MOLECULES IN G1.6−0.025—“HOT” CHEMISTRY IN THE ABSENCE OF STAR FORMATION AT THE PERIPHERY OF THE GALACTIC CENTER REGION

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ABSTRACT

We present molecular line mapping of the Giant Molecular Cloud G1.6−0.025, which is located at the high-longitude end of the Central Molecular Zone (CMZ) of our Galaxy. We assess the degree of star formation activity in that region using several tracers, and find very little. We made a large-scale, medium (2′) resolution map in the $J = 2 − 1$ transition of SiO for which we find clumpy emission over a $\sim 0′′3 × 0′′3$ sized region stretching along the Galactic plane. Toward selected positions we also took spectra in the easy-to-excite $J_k = 2_k − 1_k$ quartet of CH$_3$OH and the carbon monosulfide (CS) $2 − 1$ line. Throughout the cloud these CH$_3$OH lines are, remarkably, several times stronger than both the CS and the SiO lines. The large widths of all the observed lines, similar to values generally found in the Galactic center, indicate a high degree of turbulence. Several high LSR velocity clumps that have 50–80 km s$^{-1}$ higher velocities than the bulk of the molecular cloud appear at the same projected position as “normal” velocity material; this may indicate cloud–cloud collisions. Statistical equilibrium modeling of the CH$_3$OH lines observed by us and others yields relatively high densities and moderate temperatures for a representative dual position velocity. We find $8 × 10^5$ cm$^{-3}$/30 K for material in the G1.6−0.025 cloud and a higher temperature (190 K), but a 50% lower density in a high-velocity clump projected on the same location. Several scenarios are discussed in which shock chemistry might enhance the CH$_3$OH and SiO abundances in G1.6−0.025 and elsewhere in the CMZ.

Key words: Galaxy: center – ISM: clouds – ISM: molecules – radio lines: ISM

1. INTRODUCTION: THE CENTRAL MOLECULAR ZONE AND ITS (LITTLE) STAR FORMATION ACTIVITY

“Ordinary” giant molecular clouds (GMCs) in the Galactic disk have sizes of tens of parsecs, temperatures, $T_{	ext{kin}}$, in the low tens of K, and densities, $n$, of order hundred cm$^{-3}$. Embedded in these GMCs are regions of star formation with much higher temperatures and densities. In contrast, the gas in the Central Molecular Zone (CMZ; see e.g., Morris & Serabyn 1996) of our Galaxy, stretching from Galactic latitude, $l$, $\sim +1/2^\circ$ to $-1/2^\circ$ in a $\sim ±0.3$ wide band in latitude, $b$, around the Galactic center (GC; Bally et al. 1987, 1988; Dahmen et al. 1997, 1998; Oka et al. 1998), is in general characterized by much higher temperatures, densities, and more turbulence, resulting in larger linewidths ($\gtrsim 10$–30 km s$^{-1}$). Güsten & Philipp (2004) presented a recent review.

To get a handle on the chemistry and physical conditions in these peculiar clouds, multitransition measurements of molecules other than the ubiquitous and easily thermalized carbon monoxide (CO) are highly desirable. By observing many lines from a given species and modeling the results using, e.g., large velocity gradient (LVG) methods, one can derive the densities and temperatures of the GC clouds, which are known to be significantly higher than values in Galactic disk clouds, but still relatively ill-constrained by existing data. Extensive surveys of carbon monosulfide (CS), $^{13}$CO, and C$^{18}$O have been made mostly with coarse spatial resolutions of 2′ and 9′, respectively (Bally et al. 1987; Dahmen et al. 1997) and, in a smaller region around the GC itself, of cyanoaacetylene (HC$_2$N), ammonia (NH$_3$), and silicon monoxide (SiO) with beam sizes between 40′′ and 140′′ (Güsten et al. 1981; Walmsley et al. 1986; Martin-Pintado et al. 1997). Walmsley et al. observed several HC$_2$N transitions within 1/5 of the GC and found that the bulk of the gas has $T \approx 80$ K and $n \approx 10^4$ cm$^{-3}$, while 20% of its mass may exist in higher ($10^5$ cm$^{-3}$) density clumps. Astonishingly, a large number of complex organic molecules have been found to show widespread emission all over the CMZ (see Section 6).

Whether tidal forces, stronger turbulence, higher densities, and stronger magnetic fields (compared to Galactic disk clouds) favor star formation or hinder it can be argued either way. It is a fact that the spectacular Arches and Quintuplet clusters provide testimony for violent star formation a few million years ago (Figer et al. 1999, 2002). Figer et al. (2004) argue that the ongoing star formation is responsible for the observed central stellar cusp. From Infrared Space Observatory (ISO) and Spitzer Space Telescope infrared wavelength data Schuller et al. (2005) derive a star formation rate in the CMZ of 0.2 $M_\odot$ yr$^{-1}$ over the past $\sim 0.5$ Myr, which is an appreciable fraction of our whole Galaxy’s star formation rate.

However, apart from the star-formation-wise extremely active Sgr B2 region, little of what is commonly assumed to be evidence for on-going high-mass star formation is found in the GC GMCs at present, such as (ultra)compact H II regions, H$_2$O and CH$_3$OH masers. The submillimeter-detected dust ridge identified by Lis & Carlstrom (1994) marks the highest column density material of the general GC dust emission/molecular cloud distribution (Pierce-Price et al. 2000). It has the potential to harbor proto-cluster cores, with the massive ($1 \times 10^6$ $M_\odot$) Infrared Dark Cloud M0.25+0.11 the most prominent example (Lis et al. 1994; Lis & Menten 1998). However, in this ridge, namely in M0.25+0.11, and also in the larger GC region only few markers of star formation have been found; just very few H$_2$O masers and compact continuum sources (Güsten & Downes 1981; Lis et al. 1994). Caswell (1996) covered an area of extent $l = ±0′/9$, $b = ±0′/5$ in a sensitive interferometric search for 6.7 GHz Class II methanol masers, which are unambiguous tracers of high-mass star formation. He only found 23 maser sites with nearly half of them located in the Sgr B2 complex alone.
2. THE PECULIAR G1.6−0.025 MOLECULAR CLOUD

2.1. Extended, Warm, Molecular Gas

The molecular cloud G1.6−0.025 lies at the very easternmost longitude edge of the cloud complexes making up the CMZ that were mapped in CO, 13CO, C18O CS, and other molecules (Bally et al. 1987, 1988; Dahmen et al. 1997, 1998; Oka et al. 1998; Martin et al. 2004). Maybe because of its location, this cloud received comparatively little attention in the past. However, the few observations that do exist reveal a fascinating chemical picture.

For further reference, we show, in Figure 1, an image of the velocity-integrated emission in the J = 2 − 1 transition of SiO discussed in Section 4.1.

Apart from the low-resolution surveys in CS and C18O, G1.6−0.025 has been mapped in several inversion transitions of NH3, by Gardner et al. (1985), who found remarkably strong emission in the (J, K) = (1, 1), (2, 2), and (3, 3) lines, with the (3, 3) line possibly being inverted toward one position. The NH3 observations indicate that the cloud is warm (probably > 50 K) but Gardner et al. do not give a thorough discussion of the temperatures suggested by the NH3 data. Gardner & Herbst (2006, and references therein). Later in this paper (in Section 5.2) we will argue that in the case of G1.6−0.025 these abundances may be the result of shock chemistry.

