The Molecular Gas Environment in the 20 km s\(^{-1}\) Cloud in the Central Molecular Zone

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Abstract

We recently reported a population of protostellar candidates in the 20 km s\(^{-1}\) cloud in the Central Molecular Zone of the Milky Way, traced by H\(_2\)O masers in gravitationally bound dense cores. In this paper, we report molecular line studies with high angular resolution (\(\sim 3''\)) of the environment of star formation in this cloud. Maps of various molecular line transitions as well as the continuum at 1.3 mm are obtained using the Submillimeter Array. Five NH\(_3\) inversion lines and the 1.3 cm continuum are observed with the Karl G. Jansky Very Large Array. The interferometric observations are complemented with single-dish data. We find that the CH\(_3\)OH, SO, and HNCO lines, which are usually shock tracers, are better correlated spatially with the compact dust emission from dense cores among the detected lines. These lines also show enhancement in intensities with respect to SiO intensities toward the compact dust emission, suggesting the presence of slow shocks or hot cores in these regions. We find gas temperatures of \(\gtrsim 100\) K at 0.1 pc scales based on RADEX modeling of the H\(_2\)CO and NH\(_3\) lines. Although no strong correlations between temperatures and linewidths/H\(_2\)O maser luminosities are found, in high-angular-resolution maps we note several candidate shock-heated regions offset from any dense cores, as well as signatures of localized heating by protostars in several dense cores. Our findings suggest that at 0.1 pc scales in this cloud star formation and strong turbulence may together affect the chemistry and temperature of the molecular gas.

Key words: Galaxy: center – ISM: clouds – stars: formation

1. Introduction

The Central Molecular Zone (CMZ) is the inner \(\sim 500\) pc of the Galaxy (Morris & Serabyn 1996) and contains more than \(10^7\) \(M_\odot\) of dense molecular gas (mean density in clouds \(\sim a\) few \(10^4\) cm\(^{-3}\); Ferrière et al. 2007). Within the CMZ are a series of massive molecular clouds with typical projected scales of 10 pc and masses of \(10^5\) \(M_\odot\). These clouds are characterized by large turbulent linewidths (FWHM \(\sim 10-10^2\) km s\(^{-1}\); Shetty et al. 2012; Kruijssen & Longmore 2013). Spectral line studies using single-dish observations have found interesting gas properties related to such strong turbulence. Mappings of shock tracers, such as SiO, revealed that their emission is widespread but non-uniform, suggesting large-scale shocks at \(\geq 1\) pc scales (Martín-Pintado et al. 1997; Riquelme et al. 2010; Jones et al. 2012). Widespread emission of organic molecules has been detected, and these molecules are suggested to be released from grain mantles by shocks (Martín-Pintado et al. 2001; Requena-Torres et al. 2006, 2008). In addition, efforts have been made to map gas temperatures in the CMZ using multiple transitions of NH\(_3\) or H\(_2\)CO, which have revealed ubiquitously high temperatures (50–100 K or higher) at \(\geq 1\) pc scales and suggested that turbulent shocks could be the heating source (Ao et al. 2013; Mills & Morris 2013; Ginsburg et al. 2016; Immer et al. 2016). These studies indicate that strong turbulence plays a vital role in shaping the molecular gas environment in the CMZ clouds at \(\geq 1\) pc scales, although the origin of the turbulence is under debate (e.g., Rodriguez-Fernandez et al. 2006; Kruijssen et al. 2015).

However, an ambiguity exists in single-dish observations that use linewidths to indicate turbulent strength: at angular resolutions of \(\sim 30''\) (1 pc at the distance of the CMZ) and above, linewidths may have contributions from unresolved systematic motions (e.g., rotation, infall) and thus may be questionable to be a good indicator of turbulence (e.g., discussions in Henshaw et al. 2016). Higher angular resolutions of \(3''\) (0.1 pc) would help to resolve systematic motions of dense cores within clouds in order to evaluate the impact of turbulence on gas.

Star formation is one of the key factors in shaping the gas environment in galaxies (Kennicutt & Evans 2012). Active star formation can reveal itself by heating the ambient gas (e.g., hot molecular cores, Araya et al. 2005) as well as changing the chemical composition of gas (e.g., enhancement of SiO emission by outflows, Garay et al. 2000). However, it remains unclear whether star formation has a major impact on the molecular gas in addition to strong turbulence in the CMZ clouds. The overall star formation rate (SFR) in the CMZ measured with infrared luminosities is \(\sim 0.05-0.15\) \(M_\odot\) yr\(^{-1}\) (Barnes et al. 2017), which is significantly lower than expected from the well-established correlation between the amount of dense gas and star formation (Longmore et al. 2013), e.g., the Kennicutt-Schmidt relations (Kennicutt 1998; Kennicutt & Evans 2012). Kruijssen et al. (2014) discussed mechanisms that...
may explain the currently low SFR in the CMZ, including strong turbulence, high virial ratios, acoustic instabilities, and episodic cycling. They present a self-consistent scenario in which star formation in the CMZ may proceed episodically, regulated by turbulence driving and feedback. This idea was quantified by Krumholz & Kriijssen (2015) and Krumholz et al. (2017), who showed that the combination of these mechanisms implies that a wide range of star-forming environments should be present within the CMZ, with widely varying degrees of star formation activity.

Except for a few active star-forming regions such as Sgr B2, most of the clouds in the CMZ have been found to be relatively quiescent in star formation (Guesten & Downes 1993; Lis et al. 1994; Immer et al. 2012; Kauffmann et al. 2016). An example is G0.253+0.016, which shows quite inactive star formation (e.g., a weak H2O maser, Lis et al. 1994; a likely gravitationally bound dense core, Kauffmann et al. 2013; Johnston et al. 2014; Rathborne et al. 2014b; and no evidence of free-free emission from Hα regions, Rodríguez & Zapata 2013; Mills et al. 2015). Observations of spectral lines show that the gas in G0.253+0.016 is dominantly influenced by strong turbulence (Rathborne et al. 2014a, 2015), but little evidence of being affected by star formation has been found. In other CMZ clouds, it remains to be answered to what extent star formation can affect the environment, and observations with angular resolutions of $\lesssim 3^\prime$ (0.1 pc) are required to match the scale of dense cores where star formation takes place ($\lesssim 0.1$ pc; Kauffmann et al. 2008; Lu et al. 2014).

Therefore, to examine the impact of turbulence and star formation on the molecular gas environment in CMZ clouds, interferometric observations that can provide $\sim 3^\prime$ or better angular resolutions are necessary. We also need an optimized sample for our study, e.g., a CMZ cloud with more active star formation than G0.253+0.016.

In our recent work (Lu et al. 2015), we studied star formation in the 20 km s$^{-1}$ cloud, a massive ($\gtrsim 10^5 M_\odot$) molecular cloud in the Sgr A complex (Ferrière 2012). Single-dish observations have found this cloud to be extremely turbulent with a linewidth of $\gtrsim 10$ km s$^{-1}$ at 1 pc scales and a large velocity gradient of 2–5 km s$^{-1}$pc$^{-1}$ along its major axis (Coil & Ho 1999; Tsuboi et al. 2011). Lu et al. (2015) detected 18 H2O masers and associated dense cores in this cloud, thus revealing a population of deeply embedded protostellar candidates. Therefore, with both strong turbulence and relatively active star formation activity, the 20 km s$^{-1}$ cloud is an appropriate sample for understanding the interplay between star formation and the environmental molecular gas.

Here we continue to use high-angular-resolution interferometric observations of molecular lines to study the molecular gas environment in the 20 km s$^{-1}$ cloud. We use a number of molecular lines at 1.3 mm wavelengths including both dense gas tracers (e.g., H2CO) and shock tracers (e.g., SiO), and five NH3 lines at 1.3 cm wavelengths (K band) that are conventional dense gas tracers. Moreover, multiple transitions of H2CO and NH3 can be used as thermometers to reveal the impact of star formation and turbulence on gas temperatures, in which the two lines may trace different gas components in terms of chemistry and/or density, thus complement each other. In Section 2 we outline our interferometric and single-dish observations as well as archival data used in this paper. In Section 3 we present the results, including the 1.3 mm continuum and spectral lines, the 1.3 cm continuum, the NH3 lines, and gas temperatures derived from H2CO and NH3. In Section 4 we focus on two points: the impact of star formation and turbulence on the chemical composition of gas (spatial correlations between dust and spectral line emission, enhancement of emission of shock tracers), and the heating of gas at 0.1 pc scales by star formation and turbulence. We draw our conclusions and summarize our results in Section 5. In this paper we adopt a distance to the Galactic Center of 8.34 kpc (Reid et al. 2014).

