiescent gas (Martin-Pintado et al. 1992). Since SiO and the CS isotopologues have similar dipole moments and energy level distributions, the derived flux ratio between these molecules can trace shocks without being sensitive to the assumed physical conditions.

Figure 7 shows the velocity integrated CS/C\(^{34}\)S 1–0 line ratio. Above \(\sim 40\) GHz, difficulties in calibrating the several arcsecond GBT pointing offsets can potentially lead to a \(\sim 30\%\) uncertainty in absolute flux level. This uncertainty does not affect the derived CS/C\(^{34}\)S 1–0 ratio since these two lines are simultaneously observed. We found that the CS/C\(^{34}\)S 1–0 ratio is \(\sim 6–12\) toward the 50 km s\(^{-1}\) cloud and the 20 km s\(^{-1}\) cloud. The earlier NRO 45 m Telescope observations of CS 1–0 and C\(^{34}\)S 1–0 only robustly detected the C\(^{34}\)S 1–0 emission at the reference point located 3\(^{\prime}\) north and 3\(^{\prime}\) east of the Sgr A\(^*\), and showed a CS/C\(^{34}\)S 1–0 ratio of 8 (Tsuboi et al. 1999). Considering that the NRO 45 m Telescope observations were more beam smoothed, our results are consistent with the previous observations. Assuming an abundance ratio of \([X(\text{CS})]/[X(\text{C}^{34}\text{S})] = 22.6\) (Freking et al. 1980; Tsuboi et al. 1999), the optical depth \(\tau\) of CS 1–0 can be estimated based on the following relation

\[
\frac{S_{\text{CS}}}{S_{\text{C}^{34}\text{S}}} = \frac{1 - \exp(-\tau)}{1 - \exp(-\tau/22.6)},
\]

where \(S_{\text{CS}}\) and \(S_{\text{C}^{34}\text{S}}\) are the fluxes of the CS and the C\(^{34}\)S lines. The line ratio \(S_{\text{CS}}/S_{\text{C}^{34}\text{S}} = 14.2\) when \(\tau = 1\). From Figure 7, the majority of the optically thick CS 1–0 line (\(\tau = 1.5–4\), i.e., CS/C\(^{34}\)S 1–0 ratio \(\sim 6–12\)) is seen toward the 50 km s\(^{-1}\) cloud and the 20 km s\(^{-1}\) cloud. The C\(^{34}\)S 1–0 line is optically thin over the observed field.

The SiO 1–0 line is \(\sim 1.5–2\) times fainter than the CS 1–0 line (Figure 6). Assuming the optically thin limit, the velocity integrated SiO/C\(^{34}\)S 1–0 line ratio (Figure 8) traces the abundance ratio. We present the velocity channel maps of the SiO/C\(^{34}\)S 1–0 line ratio in Figure 9 to trace the velocity structures of the shocked gas. While the SiO/C\(^{34}\)S 1–0 ratio is
Figure 6. Molecular gas in the central 20 pc region in the Galactic center. (a) The velocity integrated CS 1–0 emission ($\sigma \sim 0.7$ K km s$^{-1}$). The symbols are described in Figure 1. Labels of the large scale gas streamers are consistent with those in Liu et al. (2012). (b) The velocity integrated C$^{34}$S 1–0 emission (grayscale and black contour). Contour spacings are 2$\sigma$ starting at 2$\sigma$ ($\sigma \sim 0.7$ K km s$^{-1}$). (c) The velocity integrated SiO 1–0 emission (grayscale and black contour). Contour spacings are 10$\sigma$ starting at 10$\sigma$ ($\sigma \sim 0.15$ K km s$^{-1}$). (d) The velocity integrated $^{13}$CS 1–0 emission (grayscale and black contour). Contour spacings are 4$\sigma$ starting at 4$\sigma$ ($\sigma \sim 0.15$ K km s$^{-1}$). The few $^{13}$CS peaks at R.A. = 17$^h$45$^m$34–35$^s$ may be caused by ambiguities in baseline subtraction. The rms noise level of the velocity integrated images are estimated based on the integration of the signal over a 13 km s$^{-1}$ velocity range, which is the median of the fitted velocity dispersion (see Table 1). The green contours in panels (b) and (d) show the free–free model subtracted SMA+JCMT 0.86 mm continuum image. The 0.86 mm continuum image contour spacings are 7.5$\sigma$ starting at 7.5$\sigma$ ($\sigma = 24$ mJy beam$^{-1}$). The blue star labels the location of Sgr A$^*$. (A color version of this figure is available in the online journal.)
already high in the entire map area, it appears to be enhanced in the 20 km s\(^{-1}\) cloud and the Southern Arc. Based on the correlation between NH\(_3\) and 1.2 mm dust emission and the locations of OH masers, Wright et al. (2001) also suggested that these regions could be shock heated. Our observations do not have sufficient angular resolution to resolve the shock fronts. Whether the shocks are created by the supernova shell to the south of Sgr A East, or are created due to the non-circular orbits of the clouds, are not yet distinguished.