Given that several of the cloud’s characteristics (high linewidths, high abundances of usually rare species) are typical for GC GMCs, we assume in the following that G1.6−0.025 is at the same distance as the GC, i.e., 8 kpc (Reid 1993). Other evidence for placing the cloud there are the high [H213CO]/[H2CO] and [H218CO]/[H2C18O] isotopic abundance ratios, which are by factors of 4 and 2 higher, respectively, than values found in the solar neighborhood, but typical for the GC region (Gardner & Whiteoak 1981, 1982). Its projected distance from the GC is ca. 200 pc.

In this paper we report medium spatial resolution (2′) mapping observations of G1.6−0.025 in the J = 2 − 1 rotational line of silicon monoxide (SiO). Furthermore, we observed selected positions in the 2 − 1 line of carbon monosulfide (CS) and several methanol (CH3OH) transitions. As described by Leurini et al. (2004), newly calculated collisional rate coefficients now allow meaningful modeling of methanol excitation to obtain densities and kinetic temperatures (see Section 5.1). Using all this information, we summarize the available chemical information for G1.6−0.025 and in Section 5.2 discuss possible reasons for the observed picture.

2.2. (Almost Non-)Existent Active Massive Star Formation in G1.6−0.025

In order to assess whether G1.6−0.025’s peculiar chemistry could be energetically driven by the influence of young high-mass stars, we conducted a census of observational phenomena and, in particular, of tracers of on-going high-mass star formation activity in the region and its surroundings. For this, we conducted a literature search using the SIMBAD6 database. We searched for all astronomical objects contained in that database in a circle of 0.3 radius with l, b = 1:4, 0:0 at its center. We found a total of 138 objects, many of which are foreground (some of them OH/IR) stars and planetary nebulae. However, also a few compact radio continuum sources were found, for some of which, as discussed in the following, multiwavelength data are available, allowing a characterization.

For our purposes, we are only interested in objects that are (most probably) associated with G1.6−0.025 and may have some influence on their environment. Given this, it is straightforward to eliminate radio sources from our list that are not coincident with IRAS point sources. A spot check reveals that, e.g., G1.285−0.054, which has no associated IRAS source is, both, variable and has a negative, nonthermal spectral index and is therefore in all likelihood of extragalactic origin. On the other hand, IRAS sources without detected radio emission may be important, as there is no established correlation between the radio and IR luminosities of very young high-mass protostellar objects; see the famous case of Orion IRc2 (Menten & Reid 1995).

OH/IR objects are easy to eliminate from our list since they can be identified by their IRAS colors (as established by van der Veen & Habing 1988) and/or the presence of 1612 MHz OH maser emission.

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4 Strictly speaking G1.6−0.025 is only the cloud fragment delineated by the square in Figure 1. For simplicity’s sake, we refer by that name to the whole ∼ 0:8 × 0:35 sized region shown in that figure.

5 See Menten (1991) for the nomenclature/classification of CH3OH masers.

6 http://simbad.u-strasbg.fr/Simbad.
The only IRAS sources in the general region that are definitely associated with star formation are IRAS 17450–2742 and 17457–2743 which are coincident with the compact H II regions Sgr D 7 and 8, respectively (Liszt 1992); the latter one is also known as GSPRS5 1.396-0.006 (Becker et al. 1994). We note that these sources are not coincident with any molecular peak in the cloud. Observed and derived properties for them can be found in Table 1. While Liszt determines for Sgr D 7 a size of 1.6 arcsec, he finds source 8 unresolved in his 13'' × 23'' beam. Becker et al. (1994), with 4'' beam size, do not detect source 7 at either 1.4 or 5 GHz, most certainly “resolving it out” and find source 8 unresolved at either frequency. Assuming a size of 2'' for source 8 and an electron temperature of 10000 K we calculate an optical depth, τ, of the free–free emission of 0.47, 0.29, and 0.03 at 1.4, 1.6, and 5 GHz, respectively. For source 7 we determine τ = 0.003. Using the formula given by Megez et al. (1974) we derive that Lyman continuum photon fluxes of 2 × 10^48 s^{-1} and 1.4 × 10^47 s^{-1} are needed to produce the compact H II regions Sgr D 7 and 8, respectively. According to the Tables given by Panagia (1973) these values correspond to zero-age main-sequence (ZAMS) spectral types of O9 and B0, respectively.

To determine the neutral gas masses and luminosities of these sources from the IRAS data in the same way as described by Lis & Menten (1998), Planck functions were fitted to the measured 12, 25, 60, and 100 μm flux densities to determine dust temperatures (see Table 1). We used the formulae given therein and in the paper by Motte et al. (2003) to determine the gas masses listed in Table 1 for Sgr D 7 and 8 (taking the upper limits in the table at face value). Integrating over the spectral energy distributions we derive the bolometric luminosities given in Table 1, which, again according to Panagia (1973), are produced by a B0 and a B1 ZAMS star, respectively. These spectral types are very similar to those inferred from the Lyman continuum fluxes.

All in all we conclude that, apart from the two sources discussed above, there is presently very little star-forming activity in G1.6–0.025 and consider it highly unlikely that star-formation activity contributes to its enhanced temperature in a significant way.

### 2.3. A Possible Connection to the G1.4–0.1 Supernova Remnant

The supernova remnant (SNR) G1.4–0.1, which lies partially in the area mapped by us clearly interacts with molecular gas. Yusef-Zadeh et al. (1999) found 1720 MHz OH maser emission at l, b = 1°41'64", −0°13'23" (see Figure 1) at a velocity of −2.4 km s^{-1}, which is blueshifted relative to almost all of the gas we observe. Possibly the masing gas is located in the portion of the swept-up molecular material coming toward us and thus amplifying the continuum background. Lockett et al. (1999) constrain the conditions for the occurrence of these masers to temperatures between 50 and 125 K, densities and OH column densities around 10^5 cm^{-3} and 10^{16} cm^{-2}, respectively, typical for post magnetohydrodynamic (“C”)-shock material. These numbers can be compared with the values derived from our methanol modeling in Section 5.1.

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**Table 1**

| Radio Name Sgr D 7 | Sgr D 8 | References |
|------------------|--------|------------|
| α_B1950          | 17 45 01.3 | 17 45 47.1 | 1.2 |
| δ_B1950          | −27 42 17 | −27 43 45 | 1.2 |
| t                | 1.330   | 1.397     | 1.2 |
| b                | 0.091   | 0.006     | 1.2 |
| S(1.4 GHz)(mJy)  | ...     | 26        | 1   |
| S(1.6 GHz)(mJy)  | 222     | 21        | 2   |
| S(5 GHz)(mJy)    | ...     | 24.2      | 1   |
| IRAS Name        | 17450–2742 | 17457–2743 | 3 |
| S(12 μm)(Jy)     | 9.79    | 5.54L     | 3   |
| S(25 μm)(Jy)     | 28.30   | 3.13L     | 3   |
| S(60 μm)(Jy)     | 462.40  | 85.82L    | 3   |
| S(100 μm)(Jy)    | 782.90  | 386.60L   | 3   |
| T_d,25–60(K)     | 47      | 43.5      | 4   |
| T_d,25–100(K)    | 43.5    | 38.5      | 4   |
| L_{25–60}(L_⊙)   | 2.6 × 10^4 | 4.5 × 10^3 | 4 |
| L_{25–100}(L_⊙)  | 4.1 × 10^4 | 1.0 × 10^4 | 4 |
| M_{25–60}(M_⊙)   | 33      | 9         | 4   |
| M_{25–100}(M_⊙)  | 84      | 43        | 4   |

**Notes.** Flux densities are denoted by an S. T_ν, L, and M are dust temperature, bolometric luminosity, and total mass measured from the 25 and 60 μm IRAS data when thus indices, or from the 25, 60, and 100 μm data. (1) Becker et al. (1994) (2) Liszt (1992) (3) SIMBAD: a:- denotes an uncertain value and an L an upper limit. (4) D. C. Lis (2006), private communication.