2. Observations and Data Reduction

2.1. Submillimeter Array (SMA) Observations

We observed eight positions as a mosaic in the 20 km s$^{-1}$ cloud in 2013 with the Submillimeter Array (SMA)$^{11}$ (Ho et al. 2004) at 1.3 mm wavelengths in the compact and subcompact configurations. Spectral lines between 216.9–220.9 and 228.9–232.9 GHz as well as the continuum were obtained at the same time. Details of the SMA observations and data reduction, using the IDL superset MIR, MIRIAD (Sault et al. 1995), and CASA (McMullin et al. 2007), have been reported in Lu et al. (2015). In the end, we obtained image cubes of molecular lines, with typical clean beams of $5.00 \times 2.08$ at position angles of $5^\circ$, and rms of 0.11–0.14 Jy beam$^{-1}$ per 1.1 km s$^{-1}$ velocity bin. In Section 2.6 we discuss the combination of the SMA and single-dish data.

2.2. Karl G. Jansky Very Large Array (VLA) Observations

We observed three positions as a mosaic in the 20 km s$^{-1}$ cloud in 2013 with the National Radio Astronomy Observatory (NRAO)$^{13}$ Very Large Array (VLA) at K band in the DnC configuration. The H2O maser transition at 22.2 GHz, five NH3 inversion transitions from $(J, K) = (1, 1)$ to $(5, 5)$, two CCS lines and one NH2D line, as well as the continuum using a total bandwidth of 1 GHz were observed. Details of the VLA observations and reduction of the H2O maser and continuum data, using CASA, have been reported in Lu et al. (2015). The CCS and NH2D lines were not detected at a sensitivity of 2.0 mJy per $3^\prime \times 3^\prime$ beam per 1 km s$^{-1}$.

For the NH3 (1, 1) and (2, 2) transitions, the 16 MHz wide subbands were split into 1024 channels, leading to a velocity coverage of 200 km s$^{-1}$ and a channel width of 0.2 km s$^{-1}$, which can cover all the hyperfine splittings of these two transitions. For NH3 (3, 3)–(5, 5), the satellite components of the hyperfine splittings are usually much weaker, therefore the 8 MHz wide subbands, split into 512 channels, were used to cover the main components only, with a velocity coverage of 100 km s$^{-1}$ and a channel width of 0.2 km s$^{-1}$. To increase the signal-to-noise ratios, we regridded the visibility data to a velocity bin of 1 km s$^{-1}$ before CLEANing.

Then we imaged the NH3 data with CASA 4.5.0. From the early versions of the CLEANed images, we noted that the emission of NH3, especially that of NH3 (3, 3), is extended in nature, thus the canonical CLEAN with pixel-by-pixel clean

$^{11}$ The SMA is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica.  
$^{12}$ https://www.cfa.harvard.edu/~cqi/mircook.html  
$^{13}$ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
component-finding algorithm did not recover such emission well. This is evidenced by the extended stripes and strong negative bowls seen in the images. Therefore, we used the multiscale CLEAN in CASA, which implements a multiscale clean component-finding algorithm to improve the imaging of extended structures. We used multiscale parameters of 0, 5, 20, and 80 pixels, corresponding to angular scales of 0", 3", 12", and 48". The stripes and negative bowls are significantly suppressed in the obtained images. The typical rms of the images is 1.8–2.0 mJy beam\(^{-1}\) per 1 km s\(^{-1}\) velocity bin, with beams of 3\(\text{"} 0\times 2\text{"} 1\) at position angles of 10\(\text{"}\).

In Section 2.6 we discuss the combination of the VLA and single-dish NH\(_3\) data. Similarly, we reprocessed the VLA 1.3 cm continuum data that also present extended structures with multiscale CLEAN.

2.3. Caltech Submillimeter Observatory (CSO)

**Heterodyne Observations**

In April 2014, we observed a 2.5 \times 4.0 area in the 20 km s\(^{-1}\) cloud in the on-the-fly position-switching mode with the Caltech Submillimeter Observatory (CSO). The heterodyne receiver was tuned to cover the same frequency range as the SMA observations in the double-sideband mode. The wideband Fast Fourier Transform Spectrometer (FFTS2) and the Fast Fourier Transform Spectrometer (FFTS1) backends were connected to the receiver in parallel. The FFTS2 was used to cover 228.9–232.9 GHz, which in the double-sideband mode also sampled 216.9–220.9 GHz. The channel width is ~0.27 MHz, corresponding to ~0.35 km s\(^{-1}\) at 230 GHz. The FFTS1 was used to cover 231.9–232.9 GHz as well as 216.9–217.9 GHz in the double-sideband mode, in order to observe the SiO 5–4 line at ~217.1 GHz with a finer channel width of ~0.12 MHz than the FFTS2, corresponding to ~0.16 km s\(^{-1}\) at 230 GHz. However, the FFTS2 data are adequate for our purpose hence the FFTS1 data are not used in this paper. The on-the-fly mapping was done in two orthogonal directions, between which we shifted the IF frequency by 50 MHz to separate spectral lines from the two sidebands. The optical depth at 225 GHz relative to zenith during the observation was 0.07–0.10, corresponding to precipitable water vapor of 1.3–2.0 mm. The system temperature of FFTS2 was 250–300 K during the observation. We derived a beam efficiency of 0.66 by observing Mars.

There is an atmospheric feature, probably a H\(_2\)O absorption line, at ~231.3 GHz, corresponding to ~218.6 GHz in the lower-sideband with the double-sideband mode. The full width at zero intensity of the feature is 0.3–0.4 GHz, depending on the choice of the continuum baseline. Therefore, two H\(_2\)CO lines (3_2\(\rightarrow\)2_1 and 3_2\(\rightarrow\)2_0), the CH\(_3\)OH 4_2\(\rightarrow\)3_1,0 line, and possibly the HC\(_3\)N 24–23 line (cf. Figure 2) were affected. All other lines detected by the CSO were free of atmospheric contamination or double-sideband confusion. We processed the data with the CLASS package\(^{14}\) and obtained the final images after a baseline subtraction and a correction for the beam efficiency.

2.4. Archival Atacama Pathfinder EXperiment (APEX) Heterodyne and Bolocam Galactic Plane Survey (BGPS) Data

We used spectral line data from the Atacama Pathfinder EXperiment (APEX) at 218–219 GHz that cover the three H\(_2\)CO lines as well as the HC\(_3\)N and CH\(_3\)OH lines, which were released by Ginsburg et al. (2016). These data readily complement our CSO heterodyne data that missed this frequency range because of the atmospheric contamination.

The 1.1 mm continuum data were obtained from the Bolocam Galactic Plance Survey (BGPS) v2.1 (Ginsburg et al. 2013). The intensities were multiplied by a factor of 0.5 to convert them into those at 1.33 mm (equivalent to the IF frequency of the SMA observations, 225 GHz) for the use of data combination, assuming a dust emissivity index of 2 (D. Walker et al. 2017, in preparation).

2.5. Green Bank Telescope (GBT) NH\(_3\) Data

We used the NH\(_3\) inversion lines from (J, K) = (1, 1) to (5, 5) from the NRAO Green Bank Telescope (GBT) observations (PI: H. B. Liu). The observations were made on 2011 November 7. The (J, K) = (3, 3) to (5, 5) data have been published in Minh et al. (2013) and details of the observations can be found therein. The GBT observations fully cover the VLA mosaic field and can hence be combined with the latter to recover diffuse NH\(_3\) emission.

2.6. Combination of the Interferometer and Single-dish Data

In order to recover the missing fluxes in the interferometric observations, we combined the SMA and VLA data with single-dish data from CSO, APEX, or GBT, using the feather task in CASA.