The earlier IRAM 30 m Telescope observations additionally showed the enhanced SiO emission toward the 50 km s\(^{-1}\) cloud and around the Southern Ridge and the W-4 Streamer. Our GBT observations of SiO 1–0 only covered a small part of the 50 km s\(^{-1}\) cloud, and did not significantly detect the Southern Ridge. The W-4 Streamer is only marginally detected in our C\(^3\)S 1–0 observations.

### 4.2. The Molecular Gas Environment Around the Masers

The 1720 MHz OH masers and the 1612 MHz OH masers trace the \(n_{\text{H}_2} \sim 10^5\) cm\(^{-3}\) and \(n_{\text{H}_2} \gtrsim 10^3\) cm\(^{-3}\) postshock gas in supernova remnants (assuming \(T \sim 75\) K; Pihlström et al. 2008; Pavlakis & Kylafis 1996). The 22 GHz H\(_2\)O masers are collisionally excited at higher densities \(n_{\text{H}_2} \sim 10^7\)–\(10^9\) cm\(^{-3}\); Elitzur et al. 1992), and are often found in star-forming regions. The collisionally excited Class I CH\(_3\)OH masers are regarded as the unambiguous signposts of ongoing high-mass star formation in typical molecular clouds (Menten et al. 1992; Yusef-Zadeh et al. 2008). However, the Galactic center (e.g., inner 2–20 pc) gas streamers are warmer and 10 times more turbulent than the other star-forming molecular clouds. In such extreme environments, the Class I CH\(_3\)OH masers may also be excited in cloud interactions although not yet observationally confirmed (Sjouwerman et al. 2010).

From Figure 13, we can see that on \(\sim 10\) pc scales, while the distribution of the OH masers follows a shell like geometry, the CH\(_3\)OH and H\(_2\)O masers are more scattered over the field. In the higher angular resolution dust continuum image (Figure 1), we see that the CH\(_3\)OH and H\(_2\)O masers are preferentially detected near the \(\lesssim 0.5\) pc scale localized overdensities. The only exceptions are the CH\(_3\)OH masers associated with the region H that is located near the central bright free–free continuum sources. The flux at region H may be biased by the uncertainties in interferometric imaging and the free–free model subtraction (Appendix C). In addition, the molecular gas in region H may be photo-ionized by the central engine Sgr A*.

We summarize the observed intensity of the dust continuum emission and the velocity integrated SiO/C\(^3\)S 1–0 ratio in Figure 10. Except for the 44.1 GHz CH\(_3\)OH masers associated with region H, the other CH\(_3\)OH and H\(_2\)O masers are detected at intensities \(\gtrsim 0.15\) Jy beam\(^{-1}\). The OH masers do not show a clear correlation with the flux of the dust continuum emission. The clusters of OH masers may only sparsely sample the geometrically thin expanding shell (Coil & Ho 1999) in projection of the bulk of the dense gas. Yusef-Zadeh et al. (2008) and Pihlström et al. (2011) only observed H\(_2\)O and CH\(_3\)OH masers toward selected high density regions, which potentially biases the corresponding maser data in Figure 10 toward higher “averaged” 0.86 mm intensity. Nevertheless, the size scales of the dense clumps in Figure 1 are generally smaller than what can be discerned from previous observations of molecular gas. We therefore do not think the spatial correlation between the clumps and the maser spots is purely an artifact due to the observational selection. As an example, the good correlation between the 0.86 mm emission clumps in region G (Figure 1, i.e., pointing E in Pihlström et al. 2011) and the JVLA detections of 44.1 GHz CH\(_3\)OH maser spots does not seem to be
coincidence, but should be interpreted with the local physical conditions.

For both the maser sources and the ambient gas, our observations do not resolve a clear correlation between the \[X(\text{SiO})/X(\text{C}^{34}\text{S})\] abundance ratio and the 0.86 mm intensity (Figure 10). On the large (e.g., >1 pc) scale, the shocked gas may be well mixed with the ambient material. The enhanced abundance of SiO in shocks lasts for a few 10^3 yr. With the \(~50–100\) km s\(^{-1}\) relative motion of gas clouds around the CND, the smeared local SiO shock fronts may have widths of 0.15–0.3 pc (i.e., \(\sim 3.8–7.5\)\), which have to be examined with sensitive higher angular resolution observations. Here we refer to Martín et al. (2012) for higher angular resolution observations of SiO emission in the 2′ field around the Sgr A*.