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**Table 2**

| Species | Transition | Frequency^a | E_b^b |
|---------|------------|-------------|-------|
| CS      | 2 − 1      | 97980.95    | 2.4   |
| SiO     | 2 − 1      | 86848.96    | 2.1   |
| CH_3OH  | 5_{1} − 4_{0}E | 84521.21 | 28.4  |
|         | 2_{1} − 1_{1}E | 96739.39 | 0.0   |
|         | 2_{0} − 1_{0}A^* | 96741.42 | 2.3   |
|         | 2_{0} − 1_{0}E | 96744.58 | 7.6   |
|         | 2_{1} − 1_{1}E | 96755.51 | 15.5  |
|         | 0_{0} − 1_{1}E | 108893.94 | 0.0   |

**Notes.**

^a Frequencies and lower state energies are taken from the JPL catalog (http://spec.jpl.nasa.gov/).

^b For the CH_3OH lines, lower level energies are relative to the 00 state for A-type lines and relative to the 1_{1} state for E-type lines.

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**Table 3**

| Nr. | L_ν | b_ν | α_{2000} | b_{2000} |
|-----|-----|-----|----------|----------|
| 1   | 1'5750 | −0.0183 | 17°49'23.7 | −27° 35'53'' |
| 2   | 1.5939 | −0.0148 | 17 49 18.6 | −27 33 54 |
| 3   | 1.6418 | −0.0641 | 17 49 43.6 | −27 33 52 |
| 4   | 1.2829 | −0.0289 | 17 48 31.9 | −27 49 27 |
| 5   | 1.3690 | −0.1000 | 17 49 13.9 | −27 49 04 |
| 6   | 1.3168 | −0.0650 | 17 49 00.8 | −27 50 55 |
| 7   | 1.4110 | +0.0260 | 17 48 51.7 | −27 42 29 |
| 8   | 1.8053 | −0.3391 | 17 48 01.6 | −27 33 08 |
| 9   | 1.48211 | +0.0264 | 17 45 51.6 | −27 38 22 |

**Notes.** The first column gives the numbers of the fiducial positions as used in Figure 5 and Table 4. The remaining columns give galactic coordinates and J2000 equatorial coordinates.
| Pos. | Species | Transition | $T_\text{A}^\ast$ (K) | $\int T_A^\ast dv$ (K km$^{-1}$) | $v_{\text{LSR}}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) |
|------|---------|------------|-----------------|-------------------------------|-----------------|-----------------|
| 1    | CH$_3$OH | $5_{-1} - 4_0 E$ | 0.53 | 4.9(0.3) | 56.2(0.2) | 8.7(0.6) |
|      |         | $0_0 - 1_{-1} E$ | <0.57 | ... | ... | ... |
|      | CS      | 2 $- 1$ | 0.31 | 4.6(4.1) | 48.0(5.5) | 13.8(6.4) |
|      |         | 2 $- 1$ | 0.71 | 11.0(4.5) | 61.2(2.3) | 14.4(3.3) |
|      | SiO     | 2 $- 1$ | 0.28 | 8.6(1.3) | 163.2(2.1) | 28.5(5.5) |
|      |         | 2 $- 1$ | 0.23 | 6.9(0.4) | 53.4(0.6) | 27.4(1.1) |
|      | SiO     | 2 $- 1$ | 0.12 | 1.2(0.3) | 60.1(0.6) | 9.9(1.4) |
|      |         | 2 $- 1$ | 0.10 | 4.1(0.2) | 163.3(1.0) | 37.0(2.3) |
| 2    | CH$_3$OH | $5_{-1} - 4_0 E$ | 0.20 | 3.1(0.3) | 51.6(0.8) | 14.1(1.7) |
|      |         | $2_k - 1_k$ | Fitting impossible | ... | ... | ... |
|      |         | $2_k - 1_k$ | Fitting impossible | ... | ... | ... |
|      |         | $0_0 - 1_{-1} E$ | <0.57 | ... | ... | ... |
|      | CS      | 2 $- 1$ | 0.23 | 1.5(0.9) | 43.7(1.1) | 5.8(3.2) |
|      |         | 2 $- 1$ | 0.62 | 12.2(1.2) | 58.7(0.9) | 18.6(2.2) |
|      | SiO     | 2 $- 1$ | 0.46 | 12.4(1.0) | 162.3(1.0) | 25.1(2.2) |
|      |         | 2 $- 1$ | 0.37 | 10.1(0.5) | 60.3(0.6) | 26.0(1.5) |
|      | SiO     | 2 $- 1$ | 0.21 | 7.0(0.3) | 157.9(0.6) | 30.8(1.6) |
| 3    | CH$_3$OH | $5_{-1} - 4_0 E$ | 0.44 | 4.2(0.2) | 51.9(0.3) | 8.9(0.8) |
|      |         | $2_k - 1_k$ | 1.3 | 12.6(0.5) | 56.2(0.2) | 9* |
|      |         | $2_k - 1_k$ | 1.4 | 13.0(0.6) | * | 9* |
|      |         | $2_k - 1_k$ | 1.4 | 13.3(0.4) | * | 9* |
|      |         | $2_k - 1_k$ | 0.08 | 0.7(0.4) | * | 9* |
|      |         | $0_0 - 1_{-1} E$ | <0.57 | ... | ... | ... |
|      | CS      | 2 $- 1$ | 0.33 | 13(2) | 56(2) | 73(15) |
|      |         | 2 $- 1$ | 0.61 | 15(2) | 58(1) | 23(2) |
|      | SiO     | 2 $- 1$ | 0.55 | 16(3) | 162(2) | 27(4) |
|      |         | 2 $- 1$ | 0.15 | 4(3) | 197(7) | 30(22) |
| 4    | CH$_3$OH | $5_{-1} - 4_0 E$ | 0.21 | 8.6(0.5) | 118.5(1.2) | 39.6(2.8) |
|      |         | $2_k - 1_k$ | Fitting impossible | ... | ... | ... |
|      | $0_0 - 1_{-1} E$ | <0.3 | ... | ... | ... | ... |
|      | CS      | 2 $- 1$ | 0.74 | 45(9) | 106(5) | 57(7) |
|      |         | 2 $- 1$ | 0.20 | 13(9) | 166(21) | 61(27) |
|      | SiO     | 2 $- 1$ | 0.31 | 20(1) | 116(1) | 61(2) |
|      |         | 2 $- 1$ | 0.05 | 1.1(0.2) | 179(2) | 20(4) |
| 5    | CH$_3$OH | $5_{-1} - 4_0 E$ | 0.20 | 11.5(0.7) | 79(8) | 55(4) |
|      | CS      | 2 $- 1$ | 0.25 | 6.5(1.1) | 22(3) | 24(6) |
|      |         | 2 $- 1$ | 0.89 | 33(5) | 72(2) | 35(3) |
|      | SiO     | 2 $- 1$ | 0.53 | 17(3) | 109(3) | 30(5) |
|      |         | 2 $- 1$ | 0.32 | 13(2) | 63(2) | 39(3) |
|      | SiO     | 2 $- 1$ | 0.24 | 11(2) | 101(3) | 42(4) |
| 6    | CH$_3$OH | $5_{-1} - 4_0 E$ | 0.24 | 0.5(0.1) | 17.9(0.3) | 1.8(0.7) |
|      | CS      | 2 $- 1$ | 0.22 | 5.5(0.4) | 80.8(1.0) | 24.1(2.1) |
|      |         | 2 $- 1$ | 0.42 | 38(4) | 48(4) | 8(4) |
|      | SiO     | 2 $- 1$ | 0.82 | 25(3) | 84(1) | 29(3) |
|      |         | 2 $- 1$ | 0.15 | 5(1) | 44(2) | 31(3) |
|      | SiO     | 2 $- 1$ | 0.39 | 14(1) | 83(1) | 33(1) |
| 7    | CH$_3$OH | $5_{-1} - 4_0 E$ | <0.2 | ... | ... | ... |
|      | CS      | 2 $- 1$ | 0.32 | 9(3) | 82(3) | 27(5) |
|      |         | 2 $- 1$ | 0.32 | 24(4) | 100(5) | 69(12) |
|      | SiO     | 2 $- 1$ | 0.12 | 3.7(0.3) | 72(1) | 29(2) |
|      |         | 2 $- 1$ | 0.15 | 8.6(0.1) | 98(1) | 54(2) |
| 8    | CH$_3$OH | $5_{-1} - 4_0 E$ | 0.23 | 8.2(0.6) | 79.0(1.3) | 33.6(3.0) |
|      | SiO     | 2 $- 1$ | 0.24 | 8(4) | 71(1) | 32(6) |
|      |         | 2 $- 1$ | 0.16 | 10(4) | 85(7) | 60(5) |
Table 4 (Continued)

