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THE PROCESSING OF CLUMPY MOLECULAR GAS AND STAR FORMATION IN THE GALACTIC CENTER

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ABSTRACT

The Galactic center uniquely provides opportunities to resolve how star clusters form in neutral gas overdensities engulfed in a large-scale accretion flow. We have performed sensitive Green Bank 100m Telescope (GBT), Karl G. Jansky Very Large Array (JVLA), and Submillimeter Array (SMA) mapping observations of molecular gas and thermal dust emission surrounding the Galaxy's supermassive black hole (SMBH) Sgr A*. We resolved several molecular gas streams orbiting the center on $\gtrsim$10 pc scales. Some of these gas streams appear connected to the well-known 2–4 pc scale molecular circumnuclear disk (CND). The CND may be the tidally trapped inner part of the large-scale accretion flow, which incorporates inflow via exterior gas filaments/arms, and ultimately feeds gas toward Sgr A*. Our high resolution GBT+JVLA NH_3 images and SMA+JCMT 0.86 mm dust continuum image consistently reveal abundant dense molecular clumps in this region. These gas clumps are characterized by $\gtrsim$100 times higher virial masses than the derived molecular gas masses based on 0.86 mm dust continuum emission. In addition, Class I CH_3OH masers and some H_2O masers are observed to be well associated with the dense clumps. We propose that the resolved gas clumps may be pressurized gas reservoirs for feeding the formation of 1-10 solar-mass stars. These sources may be the most promising candidates for ALMA to probe the process of high-mass star-formation in the Galactic center.

Key words: journals: Galaxy: center Galaxy: kinematics and dynamics Galaxy: structure ISM: clouds

1. INTRODUCTION

Molecular clouds in the ∼200 pc Galactic Central Molecular Zone (CMZ) are known to have high temperatures, strong B-fields, and largely non-virialized gas motions, which make them the most extreme environment for star-formation in our Galaxy. How the young nuclear cluster, and massive star clusters like the Arch and Quintuplet form in this environment remains the most intriguing problem in the field of high-mass star-formation.

This manuscript reviews our recent observations of molecular gas in the central ∼20 pc region of the Galactic Center, namely the Sgr A region. This is the nearest star-forming region to the supermassive black hole Sgr A*, where gas structures are engulfed in a parsec scale high velocity (±50–100 km s^{-1}) accretion flow. Our sensitive single-dish molecular line mapping observations have resolved the nature of the large scale accretion flows in this region in new detail. High resolution interferometric observations of dust thermal emission and molecular lines have further unveiled localized gas overdensities, and allow an analysis of their stability. We briefly summarize our observations in Section 2. The results are presented in Section 3.

2. OBSERVATIONS

We observed the CS 1-0 transition and the NH_3 (1,1) to (6,6) transitions using the NRAO GBT (Liu et al. 2013; Minh et al., 2013). We observed the NH_3 from (1,1) to (7,7) transitions using the JVLA (see Mills et al., 2014 for details). These GBT and JVLA data were combined using the procedure outlined in our previous papers (Liu et al., 2012ab). We additionally made 157-pointing mosaic observations (354.1-358.1 GHz and 342.1-346.1 GHz) toward the Galactic center using the SMA, in its compact and subcompact array configurations, which simultaneously covered the dust continuum emission and the high excitation molecular lines HCN 4-3 and HCO^+ 4-3 (Liu et al., 2012b). The short-spacing continuum data were complemented by further combining them with an archival JCMT SCUBA image. A zeroth order free-free continuum emission model was constructed based on the archival VLA 7 mm observation data, and was subtracted from the combined SMA+JCMT 0.86 mm continuum image.