4.3. The Dense Molecular Clumps

The brightness temperature of the dust emission at the 0.86 mm wavelength (Appendix B) is much lower than the gas temperature (see Herrnstein & Ho 2005). The molecular gas mass can therefore be calculated from the 0.86 mm flux based on the optically thin formula

\[
M_{\text{H}_2} = \frac{2\lambda^3 R \rho D^2}{3hcQ(\lambda)J(\lambda, T_d)} S(\lambda),
\]

where \(R\) is the gas-to-dust mass ratio, \(\rho\) is the mean grain radius, \(a\) is the mean grain density, \(D\) is the distance of the target, \(Q(\lambda) \propto \lambda^{-\beta}\) is the grain emissivity, \(T_d\) is the dust temperature, \(S(\lambda)\) is the flux of the dust emission at the given wavelength, and \(J(\lambda, T_d) = 1/[\exp(hc/\lambda k_B T_d) - 1]\) (Hildebrand 1983; Lis et al. 1998). The \(c, h, k_B\) are the light speed, the Planck constant, and the Boltzmann constant, respectively. Following Lis et al. (1998), we adopt \(R = 100, a = 0.1 \mu m, \rho = 3 \text{ g cm}^{-3}\), and \(Q(\lambda = 350 \mu m) = 1 \times 10^{-4}\). We adopt \(D = 8.33\) kpc based on the measurements of Gillessen et al. (2009).

Gas temperature measurements that have a comparable angular resolution with our dust continuum map are not yet available. By measuring the rotational temperature of the NH\(_3\) molecule, Herrnstein & Ho (2005) suggested that roughly one quarter of the molecular gas comprises a hot (\(~200\) K) component, and...
the remaining gas is cool ($\sim 25$ K). We tentatively assumed an averaged gas temperature $T_{\text{gas}} = 70$ K in the dense clump. We also assumed the dust temperature $T_d = T_{\text{gas}}$ (see Chan et al. 1997 for dust temperature in the CND; see also Minh et al. 1992; Ao et al. 2013). The ranges of gas mass in the dense clump estimated based on the assumption of $\beta = 1–2$ are given in Table 1. Based on the aforementioned assumptions, without considering the foreground/background subtractions, the detected 0.86 mm flux in the inner 5 pc CND (68 Jy, see Section 3.1) corresponds to $0.98–2.3 \times 10^4 M_\odot$ of gas mass.

Our estimates of the CND mass agree reasonably well with those from earlier observations of millimeter and submillimeter dust continuum emission (e.g., Mezger et al. 1989; see also Christopher et al. 2005 for relevant debates).

If the identified gas dense clumps are virialized, then the expected one-dimensional velocity dispersion $\delta v_{\text{vir}}$ is given by

$$\delta v_{\text{vir}} = \sqrt{\frac{\alpha M G}{\delta r}},$$

(3)

where $\alpha$ is the geometric factor which equals unity for a uniform density profile and $5/3$ for an inverse square profile (Williams et al. 1994; Walsh et al. 2007), $M$ is the gas mass, $G$ is the gravitational constant, and $\delta r$ is the effective radius of the dense clump.

The effective radius $\delta r$ can be calculated based on the FWHM of the fitted 2D Gaussian (i.e., $\delta \theta_{\text{maj}}$ and $\delta \theta_{\text{min}}$ in Table 1), however, it must be corrected for the beam FWHM $\delta \theta_{\text{beam}}$ because the identified clumps are only marginally resolved. For simplicity, we adopt the corrected effective circular angular diameter of the dense clump to estimate their linear diameter (cf. Williams et al. 1994)

$$\delta \theta_{\text{eff}} = \sqrt{(\delta \theta_{\text{maj}} \times \delta \theta_{\text{min}}) - (2\delta \theta_{\text{beam}}/2.355)^2}$$

(4)

and consider the gas mass enclosed in one FWHM of the fitted 2D Gaussian when calculating the virial one-dimensional velocity dispersion. For those identified dense clumps with $\delta \theta_{\text{eff}} > 0$, we compare the results of the calculation with the one-dimensional velocity dispersion measured from the CS 1–0 line and the HCO$^+$ 4–3 line (when significantly detected) in Table 1. The mean gas number densities are calculated based on the aforementioned estimates of the clump masses and radii, and the assumptions of spherical geometry and the mean molecular weight of 2.33 (Shull & Beckwith 1982). We note that the JCMT-2 region shows double peak profiles in the CS 1–0 spectra. However, the broader line component is very faint and therefore is less likely to be associated with the dense gas clumps.