| Pos. | Species | Transition | $T_A^*$ (K) | $\int T_A^*d\nu$ (K km$^{-1}$) | $v_{LSR}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) |
|------|---------|------------|-------------|-------------------------------|-------------------------|---------------------|
| 9    | CH$_3$OH | 2$_{1} - 1_{1}$ |            |                               |                         |                     |
|      | CH$_3$OH | 5$_{1} - 4_{1}$ | 0.21        | 5(1)                          | 66(1)                   | 24(3)               |
|      |          | Fitting impossible | 0.12        | 6(1)                          | 99(6)                   | 49(8)               |

Notes. Columns are, right to left, position at which spectrum was taken (from Table 3), species, transition, corrected antenna temperature, integrated corrected antenna temperature, LSR velocity, and linewidth (FWHM), with the latter four quantities determined from multicomponent Gaussian fits. Meaningful fitting was in most cases impossible for the 2$_{1} - 1_{1}$ quartet of methanol and modeling of these and other methanol lines are discussed in Section 5.1. For the 2$_{1} - 1_{1}$ fit results for position 4 $v_{LSR}$ and $\Delta v$ are given for the $\sim$ 55 km s$^{-1}$ system only, with the linewidth fixed to the value of the 5$_{1} - 4_{1}$ emission at that velocity. The fitted velocity is that of the 2$_{1} - 1_{1}$A$^*$ lines and the velocities of the other lines were fixed to it. For that position, the CH$_3$OH equivalents of the CS 162 and 197 km s$^{-1}$ components were too difficult to fit. Upper limits given for the CH$_3$OH, 0$_{0} - 1_{0}$ line are three times the 1$\sigma$ rms noise.

Figure 1. Map of integrated SiO $J = 2 - 1$ emission of G1.6–0.025 made with the Bell Laboratories 7m telescope. Contours are 2 to 12 in steps of 2 $\times$ 1.8 K km s$^{-1}$, which is equal to the rms noise. The area within the dotted line was not mapped. The 2$'$ diameter beam (FWHM) is indicated in the upper corner of the left upper panel. Fiducial positions lying within the map boundaries are indicated. The square gives the extent of the ammonia map shown in Figure 3 of Gardner et al. (1985) and the rectangle within it the area mapped by Salii et al. (2002) in methanol lines. Methanol absorption in the 2$_{0} - 3_{1}$ line was mapped by Whiteoak & Peng (1989) over a roughly similar area as ammonia. The C$_3$H$_2$ spectra presented by Kuiper et al. (1993) were taken toward various locations within that area. The two dots mark the positions of the radio/FIR sources Sgr D7 (western) and D8 (eastern source). The square marks the position of a 1720 MHz OH maser.

Figure 2. Top to bottom: Spectra taken toward positions 1–6 of Table 3 in the $J = 2 - 1$ lines of CS and SiO.
3. OBSERVATIONS

Our observations were made with the Bell Laboratories 7 m telescope in the spring of 1995. The beamwidth at 86 GHz is ∼2′. System temperatures ranged from 300 to 400 K, but could be as high as 1200 K. Generally while mapping, the observing time per point was adjusted to retrieve uniform rms noise values. We observed the lines listed in Table 2, some of them (as listed in the table caption) with a 256 × 1 MHz filterbank, others with a 256 × 250 kHz filterbank.

We mapped only the SiO (2 − 1) line extensively over the l, b ∼ 1°0 × 0′35-sized region shown in Figures 1 and 5. Mostly high-quality spectra of this line and the others listed in Table 2 were taken toward the “fiducial” positions given in Table 3, which are marked in Figure 1. The CS and SiO spectra taken toward positions 1–6 are presented in Figure 2 and the CH₃OH spectra in Figures 3 and 4. Line parameters, obtained by Gaussian fitting are presented in Table 4. Because of the existence of multiple velocity components, large line widths and line blending, Gaussian fitting of the CH₃OH 2ₖ − 1ₖ series was not viable. The interpretation of the methanol results is discussed in Section 5.1.

4. MOLECULAR LINE DATA

As shown in Figures 2–5, we observe emission between velocities of ∼−10 and +200 km s⁻¹. Molecular gas at velocities < −100 km s⁻¹ and > +120 km s⁻¹ is usually attributed to the expanding molecular ring (EMR; Kaifu et al. 1972, 1974; Scoville 1972) around the Galactic center. Given its position, G1.6−0.025 is at the high longitude end of that ring. That the emission in all the three molecules observed by
us is much more prominent and widespread than in “normal” Galactic disk clouds favors a Galactic center location; see also the arguments brought forward in Section 2.1.

4.1. SiO Emission Distribution and Velocity Structure

Figures 1 and 5 show that the SiO $J = 2 – 1$ emission is very clumpy on different scales, the smallest of which seem to be resolved by our beam, whose HPBW corresponds to 4.7 pc. This picture is similar to that presented by the $J = 1 – 0$ line mapped by Martin-Pintado et al. (1997) with the same resolution over a similar-sized region extending the area mapped by us to smaller longitudes, i.e., from $l = +0^\circ.8$ to $l = -0^\circ.2$, covering Sgr B2 and the Galactic center proper (Sgr A). Huettemeister et al. (1998) observed the $^{28}$SiO and the $^{29}$SiO $J = 2 – 1$ and the $^{28}$SiO $5 – 4$ transitions toward CS peaks found by Bally et al. (1987). They used LVG calculations to model these two-line, two-isotopomer data to constrain density, temperature and SiO abundance toward

Figure 5. Maps of SiO $J = 2 – 1$ emission of G1.6−0.025 made with the Bell Laboratories, 7 m telescope. Each map represents the emission in $T^*_A$ units in a “channel” smoothed to a width of 27.6 km s$^{-1}$ centered on the velocity (in km s$^{-1}$) given in the left upper corner of each panel. Contours are 2 to 20 in steps of 2 times 25 mK, which is equal to the rms noise. The area within the dotted lines was not mapped. An additional area of width $-0.11 < b < 0.0$ was also mapped from $l = 2^\circ$ to $2.6^\circ$ but no emission was found within it. The $2^\circ$ diameter beam (FWHM) is indicated in the upper left corner of the upper left panel.