3. RESULTS

Figures 1, 2, and 3 show the velocity channel maps of CS 1-0, average velocity maps of the >80 km s^{-1} CS 1-0 and the HCN 4-3 emission, and the SMA+JCMT 0.86 mm dust continuum image, respectively. From Figure 1, we see that the well-known 50 km s^{-1} molecular cloud in the northeast, the eastern molecular ridge, and the northern end of the 20 km s^{-1} molecular cloud in the south constitute a projected >10 pc scale molecular arc orbiting Sgr A* (Eastern Arm, hereafter). The 2-4 pc CND is not prominent in this CS 1-0 map owing to its higher excitation conditions, but is clearly apparent in the image of HCN 4-3 (Figure 2) and high excitation NH_3 transitions. We also discovered a new molecular arc (Southern Arc) located in between the CND and the Eastern Arm (Liu et al., 2012b). Our preliminary analysis of the velocity field suggests that the Eastern Arm is following an eccentric orbit between the 50 km s^{-1} and the 20 km s^{-1} molecular clouds which are located in the background and foreground of Sgr A*, respectively (Liu et al., 2012b). The suggested locations of these molecular structures are also consistent with a previous analysis of the formaldehyde absorption line (Guesten & Downes, 1980). We note that the entire 20 km s^{-1} molecular cloud consists of multiple components along the line of sight; other components may be located at greater distances from Sgr A*.

We have proposed that the Eastern Arm and the Southern Arc are gas streams that are gravitationally accelerated toward Sgr A*. The asymmetric and clumpy CND is likely the tidally trapped innermost part of these gas streams. The excess of angular momentum in these gas streams causes some of the concentrated dense gas around the CND to recede from perihelion. These gas structures will be further stretched by the tidal and centrifugal forces, which will lead to the formation of the observed molecular arm-like features to the west of the CND (Western Arms; Figure 2). From Figure 2, we see that the Western Arms follow a south-north velocity gradient, which is consistent with the orientation of the CND rotation. In addition, we resolved the velocity gradients along individual gas arms, and confirmed that the velocities of the inner parts of the Western Arms converge to the rotational velocity of the CND. This overall geometric and kinematic picture resembles the numerical hydrodynamical simulations in Mapelli et al. (2013) and Emsellem et al. (2014). The former also has implications for the origin of the eccentric orbits of the stars surrounding Sgr A*.

Despite the fact that these molecular clouds/streams are subjected to strong ionizing flux and the pressure of the hot ionized gas, they still show high-mass star-forming signatures, including ultracompact HII regions in the west of the 50 km s^{-1} cloud. Our SMA+JCMT 0.86 mm dust continuum image which has an unprecedentedly large field-of-view, for the first time, reveals the abundant 0.1–0.2 pc scale, 10-10^2 $M_\odot$ dense clumps, in the 5′ field including the CND and the exterior gas streams (Figure 3; Liu et al., 2013). These massive gas concentrations are the most probable gas reservoirs for massive star formation in the Galactic center. However, the HCN 4-3 observations indicate that the velocity dispersions of these dense clumps and their parent molecular clouds are ∼10-20 times higher than their virial velocity dispersions (Liu et al. 2013), which is in contrast to the typically virialized gas cores in high-mass star-forming regions outside of the CMZ (e.g. Lu et al., 2014). Instead of these sources being localized gas structures which are solely bound by (self-)gravity, we alternatively hypothesize that these resolved dense clumps embedded in highly turbulent warm/hot gas may be confined by external pressure, and may be considered an extreme case of a pressurized Bonnor-Ebert sphere. , If this is the case, the inner part of these clumps may still form hydrostatic cores and stars. Following the formulae given by McKee & Tan (2002), we estimated that the final stellar mass m_{*f} in these clumps could be in the range of 0.89–13 $M_\odot$. Figure 3 shows that the 22 GHz water masers and 36.2 GHz and 44.1 GHz CH_3OH masers closely follow the distribution of the dense clumps. Some of these masers may be signatures of high-mass star-formation, although they can also be excited in clump-clump collisions. The localized gas structures resolved in our GBT+JVLA NH_3 images are in excellent agreement with those present in Figure 3. Comparing the observed NH_3 (hyperfine) line ratios will provide robust diagnostics for gas excitation conditions in the gas clumps. In the near future, high angular resolution molecular line observations of ALMA can elucidate the detailed structures and kinematics in these dense clumps, which will allow these sources to be probed for star-formation signatures like rotating disks or outflows.