We found that the dense clumps listed in Table 1 have $\sim 10–10^3 M_\odot$ of molecular gas, which can be adequate gas reservoirs to form high-mass stars. However, the mean gas number density in these dense clumps is generally between $10^5–10^6$ cm$^{-3}$, which is marginally unstable against the tidal force (Morris 1993; Liu et al. 2012). The GBT observations of CS 1–0 suggest that the identified dense clumps are all embedded in a very turbulent environment, which has one-dimensional velocity dispersion of 10–30 km s$^{-1}$.
masers (black), the 36.2 GHz CH$_3$OH masers (magenta), and the 44.1 GHz masers (green), the 1612 MHz OH masers (light blue), the 22 GHz water masers (blue) are presented by colored symbols. For masers, the lower limit of the velocity integrated SiO \(/ \Sigma \) ratio is given if the C$_{34}$S 1–0 emission is not robustly detected. The data points located outside of the field of view of either the 0.86 mm image or the SiO image are not presented.

A color version of this figure is available in the online journal.

(see Tsuboi & Miyazaki 2012). The kinetic energy of the gas may be dissipated on smaller scales. The higher angular resolution SMA observations of HCO$^+$ 4–3 toward the enclosed Region A, Bn, B, Bs, and JCMT-1n detect the 2–3× smaller velocity dispersion in the localized dense clumps. Nevertheless, the observed HCO$^+$ 4–3 velocity dispersions are still 10 times higher than the virial velocity dispersions of the dense clumps. Our preliminary analyses do not yet find any (self-)gravitationally bound gas structures on $\lesssim$0.5 pc scale.

Although our HCO$^+$ 4–3 image only traces dense clumps in the warmer environments, HCN 1–0 and HCO$^+$ 1–0 spectra from previous $3'' \times 4''$ resolution BIMA array observations also showed broad line profiles in the central $5' \times 5'$ field (Wright et al. 2001). Observations of the lower excitation gas tracers HCN 1–0 and HCO$^+$ 1–0 trace the velocity dispersion of the dense clumps in the central $5' \times 5'$ field (Wright et al. 2001). With $3'' \times 4''$ angular resolution, the BIMA spectra are contaminated by emission from the diffuse and more turbulent ambient gas as traced by CS 1–0, however, a deconvolved HCN 1–0 image at $\sim$2$''$ resolution (Güsten et al. 1987b) shows only the integrated image) also shows line widths that are much larger than the virial velocity dispersions of the dense clumps. Unless these dense clumps are composed of dense, bound cores, or the gas kinetic energy can be dissipated efficiently, they may be dispersed in one dynamical timescale (i.e., $\delta v / \delta t \sim 5.3 \times 10^3$–2.6 $\times 10^4$ yr for the HCO$^+$ 4–3 emission clumps in Table 1). Higher angular and velocity resolution spectral line observations are required to see whether (self-)gravitationally bound gas structures exist on a smaller scale.

Alternatively, these dense clumps embedded in the extremely turbulent molecular clouds may be confined by the high external pressure. If small scale virialized gas structures do exist inside the dense clumps, then hydrostatic cores and stars may still form. Assuming approximate hydrostatic equilibrium of the embedded star-forming cores with masses $M_{\text{core}}$, the radius $r_c$, the mean gas number density $n_H$, and the rms velocity dispersion $v_{\text{rms}}$ of the cores, as well as the final stellar mass $m_*=\epsilon_{\text{acc}}M_{\text{core}}$, can be estimated based on the following formulae (details see McKee & Tan 2002):

$$r_c = 0.074 (m_*/30 M_{\odot})^{1/2} \Sigma^{-1/2} \text{ pc}, \quad (5)$$

$$n_H = 1.0 \times 10^6 (m_*/30 M_{\odot})^{-1/2} \Sigma^{3/2} \text{ cm}^{-3}, \quad (6)$$

$$v_{\text{rms}} = 1.65 (m_*/30 M_{\odot})^{1/4} \Sigma^{1/4} \text{ km s}^{-1}, \quad (7)$$

where $\Sigma$ is the mean clump surface mass density in units of g cm$^{-2}$, and $\epsilon_{\text{acc}}$ (assumed to be 0.5 here) is the fraction of the core mass which is eventually accreted onto the central star. From Figure 1, the majority of the densest clumps are embedded in the region above the 12$\sigma$ contour level (i.e., $288 \text{ mJy beam}^{-1}$), which corresponds to the $\Sigma$ of 0.31–0.76 g cm$^{-2}$. Based on the values in Table 1, we adopt a fiducial value $n_H \sim 10^6$ cm$^{-3}$ for an example. We estimate the core radius $r_c \sim 0.023–0.056$ pc (0.58–1.4$''$), the rms velocity dispersion 0.51–1.3 km s$^{-1}$, and the final stellar mass $m_* \sim 0.89–13 M_{\odot}$.