First, we combined the SMA 1.3 mm continuum data and the BGPS data. We weighted the BGPS image with the primary beams of the SMA to suppress the signal outside of the SMA primary beams. Then we used the feather task to combine the two data sets, with a lowpass filtering at a spatial scale of 10 m (corresponding to an angular scale of 36\(\text{"}\) at the wavelength of 1.33 mm) for the BGPS data to filter out the high spatial frequency data.\(^{15}\) At last we compared the fluxes of the combined image and the BGPS image to check the consistency. The difference between total fluxes within the FWHM of the SMA primary beams (see the dotted loop in Figure 1) for the combined image and the BGPS image (weighted by the SMA primary beams) is 1.6\%\(^{\text{a}}\), which we considered to be acceptable.

The results are presented in Section 3.1.

Similarly, we combined the SMA and single-dish spectral line data. For several spectral lines around 218.6 GHz, including H\(_2\)CO 3_2\(\rightarrow\)2_1 and 3_2\(\rightarrow\)2_0, CH\(_3\)OH 4_2\(\rightarrow\)3_1,0, and HC\(_3\)N 24–23, the CSO data were affected by an atmospheric feature, therefore we used the APEX data, which are free from contamination. The H\(_2\)CO 3_2\(\rightarrow\)2_0 line in the CSO data was not affected by the atmospheric feature. However, later in Section 3.5 we use line ratios of H\(_2\)CO to derive gas temperatures. To avoid any offset between H\(_2\)CO images, we

\(^{14}\) http://www.iram.fr/IRAMFR/GILDAS

\(^{15}\) In principle, we should use a lowpass filtering at 12 m (31\(\text{"}\) at the wavelength of 1.33 mm), which provides the same spatial frequency as the original BGPS data with a 10 m dish at the wavelength of 1.1 mm. However, due to the limitation of the feather task, we are unable to set such a large parameter. Using 10 m is more aggressive for filtering high spatial frequency data. We have confirmed that varying the lowpass filtering parameters does not affect the resulting image (variation in total fluxes <1%, variation in intensities <1/3 of the rms).
also made combined images with the APEX data for H₂CO 3_0,3–2_0,2. For the other lines we used the CSO data. We first weighted the single-dish images with the primary beams of the SMA, then combined them with the SMA images using the feather task with a lowpass filtering of spatial scales at 10 m (36″ at the wavelength of 1.33 mm) for the CSO data or 12 m (31″ at the wavelength of 1.33 mm) for the APEX data. The VLA and GBT NH₃ data were combined following the same procedures. The feather task was run with a lowpass filtering of spatial scales at 100 m (360″ at the wavelength of 1.3 cm) for the GBT data.

All the combined images processed above have been convolved with primary beams of the interferometers. We also applied primary-beam corrections to them to obtain correct fluxes. In the following sections, we identify structures using the combined images and measured fluxes using the primary-beam-corrected images.

3. Results

3.1. SMA+BGPS Dust Emission

Lu et al. (2015) reported the discovery of 17 dense cores traced by the SMA 1.3 mm continuum emission. Here we use the combined SMA and BGPS continuum data to trace the diffuse dust emission in the cloud. Later in Section 4.1 we use the SMA-only data and the combined SMA+BGPS data to represent compact and diffuse dust emission, respectively.

The BGPS map, the continuum image made with the SMA data, and the image made with the combined SMA+BGPS data are shown in Figure 1. The total 1.3 mm continuum flux, within the FWHM of the SMA primary beams, estimated from the primary-beam-corrected SMA+BGPS image, is 19.2 Jy. The 1.3 cm continuum flux in the same area observed by the VLA is ~0.4 Jy (Lu et al. 2015). There is no evidence of any optically thick free-free emission in the area at the considered frequencies. When we assume a completely flat spectral index from 1.3 cm to shorter wavelengths, the flux of 0.4 Jy does not make significant difference to the total flux at 1.3 mm. Therefore we conclude that the 1.3 mm continuum is dominated by dust emission.

The dust emission maps in Figure 1 demonstrate that the SMA observations are able to resolve dense cores at 0.1 pc scales. Therefore, in the following we use them as well as VLA observations that have an even higher angular resolution to study the gas environment of star formation in the 20 km s⁻¹ cloud.

3.2. SMA+CSO/APEX 1.3 mm Spectral Lines

The SMA, CSO, and APEX observations detected a number of molecular lines in the 20 km s⁻¹ cloud. In Figure 2, spectra of the full SMA 8 GHz band are presented for the most massive dense cores in each of the five clumps. The detected spectral lines in general can be classified into several groups based on...
their excitation conditions (e.g., critical densities\textsuperscript{16}: \(^{12}\)CO and \(^{13}\)CO 2–1 lines have low critical densities \((10^2–10^3 \text{ cm}^{-3})\) and become optically thick quickly, therefore are usually diffuse gas tracers; \(^{12}\)CO, HC\(_3\)N, HNCO, CH\(_3\)OH, CH\(_3\)CN, and \(^{13}\)CS transitions have high critical densities \((10^5–10^6 \text{ cm}^{-3})\) and are usually dense gas tracers; SiO, HNCO, SO, and CH\(_3\)OH molecules are usually released to the gas phase from dust by shocks, hence their lines are usually shock tracers, although they may not uniquely trace shocks in the CMZ.

The integrated intensities over velocities, represented by the zeroth-moment maps, of all the lines detected in the SMA observations are shown in Figure 3. Except when otherwise noted, we integrated over \(V_{\text{lsr}}\) between –20 and 40 km s\(^{-1}\), and discarded pixels below 5\(\sigma\) in the datacubes when making the moment maps. For the \(^{13}\)CO line that is broad in velocity, we integrated between –40 and 60 km s\(^{-1}\). For the \(^{12}\)CO 3\(_2\),2–2\(_2,1\) and CH\(_3\)OH 4\(_2,2\),3–3\(_1,2\) lines that are blended with each other along several lines of sight, we integrated them between –20 and 28 km s\(^{-1}\), and between –15 and 40 km s\(^{-1}\), respectively, to avoid blending. In the following we discuss these lines by groups.

3.2.1. Diffuse Gas Tracers

\(^{12}\)CO and \(^{13}\)CO 2–1 in 20 km s\(^{-1}\) cloud spread diffusely in both emission and absorption. They are both extended beyond the mapped area according to single-dish observations (e.g., Oka et al.\textsuperscript{1998, 2012}), hence image fidelity may suffer from strong side-lobes from emission outside of the region, even after combining with single-dish data. We attempted to search for signatures of bipolar outflows traced by \(^{12}\)CO or \(^{13}\)CO emission, but were unable to confirm any due to the complex kinematics. Therefore, we only show an integrated intensity map of \(^{13}\)CO 2–1 in Figure 3 and proceed to discuss the other lines.

C\(_{18}\)O 2–1 does not show absorption features and its emission is less extended, as shown in Figure 3. We discuss its correlation with dust emission in Section 4.1.

3.2.2. Dense Gas Tracers

For the \(^{13}\)CS line, the CSO data are contaminated by the atmospheric line, while the APEX data do not cover this frequency, so we only use the SMA data. For the other dense gas tracers, including \(^{12}\)CO, HC\(_3\)N, and CH\(_3\)CN, we use the

\textsuperscript{16} The critical density, assumed to be optically thin and without a background, is the density for which the net radiative decay rate from the upper level to the lower level equals the rate of collisional depopulation out of the upper level for a multilevel system (Shirley 2015). A temperature of 100 K is assumed when calculating critical densities in this section.
combined SMA and CSO/APEX data. As shown in the integrated intensity maps (not corrected for primary-beam responses in order to have a uniform rms) of the lines detected in the SMA+CSO/APEX observations (except for $^{13}$CS, which includes only the SMA observation), in units of $Jy \, beam^{-1} \, km \, s^{-1}$. In all panels, contours show the SMA+BGPS combined 1.3 mm continuum emission with identical levels as in the right panel of Figure 1. Dashed loops show the FWHM of the SMA primary beams. The synthesized beam of the SMA is shown in the lower left corner of each panel. In the SiO map, four candidates of shock-heated regions are marked by boxes, which are also marked in Figures 6 and 7 and discussed in Section 4.3.2.

3.3. Embedded Ionizing Source in a Dense Core

As reported in Lu et al. (2015), the VLA 1.3 cm continuum observations confirm the existence of an H II region in the C4 clump (e.g., SgrA-G in Ho et al. 1985), with a peak intensity of 17.5 mJy/beam ($\sim 175\sigma$ levels). In addition, as shown in Figure 4, there is weak compact 1.3 cm continuum emission on filamentary structures that have been seen in e.g., G0.253 +0.016 as signatures of pc-scale shocks (Johnston et al. 2014). We discuss the enhancement of these tracers in Section 4.2.