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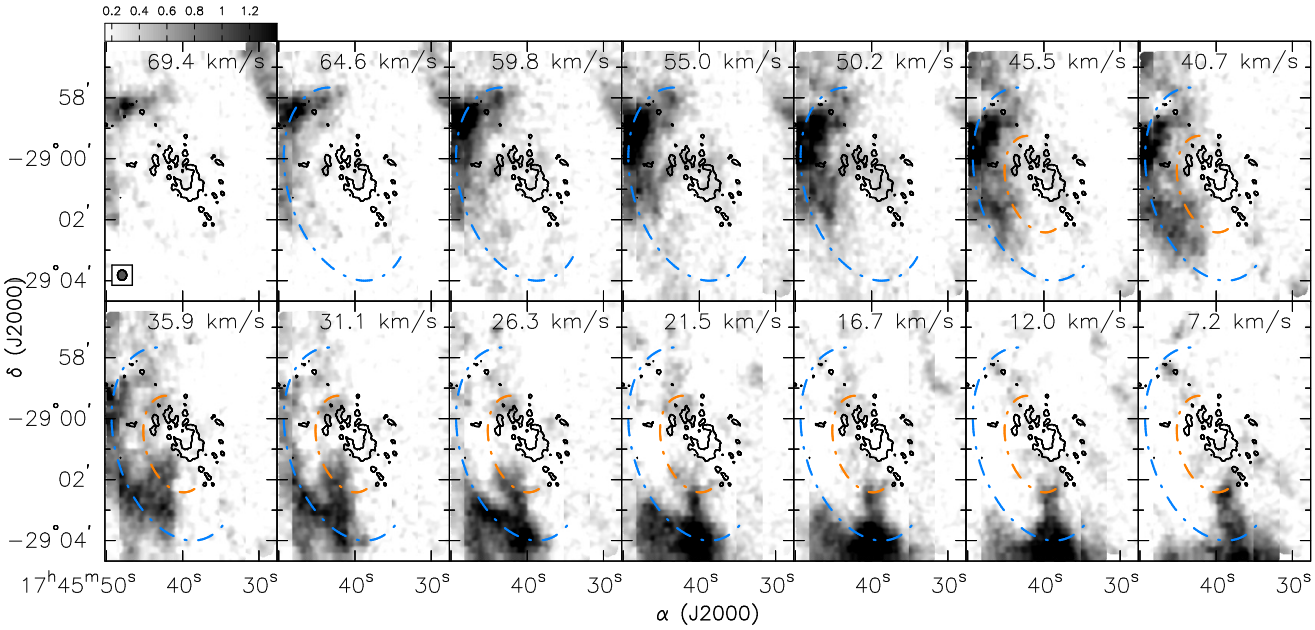

Figure 1. Velocity channel maps of the CS 1-0 line (gray scale; smoothed to $\theta_{maj} \times \theta_{min}$=20″×18″, regridded to 4.8 km s^{-1} velocity resolution). The color bar is in Kelvins. White contours show the 300 Jy beam^{-1} km s^{-1} level of the velocity integrated HCN 4-3 intensity map ($\theta_{maj} \times \theta_{min}$=5″.9×4″.4; taken by SMA), to indicate the warm CND. The orange dashed-dotted arc is drawn to indicate the Southern Arc. The light blue dashed-dotted arc is drawn to indicate the Eastern Arm consisting of the well-known 50 km s^{-1} molecular cloud, the 20 km s^{-1} cloud, and the molecular ridge located in between.