Two quantities can be estimated with <0.5 resolution Atacama Large Millimeter/submillimeter Array (ALMA) observations in the near future. The corresponding core mass $M_{\text{core}} = 2 \times m_*$ in our estimates is several times smaller than the masses of the parent gas clumps listed in Table 1, so it may be reasonable.

As discussed in the previous section, the dense clumps embedded in some regions (e.g., A, B, D, E, F, G) are associated with the 22 GHz water maser and the 36.2 GHz and 44.1 GHz Class I CH$_3$OH masers, which are often seen in the early phase of high-mass star-formation. In addition, the earlier VLA observations of the 2 cm and the 6 cm continuum emission have found ultracompact HII regions embedded with several OB stars in the east of the 50 km s$^{-1}$ cloud (e.g., Ho et al. 1985). The observed high HCO$^+$ 4–3 velocity dispersion may be interpreted by (proto)stellar feedback. However, Sjouwerman et al. (2010) also suggested that the 36.2 GHz Class I CH$_3$OH masers can be excited at the post shock regions created by cloud–cloud collisions. High angular resolution molecular line observations and studies of the maser proper motion may distinguish these two cases, although they are not mutually exclusive. In fact, it has been argued that the predominant mode of star formation is via external compression of molecular clouds by cloud collisions and supernova (Morris 1993). The high-mass star formation can also be induced by active galactic nucleus activity (Silk et al. 2012). In these cases, the physical properties of the molecular gas reservoir feeding the high-mass star formation may be very different from the typical OB star-forming cores.

4.4. The Non-uniform CND

Previous interferometric spectral line observations have shown abundant localized structures in the central 2–4 pc CND (see Christopher et al. 2005; Montero-Castaño et al. 2009; Martín et al. 2012 and references therein). The distributions of the spectral line emission, however, are sensitive to the local temperature, volume density, chemical abundances, and other
radiation transfer effects such as the foreground absorption or self-absorption. The optically thin 0.86 mm dust thermal continuum emission is a more robust tracer of the gas mass (e.g., Hildebrand 1983). Without being subjected to missing flux, our JCMT+SMA 0.86 mm dust continuum image (Figure 1) successfully reproduces the clumpy CND structures seen in the spectral line observations (e.g., Figure 4). It appears that some previously known clumps in the CND are not merely due to excitation or radiation transfer effects. For example, the 0.86 mm emission clumps A and Bn (Table 1; Figure 3) coincide with the HCN 4–3 emission clumps CC and BB reported by Montero-Castaño et al. (2009). As can be expected, we found that around the CND, the velocity integrated HCO+ 4–3 intensity is correlated with the intensity of the 0.86 mm continuum emission (Figure 11).

However, in Figure 11, we see that the correlation between the HCO+ 4–3 emission and the 0.86 mm emission is dominated by at least two distinct populations that can be discerned with our current angular resolution and sensitivity. We selected the high HCO+ 4–3 intensity parts of the two dominant populations as Zone 1 and Zone 2 in Figure 11, and additionally one high HCO+ 4–3 intensity and high 0.86 mm intensity population as Zone 3, and one high 0.86 mm intensity population as Zone 4. We argue that these high intensity pixels are more likely to be associated with compact bright clumps, for which the HCO+ 4–3 intensity is less biased by missing flux.

The spatial distributions of the pixels in these four zones are not random. For example, the pixels in Zone 1 seem to trace the two arc-shaped clumps west of the CND, the eastern edge of the CND, and the clumps located northwest of the Sgr A*.