Table 5

| Position | $T_k$ (K) | $n(H_2)$ (cm$^{-3}$) | $N$(CH$_3$OH-A) (cm$^{-2}$) | $N$(CH$_3$OH-E) (cm$^{-2}$) |
|----------|-----------|-----------------|------------------|------------------|
| 2        | 190       | $3.6 \times 10^4$ | $5 \times 10^{14}$ | $5 \times 10^{14}$ |
|          |           | Extended cloud   | $9 \times 10^{14}$ | $9 \times 10^{14}$ |
| 3        | 16        | $4 \times 10^4$  | $1 \times 10^{14}$ | $1 \times 10^{14}$ |
|          | 60        | $6 \times 10^4$  | $6 \times 10^{14}$ | $6 \times 10^{14}$ |

Table 6

| Transition | Frequency (GHz) | $T_{\text{obs}}$ (K) | $T_{\text{mod}}$ (K) | $T_{\text{obs}}$ (K) | $T_{\text{mod}}$ (K) | References |
|------------|-----------------|----------------------|----------------------|----------------------|----------------------|------------|
| $2_0 - 3_1E$ | 12.179          | -1.25                | -0.25                | -0.38                | -0.24                | 1          |
| $4_{-1} - 3_0E$ | 36.169          | ~0.4                 | 0.5                  | ~0.4                 | 0.26                 | 2          |
| $5_{-1} - 4_0E$ | 84.521          | 0.34                 | 0.23                 | 0.26                 | 0.10                 | 3          |
| $2_1 - 1_1E$ | 96.739          |                      |                      |                      |                      |            |
| $3_0 - 2_0E$ | 96.741          | 1.85                 | 1.63                 | 1.05                 | 0.66                 | 3          |
| $2_0 - 1_0E$ | 96.745          |                      |                      |                      |                      |            |

Notes. Position denotes the position (from Table 3) toward which the fitted spectra were taken. $T_k$ and $n(H_2)$ are the best fit values for the kinetic temperature and the molecular hydrogen density, respectively. $N$(CH$_3$OH-A) and $N$(CH$_3$OH-E) are the best fit column densities of A- and E-type methanol, respectively. The calculations assume that both the high velocity clump and the extended cloud are extended relative to the telescope beam.

References. (1) Whiteoak & Peng 1989; (2) Salii et al. 2002; (3) This work.

Figures 1 and 5 show that the SiO $J = 2 – 1$ emission is very clumpy on different scales, the smallest of which seem to be resolved by our beam, whose HPBW corresponds to 4.7 pc. This picture is similar to that presented by the $J = 1 – 0$ line mapped by Martin-Pintado et al. (1997) with the same resolution over a similar-sized region extending the area mapped by us to smaller longitudes, i.e., from $l = +0^\circ.8$ to $l = -0^\circ.2$, covering Sgr B2 and the Galactic center proper (Sgr A). Huettemeister et al. (1998) observed the $^{28}$SiO and the $^{29}$SiO $J = 2 – 1$ and the $^{28}$SiO $5 – 4$ transitions toward CS peaks found by Bally et al. (1987). They used LVG calculations to model these two-line, two-isotopomer data to constrain density, temperature and SiO abundance toward
all these positions. Their data are consistent with a hot $T > 100$ K, low density medium $\sim 10^4$ cm$^{-3}$, in which, particularly, the higher $J$ SiO transitions are highly subthermally excited. One of the positions they observed, at $l, b = +1.31, -0.31$, is within $\approx 2\arcmin$ of our position 6. Toward this position, they found the highest fractional SiO abundance ($10^{-8}$) of all the 33 positions they observed, which are spread over the whole of the CMZ. Huettemeister et al. (1998) invoke a shock origin for the elevated SiO abundance there and also toward other locations for which models of the Galactic bar gravitational potential predict cloud–cloud collisions (see Section 4.3 and 5.2).

Figure 6. Best LVG fit toward position 2 overlaid on the real data for the $5_{-1} - 4_{-0} E$ line (upper panel) and the $2_{k} - 1_{k}$ quartet of lines (lower panel).

Figure 7. Same as Figure 6 for position 3.

4.2. Methanol Emission

Toward all of the positions listed in Table 2 the emission from the $2_{k} - 1_{k}$ $^8$ quartet of CH$_3$OH is stronger than that of the SiO line, and, amazingly, even stronger than that of the CS line (see Table 4, Figures 3 and 4). Given their strong blending, it is impossible to determine the properties of these lines by fitting

$^8$ The projection of the angular momentum quantum number, $k$, runs from $-J$ to $+J$ for $E$-type CH$_3$OH. For $A$-type CH$_3$OH a capital $K$ is used, with $0 \leqslant K \leqslant J$. When referring in one expression to levels from both species, lowercase $k$ is used.
Gaussians in any meaningful way. Instead we performed the model calculations described in Section 5.1 to predict intensities for these lines and the 84 GHz $5_{-1} - 4_0 E$ transition and, in turn, to constrain the physical parameters of the emission region.

4.3. Evidence for Cloud–Cloud Collisions

We note that we find a spatial coincidence (at $l, b = 1.23, -0.05$) of an SiO clump with emission in the 17.6 km s$^{-1}$ channel with one with emission in the 100 km s$^{-1}$ channel. We also observe a coincidence, at $l, b = 1.22, +0.10$, between clumps in the 100.4 and one in 155.6 km s$^{-1}$ channels. Other such coincidences can be found in the channel maps.

A similar coincidence of two clumps with widely different velocities that appear at the same projected area in space has been reported by Haschick & Baan (1993) who note, in the $4_{-1} - 3_0 E$ CH$_3$OH emission, a coincidence of a clump in the 40–70 km s$^{-1}$ velocity interval (which they call Dm) with one in the 150–167 km s$^{-1}$ interval (Em) at $l, b = 1.594, +0.015$. This particular spatial coincidence of components at these velocities was also pointed out by Salii et al. (2002), who presented a map of the high velocity emission along with the integrated emission in the $5_{-1} - 4_0 E$ and the blended $2_{-1} - 1_{-1}$ lines of CH$_3$OH for which we took spectra only toward selected positions. Both the low and the high velocity emission have a similar extent in the CH$_3$OH as the SiO emission (for the high velocity emission, see the 156 km s$^{-1}$ channel map in our Figure 5).

Haschick & Baan (1993) credit Sobolev (1992), who interpreted the $4_{-1} - 3_0 E$ CH$_3$OH data of Berulis et al. (1992) in a scenario involving a cloud–cloud collision, an intriguing idea, which is further promoted by Salii et al. (2002; see Section 5.2).

5. PHYSICAL CONDITIONS AND CHEMISTRY IN G1.6–0.025

5.1. Methanol Statistical Equilibrium Calculations

In addition to our own data and those of Salii et al. (2002), further important constraints on CH$_3$OH excitation in G1.6–0.025 come from widespread enhanced absorption (overcooling) in the 12.2 GHz $2_0 - 3_{-1} E$ line (Whiteoak & Peng 1989) and the also widespread maser emission in the $4_{-1} - 3_0 E$ line (Haschick & Baan 1993; Liechti & Wilson 1996). As explained, e.g., by Menten (1991) one expects, in the absence of a strong far-infrared field, which is certainly the case in G1.6–0.025, an overpopulation of the $k = -1$ ladder relative to the $k = 0$. Similarly, one might naively expect overcooling in the 109 GHz $0_0 - 1_{-1} E$ transition, where we observe neither absorption nor emission with a 3σ upper limit of 0.57 K. This absence is explained by our model predictions (see below).