3.2.3. Shock Tracers

The maps of SiO, HNCO, SO, and CH$_3$OH in Figure 3 show the combined SMA and CSO/APEX data. All species present

Figure 3. First panel: three-color image at 3.6, 5.8, and 8.0 $\mu$m from the Spitzer Space Telescope/IRAC (Stolovy et al. 2006). All the other panels show the integrated intensity maps (not corrected for primary-beam responses in order to have a uniform rms) of the lines detected in the SMA+CSO/APEX observations (except for $^{13}$CS, which includes only the SMA observation), in units of $Jy \, beam^{-1} \, km \, s^{-1}$. In all panels, contours show the SMA+BGPS combined 1.3 mm continuum emission with identical levels as in the right panel of Figure 1. Dashed loops show the FWHM of the SMA primary beams. The synthesized beam of the SMA is shown in the lower left corner of each panel. In the SiO map, four candidates of shock-heated regions are marked by boxes, which are also marked in Figures 6 and 7 and discussed in Section 4.3.2.

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The SMA H2O masers are reported in Lu et al. maser W11, which is spatially coincident with the compact 1.3 cm emission as of NH3 represented by the zeroth moment are shown in. Levels are in steps of 2σ between 6σ and 10σ, steps of 10σ between 10σ and 100σ, and finally 150σ, in which 1σ = 100 μJy beam−1. The synthesized beam of the VLA observation is shown in the lower left corner. The SMA-BGPS 1.3 mm continuum emission is shown in the background, while H2O masers detected by the VLA are marked by crosses. The maser W18 is consistent with a known AGB star and is marked by a red cross. The H2O maser W11, which is spatially coincident with the compact 1.3 cm emission as well as the C4–P1 dense core, is highlighted with cyan. Properties of the other H2O masers are reported in Lu et al. (2015).

The western side of the H II region at ~8σ levels. The image is not dynamic-range limited (Perley 1999), and the weak emission is unlikely to be due to side-lobes after a comparison with the dirty beam. This compact emission is spatially coincident with the C4–P1 dense core as well as the H2O maser W11 (shown in Figure 4). It thus likely represents free-free emission from an embedded ultra-compact H II (UCH II) or hyper-compact H II (HCH II) region, which can be confirmed by follow-up radio recombination line observations. No other 1.3 cm continuum emission that can be associated with any dense cores is found in the cloud (see Figure 1 of Lu et al. 2015, for a complete 1.3 cm continuum map).

We fitted a 2D Gaussian to it and obtained a flux density of 1.5 mJy. The ionizing photon rate, assuming optically thin continuum emission and an electron temperature of 10^4 K, is 1.1 × 10^{46} s^{-1} (Mezger et al. 1974), which can be produced by an early B-type star (no earlier than B0.5; Panagia 1973; Vacca et al. 1996). This is consistent with our estimate using H2O maser luminosities in Lu et al. (2015), in which W11 was suggested to trace an early B-type protostar. In Section 4.3 we discuss signatures of internal heating associated with this protostar.

3.5. Kinetic Temperatures of Gas

We used the H2CO transitions covered in the SMA+APEX observations and the NH3 transitions covered in the VLA +GBT observations to estimate gas temperatures (Ho & Townes 1983; Walmsley & Ungerechts 1983; Mangum & Wootten 1993). Both transitions can be classified as para or ortho species due to orientations of spins of the multiple H nuclei, and usually we only need to consider transitions between the same species.

First, we considered the H2CO transitions. The three H2CO transitions falling in the SMA+APEX band, 3_0−2_0, 3_2−2_1, and 3_1−2_0, are all para species. The difference between upper level energies of the first transition and the latter two is ~47 K.

We have smoothed the H2CO datacubes with a Gaussian kernel of 2″ FWHM to increase the signal-to-noise ratios, resulting in a larger beam size of 5″5 × 3″4. We used the following analysis of temperatures on the smoothed H2CO data. In Figure 6(a) we show the peak intensity ratios between the 3_1−2_0 and 3_0−2_1 transitions for the whole cloud. Pixels where H2CO 3_1−2_0 or 3_0−2_1 signals are below 5σ levels were masked. Since the 3_1−2_0 transition has a higher upper level energy, higher ratios between the two transitions qualitatively represent higher gas temperatures.

We employed the RADEX code (van der Tak et al. 2007) with a modified solver myRadex17 to implement the non-local thermodynamic equilibrium (non-LTE) conditions. The collision rates between H2CO and ortho/para-H2 were taken from LAMDA (Wiesenfeld & Faure 2013). The ortho/para ratios of H2 were calculated based on kinetic temperatures. We assumed a uniform spherical geometry and fixed the velocity gradient to a representative value of 5 km s^{-1} pc^{-1}, then generated H2CO intensities expected from models when kinetic temperatures range between

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17 https://github.com/fjdu/myRadex
and $10^3$ K in logarithmic steps of 0.1, H$_2$ number densities between $10^2$ and $10^3$ cm$^{-3}$ in logarithmic steps of 0.1, and column densities between $10^{23.3}$ and $10^{23.8}$ cm$^{-2}$ in logarithmic steps of 0.1. The abundance of H$_2$CO to H$_2$ is assumed to be $10^{-17}$ (Ao et al. 2013), hence the H$_2$CO column densities we used in the models are between $10^{14.3}$ and $10^{14.8}$ cm$^{-2}$. We have assumed a single velocity component and a beam filling factor of 1 throughout the analysis.

We used a customized routine (Zhang et al. 2014) to determine the most likely gas temperatures and H$_2$ densities that can reproduce the observed H$_2$CO $3_{0,3}$--$2_{0,2}$ intensities as well as the observed H$_2$CO $3_{2,2}$--$2_{1,1}$ to $3_{0,3}$--$2_{0,2}$ line ratios. An example is shown in the Appendix, while details of this procedure can be found in Zhang et al. (2014).

One feature we noted is that the H$_2$CO $3_{2,2}$--$2_{1,1}$ to $3_{0,3}$--$2_{0,2}$ line ratios, $R(3_{2,2}$--$2_{1,1}$/$3_{0,3}$--$2_{0,2}$), are sensitive to kinetic temperatures, but not to H$_2$ densities or column densities. In light of this, in the Appendix we fitted the line ratios versus the kinetic temperatures and derived an analytical expression:

$$T_{\text{kin}} = 17.5 \exp(4.27 R(3_{2,2}$--$2_{1,1}$/$3_{0,3}$--$2_{0,2})) \text{ K}.$$  

(1)

This equation could reproduce the kinetic temperatures from RADEX modeling as accurate as 0.08 dex (20%) between $T_{\text{kin}} = 30$–300 K. The temperatures derived from RADEX modeling have uncertainties of 0.15 dex (40%) themselves, as discussed in the Appendix, which include both systematic errors with assumed density, column density, and abundance, and also random errors with the observed H$_2$CO intensities. The overall uncertainty in the temperatures derived from Equation (1) would be 0.17 dex (~50%). We applied this relation to the line ratio map in Figure 6(a) and derived a kinetic temperature map as shown in Figure 6(b).

Second, we considered the VLA NH$_3$ transitions. Among the five transitions, the NH$_3$ (1, 1), (2, 2), (4, 4), and (5, 5) are all para species and thus can be considered jointly. Unfortunately, the NH$_3$ (1, 1) lines suffer from strong absorption, while the NH$_3$ (5, 5) lines are usually weak, therefore we chose the (2, 2) and (4, 4) lines to estimate temperatures. The difference between their upper level energies is ~137 K.