5. SUMMARY

We present a wide-field SMA mosaic toward the Galactic center. We also observed the CS/CsS/Cs 1–0 and the SiO 1–0 lines using the GBT. The optically thin 0.86 mm dust thermal continuum image with ∼5′ angular resolution confirms the 2–10 pc scale gas streamers and the detailed structures of the CND, which were seen in previous molecular line observations. We marginally resolve more than 22 massive (10^1–10^3 M_⊙) gas clumps, which are embedded in very turbulent molecular gas clouds (δv ∼ 10–30 km s⁻¹). Examination of the brightness ratio of the HCO+ 4–3 line and the 0.86 mm continuum emission shows that the non-homogenized central 2–4 pc CND has dense clumps with distinct excitation conditions or chemical abundances. While the distributions of the 1720 MHz and 1612 MHz OH maser clusters do not show obvious correlations with the dust emission, the 22 GHz water masers and especially the 36.2 and 44.1 GHz Class I CH₃OH masers are seen preferentially near the dense clumps. Even the most significant dense clumps in our selected samples are marginally unstable against the tidal force, and we do not find any self-gravitationally unstable clumps with the pixels in Zone 4. Comparing Figure 12 with the ratio of the HCN 4–3 to HCN 1–0 integrated intensity reported by Montero-Castaño et al. (2009), we deduce that the very dense clump in the southern part of the Southwest Lobe has a low gas excitation temperature. This provides hints for the cooler exterior gas clumps raining down on the warmer CND. For a dynamically evolving CND that is connected with several exterior gas streamers (see Liu et al. 2012), it is not surprising that the excitation conditions, the chemically abundances, or the dust properties are not yet homogenized.
bound gas clump associated with the Class I CH$_3$OH masers or the 22 GHz H$_2$O masers. How the OB stars form in such an environment remains puzzling. The mechanisms to form the dense clumps and the high-mass stars in the Galactic center might be very different from the mechanisms in typical giant molecular clouds. Our simple estimates suggest that if the detected dense clumps are confined by the high external pressure, then the presumably existing embedded virialized gas cores can form high-mass stars. Deep JVLA observations to search for the signature of the stellar photoionization, or ALMA observations of the high excitation hot core tracers to look for the gravitationally accelerated rotation may diagnose the OB star formation in the dense clumps.

Our GBT data suggest a mildly enhanced SiO/C$^{34}$S line ratio toward the Southern Arc and the 20 km s$^{-1}$ cloud, relative to the SiO/C$^{34}$S line ratios in the other gas streamers in the observed field. Our observations do not yet resolve the recognizable correlation between the SiO/C$^{34}$S line ratio and the intensity of the submillimeter dust emission. Higher angular resolution and more sensitive observations are required to examine whether the formation of the dense gas structures are predominantly induced by shocks.

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Facilities: SMA, GBT

APPENDIX A

SHORT SPACING INFORMATION

Short spacing information, below $\sim 7.0$ $k\lambda$, was obtained from single-dish telescope observations. We retrieved the archival public processed JCMT$^{10}$ SCUBA (ProjectID: M01BU26, observed on 2001 August 5) 0.86 mm continuum image (Figure 13; rms $\sim$ 50 mJy beam$^{-1}$). We used the MIRIAD task DEMOS to generate SMA primary beam weighted models for each SMA pointing. For each SMA field, we then resampled the primary beam weighted models in the $uv$ domain with 185 Gaussian randomly distributed visibilities using the MIRIAD tasks UVRANDOM and UVMODEL. We manually assigned a system temperature of 350 K to the visibility model to adjust the weighting.

The typical pointing accuracy for JCMT SCUBA is about 3$''$ and the tracking accuracy $\sim 1''$ (Di Francesco et al. 2008). From their JCMT SCUBA legacy survey, Di Francesco et al. (2008) also mentioned that larger pointing offsets (e.g., $\sim 6''$) occurred occasionally. When combined with the interferometric observations, pointing offsets during the single-dish observations can cause defects especially near bright compact sources. We used a limited $uv$ range of 0–3.8 $k\lambda$ for the single-dish $uv$ model to suppress the potential effect of the single-dish pointing offsets, as well as the effect of the single-dish primary beam and deconvolution errors. Although the effect of the single-dish primary beam is not fully eliminated, it is smaller than the $\sim 20\%$ absolute flux error in typical SMA observations (Appendix B). Limiting the $uv$ range implies that the single-dish primary beam causes defects primarily for structures $>33''$, and therefore should not confute the identification of local gas clumps in the streamers.