To address these issues quantitatively, we performed model calculations. Leurini et al. (2004) used the rate coefficients for collisions of CH$_3$OH with He calculated by Pottage et al. (2002) to investigate the excitation of CH$_3$OH over a range of physical parameters typical of star-forming regions. They also presented a new technique to handle the problem of deriving physical parameters of a source from spectroscopic data; the technique is based on the simultaneous fit of multiple lines in a spectrum (when present) with a synthetic spectrum computed using the LVG approach for solving the radiative transfer equations, in the derivation of de Jong et al. (1975). This analysis is particularly well suited for the case of strongly blended lines, where “by-hand” Gaussian fitting of lines with multiple components...
often leads to unreliable results. Moreover, following Cesaroni & Walmsley (1991), the effect of overlap of lines in the excitation of the CH$_3$OH molecule is taken into account defining an average optical depth and brightness temperature for lines with a frequency separation

$$\nu_i - \nu_j \leq \Delta \nu_i + \Delta \nu_j.$$  \hspace{1cm} (1)

Using the technique described above, we analyzed our data toward two of the observed positions, namely numbers 2 and 3 of Table 3, to derive the physical parameters of the region. In addition to our own data, we have also compared the predictions of our model for other CH$_3$OH lines observed toward position 2 by other authors. Our model calculations do not predict absorption in the $0_0 - 1_1 - E$ transition for a wide range of physical parameters ($n$ from $10^3$ to $10^8$ cm$^{-3}$; $T_{\text{kin}}$ from 10 to 200 K; N(CH$_3$OH) from $10^{12}$ to $10^{16}$ cm$^{-2}$). The simultaneous modeling of the $2_k - 1_k$ and $5_1 - 4_0 - E$ lines gives constraints on the column density of methanol and on the H$_2$ density. The $5_1 - 4_0 - E$ transition is strongly inverted over a wide range of physical parameters, for $n$(H$_2$) $> 10^4$ cm$^{-3}$ and CH$_3$OH column densities higher than $10^5$ cm$^{-2}$ (see Figure 8). Hence, the nondetection of obvious strong maser action (but see below) in our observations indicates low values for the column density of the gas. The $2_k - 1_k$ lines are, on the other hand, sensitive to the density of the gas (see Figure 4 of Leurini et al. (2004)).

Inspecting the $2_k - 1_k$ CH$_3$OH map presented by Salii et al. (2002) we assumed the CH$_3$OH emission to be extended compared to the 7 m telescope beam. We modeled the data with two velocity components, corresponding to the high velocity clump and to the extended cloud. The LVG fit overlaid on the

![Figure 9](image-url). Line optical depths of $4_{-1} - 3_0 - E$ (solid line) and $5_{-1} - 4_0 - E$ (dotted line) as a function of density at different CH$_3$OH column densities, $2 \times 10^{15}$ cm$^{-2}$ (upper panel) and $2 \times 10^{16}$ cm$^{-2}$ (lower panel).

data is shown in Figures 6 and 7. The results determined from the fit are given in Table 5. Table 6 shows our model predictions for the other CH$_3$OH transitions observed by other authors. Pointing and absolute calibration uncertainties and beam-size differences can make the determination of physical parameters less reliable when comparing data from different telescopes; in our case however, beam-size differences should not affect the results as, given the source sizes, beam filling factors for the different transitions are pretty close to 1.

Salii et al. (2002) determined the physical parameters toward our position 2 by analyzing several methanol transitions. Their results do differ somewhat from ours. In particular, they find somewhat smaller spatial densities and CH$_3$OH column densities. From their analysis they conclude that the high velocity clump has a hydrogen density, $n$(H$_2$), less than $10^4$ cm$^{-3}$, column densities between $4 \times 10^{11}$ and $6 \times 10^{12}$ cm$^{-2}$ and temperatures in the 150–200 K range. For the extended cloud they infer a hydrogen density less than $10^6$ cm$^{-3}$, column densities larger than $6 \times 10^{11}$ cm$^{-2}$ and a kinetic temperature of less than 80 K. Assuming that all the gas is in molecular form, this translates in spatial densities of molecular hydrogen less than $3 \times 10^3$ cm$^{-3}$ for the extended cloud and $n$(H$_2$) $< 5 \times 10^3$ cm$^{-3}$ for the high velocity clump. With these parameters, they can reproduce the observed line intensities for several transitions, but fail to explain the simultaneous deep absorptions in the $2_0 - 3_{-1} - E$ and $2_1 - 3_0 - A^+$ lines at 12.18 GHz and 156.6 GHz, and the brightness of the emission in the $J_0 - J_{-1} - E$, $J = 1, 2, 3$ blend. They conclude that the absorptions and the $J_0 - J_{-1} - E$, $J = 1, 2, 3$ blended emission come from different parts of the cloud.

Our model predictions (see Table 6) overestimate the $J_0 - J_{-1} - E$, $J = 1, 2, 3$ blended emission and underestimate the absorption in the $2_0 - 3_{-1} - E$ transition in the extended cloud, but can reproduce the simultaneous absorptions and the emission in the $J_0 - J_{-1} - E$ blend. For the high velocity clump, our predictions are in good agreement with the observations. Moreover, spatial densities of the order of a few $10^3$ cm$^{-3}$, as inferred by Salii et al. (2002), fail to reproduce our observations of the $5_{-1} - 4_0 - E$ line.

At position 2, Haschick & Baan (1993) find maser emission in the $4_{-1} - 3_0 - E$ line on top of a broad thermal-looking component. Fitting the maser component in our model would need a second, narrower component for both the high velocity clump and the extended cloud, which is not detected in our observations. Therefore we do not include in our analysis any other component to account for the narrow maser features in the $4_{-1} - 3_0 - E$ line. However, the maser action in the $4_{-1} - 3_0 - E$ and the simultaneous absence of it in the $5_{-1} - 4_0 - E$ line can give interesting constraints for the physical parameters of the regions. S. Leurini et al. (2008, in preparation) have extensively analyzed the pumping mechanisms of Class I CH$_3$OH masers.

Their calculations confirm collisions to be responsible for the excitation of Class I masers and suggest the maser action in these lines to be used as a density indicator. Both the $4_{-1} - 3_0 - E$ and $5_{-1} - 4_0 - E$ transitions are inverted at low densities; however, the inversion of $5_{-1} - 4_0 - E$ line starts with $n$(H$_2$) $> 10^4$ cm$^{-3}$ with CH$_3$OH column densities higher than $10^{15}$ cm$^{-2}$, while the $4_{-1} - 3_0 - E$ line masers also at lower densities, as Figure 9 shows, almost independently from the kinetic temperature. The above is also found by Berulis et al. (1992) and Sobolev (1992).

At lower column densities, the inversion of $4_{-1} - 3_0 - E$ line starts with $n$(H$_2$) $> 10^4$ cm$^{-3}$ and CH$_3$OH column densities higher than $10^{15}$ cm$^{-2}$, while the $4_{-1} - 3_0 - E$ line masers also at lower densities, as Figure 9 shows, almost independently from the kinetic temperature. The above is also found by Berulis et al. (1992) and Sobolev (1992).
84.5 GHz line puts an upper limit on of $\sim 10^{25} \text{cm}^{-3}$ on the spatial hydrogen density of the region, depending on the column density of methanol.