We smoothed the NH$_3$ datacubes with a Gaussian kernel of 2" FWHM to increase the signal-to-noise ratios, resulting in a beam size of 3"/6 $\times$ 2"/9. We masked pixels where NH$_3$ (2, 2) or (4, 4) signals are below 5$\sigma$ and show the peak intensity ratios between main components of these two transitions for the whole cloud in Figure 7(a). In addition, similar to the above analysis with the H$_2$CO lines, we derived kinetic temperatures under non-LTE conditions with the VLA+GBT NH$_3$ (2, 2) and (4, 4) transitions. The collision rates between NH$_3$ and para-H$_2$ were taken from LAMDA (Danby et al. 1988). The ortho/para ratios of H$_2$ were calculated based on kinetic temperatures. We assumed an NH$_3$ to H$_2$ abundance of $3 \times 10^{-8}$ (Harju et al. 1993) and used identical model grids as for H$_2$CO. An example is shown in the Appendix. We also derived a relation between NH$_3$ (4, 4) to (2, 2) line ratios, $R(44/22)$ and kinetic temperatures:

$$T_{\text{kin}} = 31.2 \exp(2.75 R(44/22)) \text{ K},$$

(2)

which could reproduce temperatures from RADEX modeling as accurate as 0.08 dex ($\leq$20%) between $T_{\text{kin}} = 30$–300 K. We assumed an overall uncertainty of 0.18 dex (~50%) in the temperatures after adding in the uncertainties in the RADEX modeling, as discussed in the Appendix. The kinetic temperatures derived using the observed line ratios with this equation are shown in Figure 7(b). More discussions on the gas temperatures can be found in Section 4.3.

4. Discussion

4.1. Correlation between the Dust and Spectral Line Emission

We study the spatial correlation between dust emission and spectral lines in order to understand the effect of star formation on the molecular gas environment. As demonstrated in Section 3.1, the compact dust emission traces gravitationally bound dense cores at 0.1 pc scales in which we found a population of H$_2$O masers. Therefore, it is a reasonable indicator of star formation in the 20 km s$^{-1}$ cloud. Correlations between the compact dust emission from dense cores and spectral lines will help to reveal underlying connections of such lines to star formation.

Here we attempt to quantitatively characterize which lines are spatially correlated with the compact dust emission based on the 2D cross-correlation analysis.\(^\text{18}\)

We take the SMA-only dust emission image and the SMA+BGPS combined dust emission image (the middle and right panels of Figure 1) to represent the compact emission from the dense cores and the diffuse dust emission, respectively. The

\(^{18}\) Based on the IDL function “correl_images.pro”: https://idlastro.gsfc.nasa.gov/ftp/pro/image/correl_images.pro.
SMA+BGPS dust emission image is used as a control sample. We reset pixels with negative intensities in these two images to 0 to keep only emission.

In addition to the SMA+CSO/APEX data, we take the VLA +GBT NH$_3$ integrated intensities maps and convolve them with the SMA primary beams. We are aware that sensitivities and dynamic ranges of the SMA and VLA observations are different, which may make a direct comparison between the 1.3 mm lines and the NH$_3$ lines problematic. Nevertheless, we include the NH$_3$ lines here for reference.

Then we normalize all the images with respect to their maximum intensities. The images under consideration are, or have been regridded, in the same coordinates, so we only need to calculate their cross-correlation coefficients, without spatially shifting one image relative to the other in order to find the maximum cross-correlation. The 2D cross-correlation coefficients derived in such way are between $-1$ and 1, with $-1$ being anticorrelated, 0 being not correlated at all, and 1 being correlated.

The 2D cross-correlation coefficients between the dust emission images and the spectral line integrated intensity maps are listed in Table 1. First, we consider correlations with the compact dust emission represented by the SMA-only dust image. Of the 18 spectral lines, the 2 CH$_3$OH lines and the SO line have 2D cross-correlation coefficients with the compact dust emission of $>0.50$. The HNCO line also has a coefficient of 0.48. On the other hand, the 3 H$_2$CO lines and the 5 NH$_3$ lines, which are conventional dense gas tracers for Galactic disk clouds, have smaller coefficients of 0.37–0.43 and 0.27–0.41, respectively. Second, we consider correlations with the control sample, the diffuse dust emission represented by the SMA+BGPS dust emission image. Large 2D cross-correlation coefficients of $\sim$0.8 are found for $^{13}$CO, C$^{18}$O, HNCO, 1 H$_2$CO line, 1 CH$_3$OH line, and 3 NH$_3$ lines. As seen in Figures 3 and 5, these lines do present diffuse emission. The CH$_3$CN, $^{13}$CS, HC$_3$N, and CH$_3$OH 8_{1,8}--7_{0,7} lines have the same or smaller 2D cross-correlation coefficients with the diffuse dust emission than with the compact dust emission. This happens when the line emission is concentrated on the compact dust emission.

Based on the 2D cross-correlation analysis, the SO line, the HNCO line, and the two CH$_3$OH lines are best correlated spatially with the compact dust emission from dense cores of all the detected lines. We also examine the correlations with a visual inspection of the maps in Figure 3. Indeed, several emission peaks of these lines are spatially coincident with the dense cores we identified, although emission peaks that are not associated with any dust emission are also found (e.g., in the southwestern part of the cloud). The most notable line is CH$_3$OH 8_{1,8}--7_{0,7}, which presents emission peaks toward all five massive clumps and is concentrated on dust cores. These lines have been observed to be enhanced by shocks (Bachiller & Pérez Gutiérrez 1997; Rodríguez-Fernández et al. 2010), but our result suggests that they also trace the dense cores in the 20 km s$^{-1}$ cloud well. A potential explanation is that they are enhanced by star formation embedded in the dense cores, as discussed in Section 4.2.

The three H$_2$CO and the five NH$_3$ lines appear to be correlated with the compact dust emission in the dense cores, but with smaller 2D cross-correlation coefficients than the four lines above. As shown in Figures 3 and 5, the two species do not present strong emission in the brightest dust peaks in the C4 clump, and NH$_3$ emission is also absent in the C1 clump. At 0.1 pc scales in this cloud, they are not good tracers of dense gas. The reason could be strong shocks in the cloud that destroy molecules.
Overall, the 2D cross-correlation coefficients between the dust and spectral line emission we found are larger than the results of Rathborne et al. (2015), which discussed the dust emission and various spectral lines at 3 mm in G0.253+0.016. We stress that a direct comparison between different observations is inappropriate. Rathborne et al. (2015) argued that the low 2D cross-correlation coefficients are due to the optically thick molecular line emission. The dust emission traced by 3 mm continuum also shows a lack of compact substructures. These factors may lead to the smaller cross-correlation coefficients between the dust and molecular line emission in G0.253+0.016.

4.2. The Enhancement in Emission of Shock Tracers toward Massive Clumps

We use the enhancement of line ratios between shock tracers to reveal the relative shock strength in the cloud. The SMA+CSO/APEX observations detected several shock tracers, including SiO, CH$_3$OH, HNCO, and SO. It has been suggested that relatively fast shocks ($\gtrsim$20 km s$^{-1}$) can destroy dust grains and release silicon (Si) into the gas phase (Guillet et al. 2009), while relatively slow shocks ($\lesssim$20 km s$^{-1}$) can evaporate ice mantles and release molecules such as CH$_3$OH, HNCO, and SO (Garay et al. 2000; Rodríguez-Fernández et al. 2010), which in turn could be destroyed by fast shocks (Garay et al. 2000; Kelly et al. 2017). Therefore, the SiO and CH$_3$OH/HNCO/SO lines can be used as tracers of fast and slow shocks, respectively, and line ratios between them are related to shock strength (e.g., Usero et al. 2006; Kelly et al. 2017). However, it must be noted that ice mantle evaporation in hot molecular cores can also be responsible for

At last, although the CH$_3$CN, HC$_3$N and $^{13}$CS lines have small 2D cross-correlation coefficients, a visual inspection of Figure 3 suggests that their emission is detected preferably on the dense cores. They are fainter than the lines discussed above, hence in our sensitivity-limited observations they present a large fraction of area of non-detection and thus tend to have small 2D cross-correlation coefficients with the dust emission images. In particular, CH$_3$CN is usually detected in hot molecular cores (e.g., Araya et al. 2005) and has hyperfine splittings that are suitable to determine gas temperatures of $>$100 K. Therefore, sensitive spectral line observations that are able to detect faint CH$_3$CN emission will be useful for studying embedded high-mass star formation in these dense cores.