We jointly deconvolved and imaged the concatenated single-dish $uv$ model and the SMA data using the MIRIAD software package (using tasks: INVERT, MOSSDI, RESTOR). The gap (3.8–7 $k\lambda$) in the $uv$ sampling may yield uncertainties in reconstructing the 14''–33'' angular scale structures. However, structures with these angular scales can be directly inspected from the single-dish image. We generated the high angular resolution continuum image with the parameters $\text{robust} = 0$ $fwhm = 4.4$ in INVERT, which yield a synthesized beamwidth $\theta_{\text{maj}} \times \theta_{\text{min}} = 5''1 \times 4''2$, and BPA $\sim 28^\circ$. To compare with the earlier observations, we also generated one lower angular resolution ($\theta_{\text{maj}} \times \theta_{\text{min}} = 7''4 \times 6''2$, BPA $\sim 44^\circ$) continuum

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure13.pdf}
\caption{The JCMT SCUBA 0.86 mm continuum image ($\theta_{\text{maj}} \times \theta_{\text{min}} = 14'3 \times 14'3$). Contour spacings are 5$\sigma$ starting at 5$\sigma$ ($\sigma = 50$ mJy beam$^{-1}$). For our convenience in discussion, we mark the peaks above the 45$\sigma$ significance level besides the Northeast Lobe and Southwest Lobe as JCMT-1,2,3. The symbols are described in Figure 1.}
\end{figure}

10 The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.
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Figure 14. Left: the residual image constructed by subtracting the JCMT SCUBA image from the smoothed high angular resolution SMA+JCMT 0.86 mm continuum image (see Appendix B). The JCMT beam is shown in the lower left. Contours are $3\sigma \times \{-2, -1, 1, 2, 3, 4, 5\}$ ($\sigma = 89$ mJy beam$^{-1}$). We note that the averaged $3\sigma$ flux density 267 mJy beam$^{-1}$ in this image corresponds to the averaged flux of $\sim 28$ mJy in each 5$''$1 $\times$ 4$''$2 SMA synthesized beam. The symbols are described in Figure 1. Right: similar to the left panel. However, the original JCMT SCUBA image was shifted toward the south by 4$''$ before being subtracted from the SMA+JCMT image. (A color version of this figure is available in the online journal.)

image with the weighting parameters $\text{robust} = 0, \text{fwhm} = 8, 8$ to enhance the sensitivity to the extended emission.

APPENDIX B

CONSISTENCY CHECK AND NOISE STATISTICS

We smoothed the high angular resolution SMA+JCMT image to the angular resolution of JCMT SCUBA, and then subtracted the JCMT SCUBA image from the smoothed SMA+JCMT image. The residual image after the subtraction is shown in Figure 14. The lower angular resolution SMA+JCMT image, and the previously published SMA HCN 4–3 image (Liu et al. 2012) are presented in Figure 15. On average, the contour intervals in Figure 14 (i.e., 267 mJy beam$^{-1}$) correspond to the 1$\sigma$ (24 mJy beam$^{-1}$) detection level of the higher angular resolution ($\theta_{\text{maj}} \times \theta_{\text{min}} = 5''1 \times 4''2$) SMA+JCMT 0.86 mm continuum image (see below).

Our overall impression from comparing Figures 14 and 15 is that the limited $uv$ sampling rate of our SMA observations cause imaging defects near the bright compact sources. This is most obviously seen around the Sgr A*, the Southwest Lobe, and the bright clump in the Southern Arc (coincide with JCMT-1). However, we found that manually shifting the JCMT image toward the south by 4$''$ can suppress the residual (e.g., Figure 14) around the Sgr A*. In our zero spacing model (see Appendix A), we did not manually correct for this 4$''$ offset for the sake of objectiveness. We do not think this potential JCMT 4$''$ pointing offset can cause very obvious imaging defects since only the $\geq 33''$ scale structures are taken for modeling the zero spacing. However, it can lead to a mismatch between the combined SMA+JCMT image and the JCMT image, which will result in some residual in Figure 14.

Beyond the aforementioned regions, the extended structures appear to be reasonably reconstructed in the SMA+JCMT image, and the residual image has an rms noise level of $\sim 89$ mJy beam$^{-1}$. The Northern/Southern Ridges, Northeast/Southwest Lobes, and the W-2,3,4 Streamers are detected in the lower angular resolution SMA+JCMT image (Figure 15, left). The extended residual features at the edge of Figure 14 are caused by the sidelobe features in the JCMT SCUBA image (e.g., the negative brightness sidelobe at northwest of Figure 13 causes the positive excess in Figure 14). These single-dish sidelobes are extended ($\geq 15''$) and should not confuse the imaging of localized gas structures. However, locally they can bias the absolute brightness in the higher angular resolution SMA+JCMT image (mostly only 2$\sigma$). The $\geq 33''$ scale defects caused by the single-dish primary beam effect discussed in the previous section appear lower than the 1$\sigma$ detection level of the SMA+JCMT image.