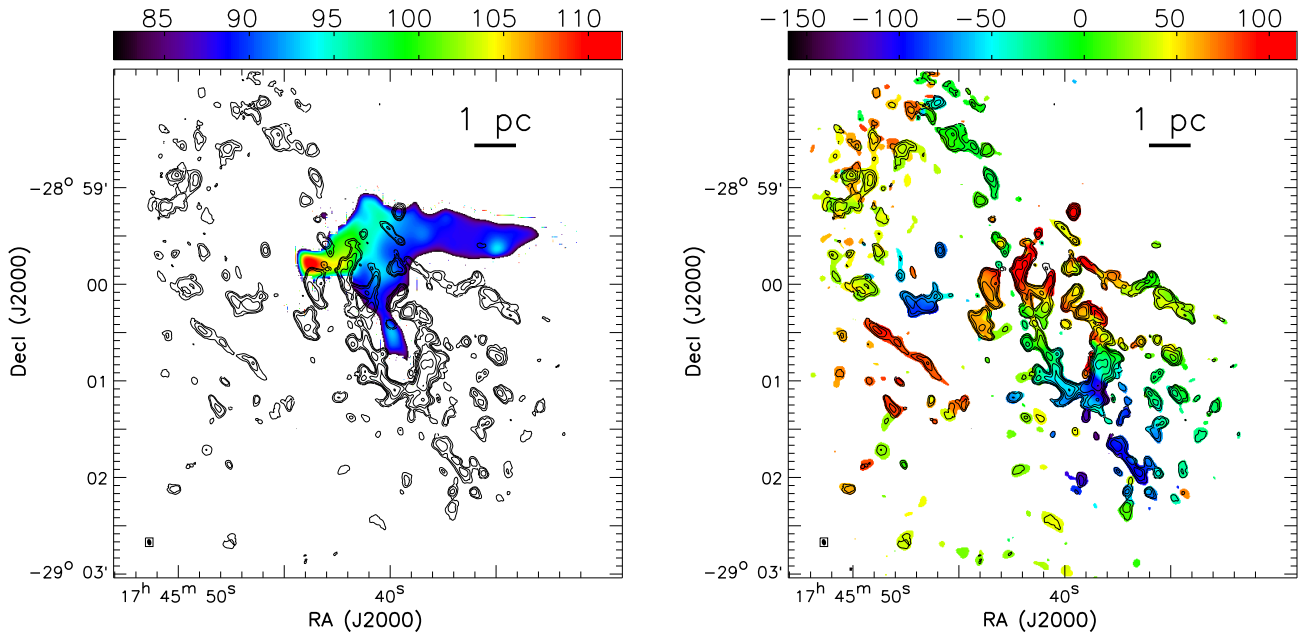

Figure 2. Molecular gas arms surrounding the Galactic CND. Left: The average velocity map of the highly redshifted CS 1-0 line emission (color), which traces the molecular arm stretching from the northwest to the north of the CND. Right: The average velocity map of HCN 4-3 (color), which resolves several molecular arms/streams connected to the CND from the west. Color bars are in km s^{-1} units. Contours in both panels show the velocity integrated intensity map of HCN 4-3. We see that the western molecular gas arms/streams follow the same sense of the velocity gradient as the CND. In addition, the line-of-sight velocities of these gas arms converge to the rotational velocity of the CND.