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Table 1: 2D Cross-correlation Coefficients between the Dust and the Molecular Lines

| Transitions | Coefficients with SMA-only Dust | Coefficients with SMA+BGPS Dust |
|-------------|-------------------------------|--------------------------------|
| $^{13}$CO 2–1 | 0.36                          | 0.78                          |
| C$^{18}$O 2–1 | 0.40                          | 0.80                          |
| H$_2$CO 3$_{0,3}$–2$_{0,2}$ | 0.37                          | 0.78                          |
| H$_2$CO 3$_{2,2}$–2$_{1,1}$ | 0.41                          | 0.58                          |
| H$_2$CO 3$_{1,1}$–2$_{0,0}$ | 0.43                          | 0.61                          |
| CH$_3$CN 12–11, $K=0,1$ | 0.43                          | 0.30                          |
| HC$_3$N 24–23 | 0.19                          | 0.19                          |
| $^{13}$CS 5–4 | 0.35                          | 0.23                          |
| HNCO 10$_{0,10}$–9$_{0,9}$ | 0.48                          | 0.79                          |
| SO 6$_{5}$–5$_{4}$ | 0.54                          | 0.74                          |
| CH$_3$OH 4$_{2,2}$–3$_{1,2}$ | 0.56                          | 0.79                          |
| CH$_3$OH 8$_{1,1}$–7$_{0,7}$ | 0.60                          | 0.60                          |
| SiO 5–4 | 0.40                          | 0.64                          |
| NH$_3$ (1, 1) | 0.41                          | 0.81                          |
| NH$_3$ (2, 2) | 0.39                          | 0.78                          |
| NH$_3$ (3, 3) | 0.40                          | 0.80                          |
| NH$_3$ (4, 4) | 0.32                          | 0.69                          |
| NH$_3$ (5, 5) | 0.27                          | 0.58                          |

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Widespread detection of SiO throughout the CMZ (Jones et al. 2012) raises questions about this interpretation. Similarly, Jiménez-Serra et al. (2010) detected diffuse SiO emission in a region with only low-velocity shocks.
the enhancement of CH$_3$OH, HNCO, or SO emission (Garrod 
& Herbst 2006).

In Figure 8 we present the ratios of integrated intensities 
between CH$_3$OH/HNCO/SO and SiO. To suppress the low 
signal-to-noise emission, we have excluded pixels with 
integrated intensities < 3.6 Jy beam$^{-1}$ km s$^{-1}$ ($\sim 5\sigma$) for all 
the lines when making the ratios.

The line ratios between CH$_3$OH/HNCO/SO and SiO show 
clear enhancement toward the compact dust emission, as shown 
in Figure 8. Based on the spatial distribution of the shock 
tracers, we speculate that fast shocks of $\gtrsim 20$ km s$^{-1}$ traced by 
the widespread SiO emission are processing gas in the entire 
cloud. Meanwhile, the increased line ratios of the slow-shock 
tracers toward the compact dust emission suggest two possible 
scenarios. First, slow shocks of $\lesssim 20$ km s$^{-1}$ in these regions 
can release these molecules. The origin of slow shocks is to be 
determined. Second, hot molecular cores may evaporate these 
molecules from dust. In particular, the C1 and C4 clumps are 
associated with luminous H$_2$O masers, and C4 is also 
associated with an UCHII region, hence they likely harbor 
high-mass protostars. In this scenario, the enhanced CH$_3$OH, 
HNCO, and SO emission in these clumps is due to star 
formation. Future sensitive spectral line observations with e.g., 
the Atacama Large Millimeter/submillimeter Array (ALMA) 
of CH$_3$CN lines in these regions will help to determine the 
existence of hot molecular cores and hence to verify the two 
scenarios.

4.3. Gas Temperatures at 0.1 pc Scales

As shown in Section 3.5, the gas temperatures derived from 
H$_2$CO and NH$_3$ lines are higher than the dust temperatures in the 
20 km s$^{-1}$ cloud that are at $\sim$18–30 K (Molinari et al. 2011). 
This discrepancy between gas and dust temperatures has been 
observed in the CMZ at $\gtrsim$1 pc spatial scales (e.g., Ao et al. 2013; 
Mills & Morris 2013; Ott et al. 2014; Ginsburg et al. 2016; Immer 
et al. 2016; Krieger et al. 2016). Our observations confirm that in the 
20 km s$^{-1}$ cloud high gas temperatures of $\gtrsim 200$ K continue 
down to 0.1 pc scales. However, no observations of dust 
temperatures in this cloud at 0.1 pc scales have been made, 
making a direct comparison between gas and dust temperatures 
unfeasible.

4.3.1. Gas Temperatures Derived from Different Tracers

We compare gas temperatures derived from the H$_2$CO and 
NH$_3$ lines. We first regrid the NH$_3$ (2, 2) and (4, 4) datacubes to 
the H$_2$CO maps that have larger pixel size, then derive 
temperatures based on NH$_3$ line ratios following the procedures 
in Section 3.5. The offset between the resulting temperature 
map and the original NH$_3$ temperature map in Figure 7 is $\lesssim 5$ K 
for most of the pixels, but increases to 30 K on boundaries of 
emission where signal-to-noise ratios are lower. Pixels with 
large temperature offsets are a small fraction of the map, and 
the offset is comparable to the uncertainty of the temperatures, 
therefore we consider the regridded temperature map to be 
acceptable.

The regridded NH$_3$ temperature map is compared with the 
temperature map derived from H$_2$CO lines (Figure 6(b)). As shown in 
Figure 9(a), for pixels where both H$_2$CO and NH$_3$ 
temperatures are available, temperatures derived from the two 
tracers are poorly correlated. This poor correlation is likely due to 
the large uncertainties in both temperatures.

One feature in Figure 9(a) is a slight overpopulation in 
higher temperatures with NH$_3$ than with H$_2$CO. This can be 
also seen in the temperature ratio map in Figure 9(b). In the 
northeastern side of the cloud, temperatures with NH$_3$ are 
$\sim$200 K, while temperatures with H$_2$CO are $\lesssim 100$ K, resulting 
in ratios of $\gtrsim 2$. Similarly high ratios are found in the 
southwestern side of the cloud, where temperatures with NH$_3$ are 
$\gtrsim 200$ K and those with H$_2$CO are $\sim 150$ K. Such 
high temperature ratios are unlikely to be due to the 50% 
uncertainties in temperatures. Given that the H$_2$CO lines have 
higher critical densities than the NH$_3$ lines ($\sim 10^5$ cm$^{-3}$ versus...
The two molecules may trace two gas components in these regions with high-temperature ratios: a less dense and warmer component traced by NH$_3$ lines, and a denser and colder component traced by H$_2$CO lines.

On the other hand, temperature ratios of $<1$ are also found. One example is the dense core C4–P1, whose temperature derived from H$_2$CO lines is higher than from NH$_3$ lines ($\sim120$ K versus $\sim70$ K, Appendix; also see position 11 in Table 2) despite large uncertainties. The density derived from H$_2$CO is also higher than from NH$_3$, although the densities highly depend on the assumed column densities and abundances. This may suggest internal heating in C4–P1, if this dense core has a centrally peaked density profile. The heating source could be embedded high-mass protostars, traced by H$_2$O masers and UCH II regions (see Section 3.3). Other candidates of such internally heated dense cores include C1–P1, C2–P1, C4–P4, and C4–P5 (positions 2, 5, 12, and 13, respectively, in Table 2).

In addition, the gas temperatures with H$_2$CO at 0.1 pc scales are systematically higher than those at 1 pc scales. Ao et al. (2013),
et al. 2005) derived temperatures of 50–100 K in the 20 km s\(^{-1}\) cloud with single-dish H\(_2\)CO data. In Figure 6(c), high temperatures of >200 K are found at 0.1 pc scales, especially toward the C1, C2, and C5 clumps. If we smooth our SMA+APEX H\(_2\)CO data to the angular resolution of 30\(''\) to match the single-dish observations, the H\(_2\)CO 3\(2\),\(2\)-2\(1\),\(1\), to 3\(0\),\(3\)-2\(0\),\(2\) line ratios range from 0.27 to 0.45 and the temperatures from RADEX modeling are 50–120 K. Therefore, the discrepancy is likely due to the angular resolution, and our observations suggest that high-temperature spots of >200 K exist at 0.1 pc scales.

4.3.2. Turbulent Heating and Protostellar Heating

We make use of the temperature maps derived from H\(_2\)CO and NH\(_3\) lines to understand the heating mechanisms in the cloud. As discussed in Ao et al. (2013), Ginsburg et al. (2016), and Immer et al. (2016), turbulent heating can reproduce the observed gas temperatures at >1 pc scales in the CMZ. When it comes to 0.1 pc scales, turbulent heating can be still present. As discussed in Ginsburg et al. (2016), the temperature can be well mixed on milliparsec scales on kiloyear timescales for turbulent heating. Indirect evidence of turbulent heating in the northern end of the 20 km s\(^{-1}\) cloud has been suggested with arguments from enhanced NH\(_3\) emission and SiO/C\(^{34}\)S line ratios (Wright et al. 2001; Liu et al. 2013).