The theoretical rms noise level of the SMA+JCMT image is $\sim 14$ mJy beam$^{-1}$. Because of the absence of emission-free areas in our map, it is difficult to directly measure the rms noise level we actually achieved. Since only the $\geq 33''$ structures in the JCMT image, which have high signal to noise ratios, are combined with the SMA data. We assumed the noise in the SMA+JCMT image only has a weak dependence on the noise.
Figure 15. The combined SMA+JCMT 0.86 mm continuum image (color). Left: color image shows the tapered SMA+JCMT 0.86 mm continuum image ($\theta_{\text{maj}} \times \theta_{\text{min}} = 7.4'' \times 6.2''$). The synthesized beam of the SMA+JCMT image is shown in the lower left. Contours show the velocity integrated SMA HCN 4–3 image taken from Liu et al. (2012) ($\theta_{\text{maj}} \times \theta_{\text{min}} = 5.9'' \times 4.4''$). Contours are 75 Jy beam$^{-1}$ km s$^{-1} \times \{1, 2, 4, 8, 16\}$. By comparing with the GBT CS 1–0 spectra, Liu et al. (2012) suggested that this HCN 4–3 image is subjected to the significant missing flux issue around the 50 km s$^{-1}$ cloud, the Molecular Ridge, the 20 km s$^{-1}$, and the Southern Arc.

Right: color image shows the high angular resolution SMA+JCMT 0.86 mm continuum image ($\theta_{\text{maj}} \times \theta_{\text{min}} = 5.1'' \times 4.2''$). Contours show the free–free continuum emission model (see Appendix C), which is smoothed to the same angular resolution with the SMA+JCMT image. Contours are 10 mJy beam$^{-1} \times \{1, 2, 4, 8, 16, 32, 64\}$.

(A color version of this figure is available in the online journal.)

in the JCMT image. We therefore can measure the rms noise level of the high angular resolution SMA+JCMT image by

$$\sqrt{(\text{rms of the residual image})^2 - (\text{rms of the JCMT image})^2} \over (\text{JCMT beam area}) / (\text{SMA+JCMT synthesized beam area}).$$

(B1)

This yields an rms noise level of 24 mJy beam$^{-1}$ (0.011 K) in the high angular resolution SMA+JCMT image, which is $\sim 1.7$ times higher than the theoretical noise level. Generally, the SMA+JCMT image is still dynamic-range limited, especially near the bright compact objects. This effect hampers the systematical search and statistical study of the clumpy structures.

APPENDIX C

FREE–FREE MODEL SUBTRACTION

The emission from the ionized mini-spiral arms can be recognized from the high angular resolution SMA+JCMT image (Figure 15). We retrieved the archival VLA Q-band observations taken on 2003 February 14, March 17, April 16, and 2004 March 14, April 21, May 16 to generate a model of 0.86 mm free–free emission. These VLA observations were taken with dual 50 MHz IFs centered at 43.314 GHz and 43.364 GHz, with full polarization. The sampling range of these VLA data is 3.7–490 $k\lambda$. However, we assume that only the localized bright components will significantly contribute to the 0.86 mm free–free continuum emission. The basic calibrations and self-calibrations were performed using the AIPS software package of NRAO. We scaled the VLA image such that the central point source Sgr A$^*$ has a flux of 1 Jy (Bower & Backer 1998; Yusef-Zadeh et al. 2011), and then smoothed the VLA image to the angular resolution of the SMA+JCMT image. The smoothed and rescaled VLA image, as the zeroth order model of the 0.86 mm free–free continuum emission, is presented in the right panel of Figure 15. The brightness of the 3 mm and the 1.3 mm emission is comparable, which can be checked in Kunneriath et al. (2012). We then subtracted the free–free emission model from the SMA+JCMT image (Figure 1). As can be seen from Figures 15 and 1, this free–free model subtraction can only manifestly change the geometry in the Northern and the Eastern ionized mini-spiral arm regions and around Sgr A$^*$ (see Zhao et al. 2009 and references therein for the ionized mini-spiral arm). We note that the scaling of the VLA image in this process cannot take into consideration the spatial variation of the spectral index (Kunneriath et al. 2012). We have checked that if we scaled the VLA image to be $\geq$20% brighter, this free–free model subtraction will induce noticeable over-subtracted features in the Northern and the Eastern ionized mini-spiral arms. Except for the location of Sgr A$^*$, in the central 1$'$ area, the free–free model subtracted SMA+JCMT image provides a lower limit for the 0.86 mm dust thermal emission.
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