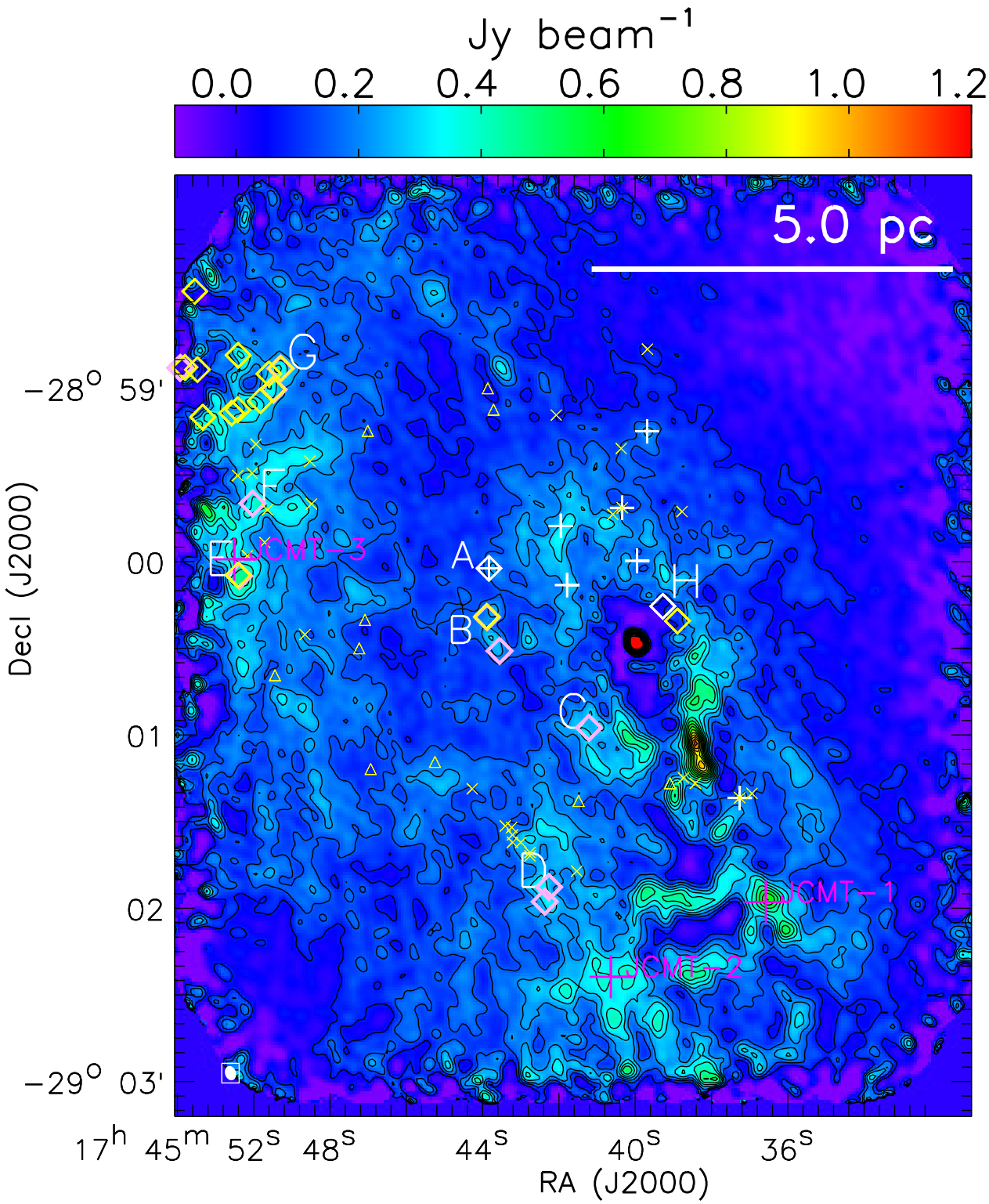

Figure 3. The SMA+JCMT 0.86 mm continuum image with a free-free model subtracted. (color and contour; this figure is reproduced from Liu et al. 2013). Contour spacings are 3σ starting at 3σ (σ=24 mJy beam^{-1}). Yellow crosses are the 1720 MHz OH masers. Yellow triangles are the compact, either thermal or low-gain masing 1612 MHz OH line sources. Pink diamonds are the 36.2 GHz Class I CH_3OH masers. Yellow diamonds are the 44.1 GHz Class I CH_3OH masers taken from EVLA observations. White crosses and diamonds are the 22 GHz water masers and the 44.1 GHz CH_3OH masers taken from GBT observations.

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