Nevertheless, comparison of $5 - 1 - A_1^0 E$ and $2_1 - 1_k$ spectra (Figures 3 and 4) shows that the former generally are narrower than the latter, which might at first look be interpreted as line narrowing accompanying maser action. However, since some of the (noisy) spectra also cover incongruent velocity ranges this might actually not be the cause for this difference in appearance. Another possibility would be the existence of two gas components in the beam with different densities and/or temperatures, which might contribute to the lines in question in different proportions. This could explain the narrower line profiles of the $5 - 1 - A_1^0 E$ line, which seems not to be excited in one of the velocity components, and the underestimate of line intensity in the model. However, the maps of the $5 - 1 - A_1^0 E$ and $2_1 - 1_k$ lines published by Salii et al. (2002) (and with a spatial resolution of $\sim 57''$), do not show any large discrepancies between the distributions of the two lines. Needless to say, the described discrepancy illustrates the qualitative nature of our results.

To summarize, our statistical equilibrium modeling of the CH$_3$OH lines observed by us and others indicates relatively high densities ($> 6 \times 10^4 \text{cm}^{-3}$) and moderate temperatures (30–60 K) for two representative positions in the G1.6−0.025 cloud at $v_{\text{LSR}} = 50 \text{ km s}^{-1}$. In the high velocity component, lower densities are inferred by the model for both positions; for position 2, a high temperature (190 K) is needed to reproduce the observations, while cold gas (16 K) is needed for position 3. The latter is puzzling as, in analogy to position 2, one might also expect an enhanced temperature for high velocity CH$_3$OH emission. High velocity SiO is not even detected toward position 3 and high velocity CS barely. Methanol abundances relative to H$_2$ are of the order of $10^{-7}$–$10^{-8}$. Finally, we note that the temperatures and densities we derive are of the same order of the values that Whiteoak & Peng (1989) derive from their modeling of the CH$_3$OH $2_0 - 3_1 E$ line.

Huettemeister et al. (1993) conducted a multitransition study of NH$_3$ inversion lines with energies of up to 408 K above ground toward 36 positions in the CMZ. They found evidence for two components pervasive throughout the CMZ, both at each position at roughly the same velocity, a cool one, $T \sim 25$ K and a hot one $\sim 200$ K. The densities of the these components are not well constrained by their observations, but they argue that the hot and cool gas have densities of $10^4$ and $10^5 \text{cm}^{-3}$, respectively.

In their study, they also included one position within the area that we mapped in SiO emission ($l, b = +1^\circ 15, -0^0 09$) and several others just abutting it, i.e., within 0.2 degrees outside its boundaries. Since they do not present data toward the positions toward which we see a high (= clump)- and a low(= general cloud)-velocity component, a direct comparison with our analysis is difficult. However, we can say that we do not see evidence for a high temperature component at the general cloud velocities toward the two positions that we analyzed, while they find evidence for both cool and hot components at these velocities.

The reason why we do not see a hot component may be a selection effect based on our choice of lines. The rotation temperatures Huettemeister et al. (1993) derived from their lowest excitation lines alone ($J, K = (1, 1)$ and (2, 2) at energies of 23 and 64 K above ground, respectively) invariably are between 18 and 40 K throughout the CMZ and mostly around 25 K. In contrast, rotation temperatures determined from the (4,4) and (5,5) lines (at 200 and 295 K above ground, respectively) are all more than 50 K, most more than 80 K, and some as high as 200 K. Since we did not observe any high excitation lines, given the experience with NH$_3$, we could not detect any hot component in G1.6−0.025 at velocities at which emission from cold as well as from hot gas arises, but only at velocities at which only the hot component emits (i.e., high velocity clumps).

To estimate the column density of molecular hydrogen and derive the [CH$_3$OH]/[H$_2$] ratio, we used the $^{13}$CO $J = 1 - 0$ data imaged by Bally et al. (1987) with the Bell Labs 7 m telescope. Assuming the local thermal equilibrium approximation, and using the kinetic temperatures derived from the analysis of the methanol emission, we computed the $^{13}$CO column densities for positions 1 and 2, for the high velocity clump and for the extended cloud, by integrating over the velocity channels corresponding to the CH$_3$OH emission. To convert the $^{13}$CO column density into a H$_2$ column density, we used a typical abundance relative to H$_2$ of $10^{-4}$ for CO and a value of 20 for the $^{12}$C/$^{13}$C isotopic ratio. This is the value Wilson & Rood (1994) give for the $^{12}$C/$^{13}$C ratio for molecular clouds in the Galactic center region. If we, however, used 11 for the latter ratio, which Gardner & Whiteoak (1981) derive for G1.6−0.025 from observations of formaldehyde isotopomers, the relative methanol abundance ratios given in the following would increase by a factor of 2.

Assuming that the column density of CH$_3$OH-A and CH$_3$OH-E are the same, our derived column densities translate into abundances relative to molecular hydrogen of $10^{-8}$ for the high velocity clump and $1 \times 10^{-6}$ for the extended cloud toward position 2 and to $10^{-9}$ and $3 \times 10^{-9}$, respectively, for position 3. The high velocity component is not detected in the $^{13}$CO line toward position 3 and we could only derive an upper limit to the H$_2$ column density based on the rms noise value of the data. Therefore, the CH$_3$OH abundance ratio estimated for this component is a lower limit to its true value.

### 5.2. Shock Chemistry in G1.6−0.025

As discussed in Sections 4.1 and 5.1 the SiO and CH$_3$OH abundances are enhanced relative to cold molecular cloud values. The observed chemical peculiarities of G1.6−0.025 could be the result of several mechanisms all involving shocks: cloud–cloud collisions (see Section 4.1), a molecular cloud–SNR interaction, and whatever is responsible for the peculiar large line widths in GC GMCs in general (increased turbulence, tidal forces).

It is tempting to assume that the high observed SiO and CH$_3$OH abundances in G1.6−0.025 have a common origin. With regard to these two species, a picture similar to G1.6−0.025 presents itself in the molecular peak M−0.02 − 0.07 (the so-called “20 km s$^{-1}$ cloud”), which lies $\sim 2'$ northeast–east of the Galactic center radio source Sgr A* at a position where the supernova remnant Sgr A East (SNR G0.0+0.0) appears to interact with a molecular cloud. Here, Martin-Pintado et al. (1997) found strong SiO ($J = 1 - 0$) emission, while Szczepanski et al. (1989) and, at higher resolution, Liechti & Wilson (1996) found very strong maser emission in the 36 GHz $4_1 - 3_0 E$ line of methanol. Just like in G1.6−0.025 the CH$_3$OH emission consists of a few narrow spikes and intense “broad” emission. 1720 MHz OH masers are also found in this region on the near-side of the SiO/CH$_3$OH emission distribution relative...
to Sgr A East facing the SNR (Karlsson et al. 2003; Pihlströmt & Sjouwerman 2006; Yusef-Zadeh et al. 2007). We emphasize the similarity to G1.6−0.025, with the SNR 1.4 − 0.1 (see Section 2.3), projected on and possibly interacting with it.

The existence of 1720 MHz OH maser emission argues, as discussed in Section 2.3, also for (C-)shock. The densities and temperature we derive from the methanol lines are very similar to the values necessary for 1720 MHz OH maser emission as discussed there. The chemistry in the molecular gas interacting with the SNR IC 443 was studied by van Dishoeck et al. (1993). One subregion, clump G I, was found to show a particularly rich chemistry. However, one dramatic difference between the molecular content of G1.6−0.025 and molecular IC 443 clump G I a is the complete dearth of any CH3OH in the latter. van Dishoeck et al. (1993) give a relatively sensitive 2σ upper limit of 0.2 K for any line in the 241.7 GHz CH3OH 5ν − 4ν series, while various SiO lines are two to three times stronger than that.