In addition, in the 20 km s\(^{-1}\) cloud where we have found signatures of star formation, we need to take protostellar heating into account. Gas temperatures of >100 K have been observed at <0.1 pc spatial scales toward hot molecular cores (Araya et al. 2005). If the luminous H\(_2\)O masers we detected indeed trace high-mass star formation, then it is possible to observe temperatures of >100 K at 0.1 pc scales once the protostars evolve to a phase of hot molecular cores. If such protostars exist, they should warm up the dust and produce significant mid-infrared emission, which is in contrast with the non-detection of point sources other than the known H\(\text{II}\) region at mid-infrared wavelengths in the 20 km s\(^{-1}\) cloud (Yusef-Zadeh et al. 2009).

The reason could be strong extinction: with a characteristic hydrogen column density of 4 \(\times\) 10\(^{22}\) cm\(^{-2}\) in the 20 km s\(^{-1}\) cloud (C. Battersby et al. 2017, in preparation), the extinction at mid-infrared (~5–30 \(\mu\)m) is ~10–20 mag (Draine 2003). High-mass star-forming regions with typical bolometric luminosities of ~10\(^5\) \(L_\odot\) (Sridharan et al. 2002) have an absolute bolometric magnitude of ~7.8, and an apparent magnitude of ~6.8 at the distance of the CMZ. Adding the extinction will decrease their apparent magnitude to 16.8–26.8, hence make them below the detection limit at mid-infrared in Yusef-Zadeh et al. (2009).

We take two approaches to explore the effect of turbulent and protostellar heating. First, we search for correlations between temperatures and linewidths, assuming the latter to be an indicator of turbulent strength (cf. Ginsburg et al. 2016; Immer et al. 2016), and between temperatures and H\(_2\)O maser luminosities, assuming the latter to be correlated with protostellar luminosities (Palla et al. 1993). Second, we attempt to look for direct signatures of turbulent or protostellar heating from our temperature maps. Evidence of strong turbulence is based on SiO emission, while evidence of star formation comes from masers and UCH\(\text{II}\) regions in dense cores.

In the first approach, we select 20 representative positions in Figures 6 and 7 and derive their temperatures from the mean H\(_2\)CO or NH\(_3\) spectra within a 5\(''\) diameter circle (~0.2 pc at the distance of the CMZ). The size of 0.2 pc is chosen because protostellar heating usually affect local gas in a radius of ~0.1 pc (Longmore et al. 2011) beyond which the temperatures drop to <50 K. These positions are located both on dense cores and offset from any dense cores.

The results are listed in Table 2. In Figure 10(a) we plot the temperatures versus the linewidths. The temperatures are derived directly from the observed line ratios using Equations (1) and (2) to simplify the process. The linewidths are measured with the mean H\(_2\)CO 3\(2\),\(2\)-2\(1\),\(1\) or NH\(_3\) (4, 4) spectra by fitting a Gaussian profile, with 1\(\sigma\) errors from the fittings listed in Table 2. For spectra with obvious multiple velocity components, we try to fit two Gaussian profiles simultaneously and take the stronger one.

We derive the Pearson correlation coefficients between the temperatures and the linewidths using inverse squares of the uncertainties in temperatures (50%) as weighting factors. We do not include the uncertainties of linewidths in the weighting factors because they are less significant. The weighted correlation coefficients, with H\(_2\)CO data only, NH\(_3\) data only, and all data together, are 0.32, 0.13, and 0.22, respectively.
They suggest weak to no correlations between the temperatures and the linewidths. This is in contrast to the statistically significant correlation found at 1 pc scales in several other CMZ clouds in Immer et al. (2016).

In Figure 10(b) we plot the temperatures versus the luminosities of the associated H2O masers, if there are any, in Figure 10(b). A H2O maser must be within 3″ projected of the selected position (∼0.1 pc projected distance) to be considered as associated. At last, we find 11 positions with associated H2O masers. The weighted Pearson correlation coefficient with all data together is 0.08. Therefore, no correlation is found between the temperatures and maser luminosities.

The temperature-linewidth and temperature-maser luminosity data suffer from several uncertainties. Although we have excluded most of the systematic motions in the cloud by resolving the dense cores at 0.1 pc scales, the linewidth may still be contaminated by unresolved multiple velocity components and thus may not be a good indicator of turbulence. Likewise, using H2O masers as a star formation tracer has large uncertainties (e.g., the occurrence rate and variability of H2O masers). Therefore, such non-correlations are not straightforward for understanding heating of gas.

In the second approach, we directly search for turbulent or protostellar heated regions in the high-angular-resolution maps from the SMA and VLA observations. This avoids the ambiguities, e.g., using linewidths to trace turbulence, and is therefore more straightforward.

We note four candidates of shock-heated regions that are marked by boxes in Figures 3, 6, and 7. On the one hand, in the SiO map in Figure 3, these regions show SiO emission that usually traces fast shocks, but they are offset from compact dust emission and hence are unlikely to be associated with protostars. On the other hand, as shown in Figures 6 and 7, temperatures in these regions (∼200 K) tend to be higher than their environment. Therefore, these regions are likely heated by shocks.

We also find a candidate of internally heated dense cores, C4–P1, as discussed in Section 4.3.1. Combined with evidence of high-mass star formation in this dense core (Section 3.3), it is likely that this core is internally heated by embedded high-mass protostars. Several dense cores, such as C1–P1, C2–P1, C4–P4, and C4–P5 also show higher temperatures with H2CO than with NH3 and therefore are likely internally heated, although their protostellar nature is to be confirmed. Future sensitive spectral line (e.g., multiple CH3CN) observations with ALMA in these candidates will help to derive their temperature profiles and confirm the embedded heating sources.

With the second approach we thus find evidence of both turbulent and protostellar heating at 0.1 pc scales in the 20 km s−1 cloud. Turbulent heating seems to be widespread in the cloud, while protostellar heating is localized in dense cores around protostars.

5. Conclusions

We have used the SMA 1.3 mm spectral line observations, the VLA NH3 line observations, and complementary single-dish observations to study properties of dense gas in the 20 km s−1 cloud, one of the massive molecular clouds in the CMZ.

The main results are listed below.

1. Various molecular lines are detected with the SMA and VLA observations, most of which are widespread and not always spatially coincident with the dense cores traced by dust emission. Analysis based on 2D cross-correlations between the dust and spectral line emission suggests that the CH3OH, SO, and HNCO lines are best spatially correlated with compact dust emission from dense cores, which may suggest connections between the excitation of these lines and star formation in the dense cores.

2. The line ratios between slow-shock tracers (CH3OH, SO, and HNCO) and the fast-shock tracer SiO show clear enhancement toward the compact dust emission, indicating the presence of slow shocks or hot molecular cores in these regions.

3. Using multiple transitions of H2CO and NH3, we estimate gas kinetic temperatures at ~0.1 pc scales under non-LTE conditions. Temperatures derived from NH3 lines are ≥2 times higher than those from H2CO lines in several regions, which may suggest two gas components, while toward the dense core C4–P1 the temperature from H2CO is higher, which may suggest internal heating. The high angular resolution data reveal high temperatures of >50 K, and at some positions >200 K at 0.1 pc scales, which are smeared to 50–100 K in lower angular resolution observations.

4. Comparisons between kinetic temperatures and line widths, and between kinetic temperatures and maser luminosities suggest no strong correlations. However, direct evidence of shock heating is found based on the temperature maps with high angular resolution, with evidence of shocks from the SiO emission. Several dense cores that are most likely protostellar heated were also discussed.

In summary, our observations reveal two potential impacts of turbulence and star formation on the molecular gas environment at 0.1 pc scales in the 20 km s−1 cloud. First, the two factors may affect the chemical composition of the molecular gas. This is supported by widespread SiO emission in the cloud, which is likely related to fast shocks, as well as spatial correlation and enhancement of CH3OH/HNCO/SO emission toward compact dust emission from dense cores, which is likely related to slow shocks or embedded high-mass star formation. Second, the two factors may heat the molecular gas. Candidate shock-heated regions of 0.1 pc scales and >200 K temperatures are found throughout the cloud, while signatures of localized heating by embedded star formation are found in several likely internally heated dense cores. Such spectral line observations with high angular resolution have been proved to be powerful in understanding gas properties in the complex environment in the CMZ. Future observations using ALMA, which will provide better spectral line sensitivity, will be important for the study of star formation and dense gas in the CMZ clouds.