As for SiO, high abundances after the passage of magnetohydrodynamic C-shocks can result from a combination of the setting free of SiO into the gas phase by sputtering of the (charged, and hence coupled to the magnetic field) grain cores by neutral particles in the region of the C-shock where the relative velocities between charged and neutral particles are large, and following gas-phase reactions (Schilke et al. 1997). This is true for pristine material, where silicon resides in the grain cores. If, as is the case in the Galactic center, molecular clouds are frequently exposed to cloud−cloud collisions, silicon may, after the initial release from the core, reside either in the gas phase (possibly some of it in SiO2 as suggested by Schilke et al. 1997) or in grain mantles, with a lower binding energy.

How is the methanol produced in shocks? Gas-phase production of methanol has been shown to be insufficient to create the observed abundances in dark, quiescent clouds by many orders of magnitude (Geppert et al. 2005). Grain surface production however seems to be efficient, as shown by Hidaka et al. (2004). This indeed is the proposed mechanism for producing the high methanol abundances found in “hot cores” around high-mass young (proto)stars, where CH3OH is created by the evaporation from grain mantles once temperatures exceed ∼ 100 K. Shocks also would be able to release material from grain mantles, either by sputtering, even at lower shock speeds than needed for SiO production, since here the more weakly bound ice mantles have to be destroyed instead of the grain cores, as needed for SiO; or by thermal evaporation in the hot shocked gas. This mechanism has indeed been evoked for explaining the high methanol abundances in shocked protostellar outflows (e.g., Bachiller & Perez Gutierrez 1997).

To evaporate methanol from ice mantles, however, these ice mantles have to be present. While there is observational evidence from infrared spectroscopy that ice mantles do exist in the cold envelopes of protostars (to be released by outflows or heating by the igniting star), the conditions for formation of ice mantles in the highly turbulent, warm and relatively low density environment of Galactic center clouds (of which G1.6−0.025 is a member) seem less favorable. Deciding if sufficient methanol abundances in ice mantles can be built up under these conditions will require detailed modeling.

Another option could be that under GC cloud conditions, ice mantles do not build up, but CO can reside long enough on the grain surface to be transformed into CH3OH, which then is desorbed either by sputtering in vortices, or just thermally desorbed. In this case, the elevated methanol abundance would not be related to any specific shock event, but be the steady state abundance under these special conditions. Modeling would certainly be illuminating, but an observational consequence of this mechanism would be a uniformly high methanol abundance in the Galactic center, which may actually apply (Requena-Torres et al. 2006).

Alternatively, in the elevated temperatures of a C-shock, CH3OH may be created by the endothermic gas-phase reactions

\[
CH_4 + OH \rightarrow CH_3OH + H \tag{2}
\]

and

\[
CH_3 + H_2O \rightarrow CH_3OH + H \tag{3}
\]

discussed by Hartquist et al. (1995), which have endothermicities of 6500 and 14,700 K, respectively. The abundances of reaction partners OH and H2O certainly would be enhanced in a shock, but to judge these reactions’ importance would require running shock models, looking also carefully at possible shock destruction mechanisms for CH3OH. Observationally, this would, just as the option of removing CH3OH from ice mantles, imply a correlation of elevated CH3OH abundances with shock events.

In practice, it will be very hard to distinguish observationally between these scenarios, because SiO, the canonical shock tracer, is so widely distributed. This suggests that either shocks are ubiquitous, or that the grains are processed to a degree that a significant fraction of silicon resides in more weakly bound form either in the gas phase or on the grain surface, so that the release mechanisms for SiO and CH3OH are similar.

While we argue above that the interaction with a SNR may influence the chemistry in at least a part of G1.6−0.025, cloud−cloud collisions resulting from the special dynamics induced by the Galactic bar potential may play a major role for G1.6−0.025 and other GC clouds as a whole (see HuetteMeister et al. 1998; Rodríguez-Fernandez et al. 2006).

6. G1.6−0.025 IS AT THE OUTER REACHES OF THE GALACTIC CENTER ORGANIC MOLECULE REGION

There actually is evidence for a giant repository of organic molecules coextensive with the CMZ, of which G1.6−0.025 demarcates the high-longitude border (Menten 2004).

The first evidence for extended organic material in the CMZ came from widespread 4.8 GHz H2CO absorption (Scoville et al. 1972); see also Zytko et al. (1992). Given the ubiquity of formaldehyde in molecular clouds (e.g. Downes et al. 1980), one might dismiss this “as nothing special.” CH3OH, on the other hand, has usually quite low abundance and is difficult to detect outside hot, dense cloud cores. Nevertheless, Gottlieb et al. (1979) found the 834 MHz (1ν − 1ν) Aν line in the CMZ in emission and extended relative to their 40′ beam, concluding it is (weakly) inverted and amplifying the strong background radio emission.

Other molecules similarly (or even) more complex than CH3OH and H2CO were found widespread throughout the CMZ, such as HCOOH and C2H5OH (Minh et al. 1992; Martín-Pintado et al. 2001) and, very recently, (CH3)2O, HCOOCH3, HCOOH, and CH3COOH (Requena-Torres et al. 2006).

Furthermore, mapping of the HNCO 5ν5 − 4ν5 transition (made serendipitously simultaneously with a C18O survey), shows that the emission in this line is extending continuously from 4ν = −0:2 to +1:7, right out to G1.6−0.025 (Dahmen et al. 1997). The possible existence of such a huge mass of organic material in our Galactic center is extremely exciting.
and its extent, chemistry, and excitation should be studied with suitable tracers.

In fact, G1.6−0.025 coincides with the third strongest peak in the integrated HNCO distribution (after the general Sgr B2 region and an area around l = 1°, b = 0°) and the ratio of the integrated intensities of the HNCO to that of the C18O line in G1.6−0.025 is the highest in the whole CMZ. Maybe it the low UV radiation field density resulting from the absence of young high mass stars in G1.6−0.025 is conducive to the existence of (fragile) complex molecules. Given this, one might also expect other complex molecules than CH3OH and HNCO to have large abundances in G1.6−0.025. Possibly the best spectral range to search for those is the 3 mm window since, given our density estimates (Section 5.1), submillimeter lines might have prohibitively high critical densities.

7. CONCLUSIONS

Here we summarize our main conclusions. We find very little evidence for star formation in over the whole − 0.2 deg2 region of the G1.6−0.025 GMC. Our large scale, medium resolution (2′) mapping in the J = 2 − 1 transition of SiO reveals clumpy emission over an ∼ 0:6 × 0:3 region stretching along the Galactic plane. Toward selected positions, we have observed emission in the 21 − 12, 22 − 11, and 12 − 11 quartet of CH3OH lines and the 22 − 11, 12 − 11 and 32 − 21 lines. Toward all of these, the CH3OH lines are several times stronger than both the CS and the SiO lines. In addition, spectra of other methanol lines where taken. The wide widths of all the observed lines, similar to values generally found in the Galactic center, indicates a high degree of turbulence. A high velocity clump with a ∼ 100 km s−1 higher velocity than the molecular cloud may indicate a cloud–cloud collision. Statistical equilibrium modeling of all the CH3OH lines observed by us and others indicates relatively high densities and moderate temperatures for one representative position in the G1.6−0.025 cloud (8 × 104 cm−3/30 K) and higher temperature (190 K), but lower density (4 × 104 cm−3) in the high velocity clump. For a second position we also find densities of several times 104 cm−3 for both the low and the high velocity emission, but a puzzling low temperature for the high velocity clump (16 K) and warmer gas (60 K) for the low velocity 50 km s−1 gas. Different scenarios are possible in which shock chemistry might enhance the CH3OH and SiO abundances in G1.6−0.025 and elsewhere in the CMZ by grain–gas chemistry or by hot gas chemistry.

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