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Appendix

Estimate of Kinetic Temperatures Using RADEX

After running myRadex with the grids discriried in Section 3.5, we derived the likelihood of the observed H2CO $3_{0,3}–2_{0,2}$ peak brightness temperatures that are reproduced at given gas temperatures, H2 densities, and several typical column densities. The gray shades in Figure 11 show the normalized likelihood for the observed H2CO transitions toward the C4–P1 dense core in the SMA+APEX data at a fixed column density of $10^{23}$ cm$^{-2}$. Details can be found in Zhang et al. (2014). As pointed out by Ao et al. (2013), the line ratios between H2CO $3_{2,2}–2_{1,1}$ and $3_{0,3}–2_{0,2}$ are more sensitive to gas densities, therefore they are poorer thermometers than the line ratios between H2CO $3_{2,1}–2_{2,0}$ and $3_{0,3}–2_{0,2}$. In Figure 11 we plot the latter line ratios from the models as black contours, which indeed are almost independent of gas densities while sensitive to kinetic temperatures.

For the H2CO lines toward the C4–P1 dense core in the SMA+APEX data, the peak brightness temperatures of the H2CO $3_{2,1}–2_{2,0}$ and $3_{0,3}–2_{0,2}$ transitions are 1.13 and 2.51 K, which leads to a ratio of 0.45. Therefore, the intersection between the ratio $= 0.45$ contour (highlighted in red in Figure 11) and the highest likelihood for H2CO brightness temperatures (brightest gray shades in Figure 11) represent the most likely gas temperatures and H2 densities that can simultaneously reproduce the observed H2CO $3_{0,3}–2_{0,2}$ intensities and the observed line ratios. Hence the estimated gas temperature is $\sim 120$ K and the estimated gas density is $\sim 10^{3}$ cm$^{-3}$. The estimated temperature and density depend on the assumed column density and H2CO abundance. For example, varying the abundance from $10^{-9}$ to $2 \times 10^{-9}$ while keeping the other conditions unchanged will bring the estimated temperature to 110 K and the estimated density to $4 \times 10^{3}$ cm$^{-3}$. In addition, the optical depth of the H2CO $3_{0,3}–2_{0,2}$ transition derived at the same time is 0.98, which suggests the H2CO line becomes optically thick and therefore sensitivity to temperatures disappears (Ginsburg et al. 2016). The rms of observed H2CO line intensities also adds an uncertainty of 30%, as shown in Figure 11. Taking all these factors into account, we assume an uncertainty of 0.15 dex (40%) for the kinetic temperatures. Note that the collision rates we used were extrapolated above 300 K (Wiesenfeld & Faure 2013; discussions in Ginsburg et al. 2016), therefore temperatures $>300$ K are not reliable (they are derived when high H2CO line ratios are found due to optically thick emission, which means that they have large uncertainties themselves).

To examine the quality of the modeling, in Figure 12 we plot the H2CO spectrum extracted toward C4–P1 in the SMA+APEX data and the model constructed with the parameters estimated above. The model reproduces the observed H2CO spectrum well. The blueshifted line wings seen in H2CO $3_{0,3}–2_{0,2}$ and $3_{2,2}–2_{1,1}$ transitions could be a different velocity component.

In Section 3.5 we have noted that the H2CO $3_{2,1}–2_{2,0}$ to $3_{0,3}–2_{0,2}$ line ratios are sensitive to kinetic temperatures, but not so to H2 densities or column densities. We limited H2 densities within $10^{4}$–$10^{5}$ cm$^{-3}$, which are the range we obtained in RADEX models, and column densities within $5 \times 10^{22}$–$5 \times 10^{23}$ cm$^{-2}$, which are from Herschel observations. Then we plot the estimated temperatures against the H2CO line ratios in Figure 13. A least-squares fit to the line ratio–log($T_{\text{kin}}$) relation between $T_{\text{kin}} = 30$–300 K led to the relation shown in Figure 13. A similar relation has been derived in Ginsburg et al. (2016) (see their Figure 6). In Section 3.5 we used this relation to directly convert observed H2CO line ratios into kinetic temperatures.

Then we applied the above analyses to the VLA NH3 (2, 2) and (4, 4) spectra. In Figure 14 we plot the modeling result for the NH3 lines toward the C4–P1 dense cores at a fixed column density of $10^{23}$ cm$^{-2}$, but using an NH3 abundance of 1.8 $\times 10^{-7}$ instead of $3 \times 10^{-8}$ in order to fit the hyperfine structures of NH3 (2, 2). The black contours show the ratios between NH3 (4, 4) and (2, 2) peak brightness temperatures from the models and the gray shades show the normalized likelihood of the observed NH3 (2, 2) peak brightness temperature (6.42 K) that is reproduced in the models. The observed NH3 (4, 4)/(2, 2) line ratio in
C4–P1 is 0.34. Therefore the estimated kinetic temperature is \( \sim 70 \) K and the estimated density is \( \sim 3 \times 10^3 \) cm\(^{-3}\). The optical depth of the NH\(_3\) (2, 2) main hyperfine component derived at the same time is 12. For the same reason of extrapolated collision rates (Danby et al. 1988), temperatures above 300 K are not reliable either. Note that if we were to use an NH\(_3\) abundance of \( 3 \times 10^{-8} \) as mentioned in Section 3.5, the estimated temperature would be \( \sim 100 \) K, but the model would not fit the NH\(_3\) (2, 2) satellite components.

In Figure 15 we also compare the NH\(_3\) spectra extracted toward C4–P1 in the VLA+GBT data with the model constructed with the parameters estimated above. The model can reproduce intensities of the observed NH\(_3\) (2, 2) and (4, 4) main hyperfine components as well as the satellite hyperfine components of NH\(_3\) (2, 2). However, because of the large optical depth, the model lines are much broader than observed.

It is possible that multiple optically thick components with small filling factors exist that lead to the high satellite-to-main line ratio in NH\(_3\) (2, 2), but do not produce broad lines because of their smaller intrinsic linewidths.

The strong NH\(_3\) (2, 2) satellite components shown in Figure 15 are not universal in the 20 km s\(^{-1}\) cloud. We only find such spectra toward several massive dense cores, including C4–P1 and C5–P1. For most of the area in the cloud, the NH\(_3\) (2, 2) satellite components are weak, suggesting optically thin emission, and the assumed NH\(_3\) abundance of \( 3 \times 10^{-8} \) can fit the observed spectra well. Therefore, we continued to use the abundance of \( 3 \times 10^{-8} \), but it must be kept in mind that in several dense cores a higher abundance is likely and resulting temperatures can be lower by 30%. Again the rms of observed
NH₃ line intensities bring in an uncertainty of 30%, as shown in Figure 14. Overall, we assume an uncertainty of 0.16 dex (45%) for the kinetic temperatures.

In Figure 16 we plot the estimated kinetic temperatures against the NH₃ line ratios from the models, within the same ranges of H₂ densities and column densities as for the H₂CO and an NH₃ abundance of 3 × 10⁻⁸. Then a least-squares fit between $T_{\text{kin}} = 30–300$ K led to the relation shown in the figure, with which we obtained the kinetic temperature map in Section 3.5.

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Figure 15. Observed VLA+GBT NH₃ (2, 2) and (4, 4) spectra toward C4–P1, shown as the black curve, and the expected spectra from the RADEX modeling, shown as the red curve. Note that the NH₃ (4, 4) spectrum has been horizontally shifted by +150 km s⁻¹. The input parameters of the model spectra are shown in the figure. The horizontal dashed lines represent ±3σ levels.

Figure 16. NH₃ (4, 4)/(2, 2) line ratios and the kinetic temperatures from RADEX models. At each temperature, we took the line ratios from models with H₂ densities between 10⁴ and 10⁵ cm⁻³, and column densities between 5 × 10²² and 5 × 10²³ cm⁻². The solid line is a least-squares fit to the ratio-log($T_{\text{kin}}$) relation between $T_{\text{kin}} = 30–300$ K.
