LARGE-SCALE GRAIN MANTLE DISRUPTION IN THE GALACTIC CENTER

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ABSTRACT

We present observations of C$_2$H$_5$OH toward molecular clouds in Sgr A and Sgr B2 and associated with thermal and nonthermal features in the Galactic center (GC). C$_2$H$_5$OH emission in Sgr A and Sgr B2 is widespread but not uniform. C$_2$H$_5$OH emission is much weaker in some molecular clouds in both complexes, in particular those with radial velocities between 70 and 120 km s$^{-1}$. While most of the clouds associated with the thermal features do not show C$_2$H$_5$OH emission, that associated with the nonthermal radio arc shows emission. The fractional abundance of C$_2$H$_5$OH in most of the clouds with radial velocities between 0 and 70 km s$^{-1}$ in Sgr A and Sgr B2 is relatively high, of a few times $10^{-8}$. The C$_2$H$_5$OH abundance decreases by more than a factor of 10 ($\approx 10^{-9}$) in the clouds associated with the thermal features. The large abundance of C$_2$H$_5$OH in the gas phase indicates that C$_2$H$_5$OH has formed in grains and released to gas phase by shocks in the last $\sim 10^5$ yr. The implications of this finding in the origin of the shocks in the GC is briefly discussed.

Subject headings: Galaxy: center — ISM: abundances — ISM: molecules — radio lines: ISM

1. INTRODUCTION

Ethanol (C$_2$H$_5$OH) was first detected by Zuckerman et al. (1975) toward the massive star-forming region in the Galactic center (GC) Sgr B2. Subsequent observations of this molecule in the interstellar medium have shown that C$_2$H$_5$OH is present only in the dense ($\gtrsim 10^4$ cm$^{-3}$) and hot (100 K) cores associated with newly formed massive stars (Irvine, Goldsmith, & Hjalmarson 1987; Millar et al. 1988; Ohishi et al. 1995; Millar, MacDonald, & Habeig 1995; Nummellin et al. 1998). In hot cores, the abundance of C$_2$H$_5$OH in the gas phase ranges from $10^{-8}$ to $10^{-9}$, and gas-phase chemistry cannot account even for the lowest fractional abundance of this molecule. Therefore, C$_2$H$_5$OH emission is considered one of the best tracers of dust chemistry (Millar et al. 1988; Charnley, Tielens, & Millar 1992; Charnley et al. 1995). Furthermore, the transient nature of the alcohol chemistry in molecular clouds makes the abundance of C$_2$H$_5$OH an excellent clock to estimate when this molecule was injected to the gas phase (Charnley et al. 1995).

The GC molecular clouds show high kinetic temperatures ($\approx 80$ K; Hüttemeister et al. 1993; Rodríguez-Fernández et al. 2001) and widespread large abundance of refractory molecules like SiO (Martín-Pintado et al. 1997). Shock waves have been invoked to explain the heating, the morphology, and the relatively large abundance of SiO in the GC (Martín-Pintado et al. 1997). Shocks are also expected to sputter molecules from the icy grain mantles, increasing the gas-phase abundance of the molecules formed in grains. Evidence for the release of molecules from grain mantles in selected molecular clouds close to Sgr A comes from the detection of C$_2$H$_5$OH and HOCO$^+$ in this region (Minh, Irvine, & Friberg 1992; Charnley & Kaufman 2000). In the scenario where shocks drive the chemistry in the GC clouds, it is expected that widespread C$_2$H$_5$OH emission closely follows that of SiO.

In this Letter we present observations of C$_2$H$_5$OH toward molecular clouds in Sgr A and Sgr B2 complexes and associated with the thermal features (arched filaments, hereafter TAF, and the Sickle) and the nonthermal radio arc (NTRA) in the GC (Lang, Morris, & Evechaurre 1999, for the nomenclature). We find that the C$_2$H$_5$OH emission in the GC is widespread, but large variations in the abundance of this molecule are found between the different GC molecular clouds. The large C$_2$H$_5$OH abundance and its variations are consistent with a scenario in which recent ($\approx 10^5$ yr) shocks dominate the chemistry in the GC by grain processing.

2. OBSERVATIONS AND RESULTS

The observations of the $J_{K_aK_c}=4_{1,4}\rightarrow 3_{0,1}$, $J_{K_aK_c}=6_{1,6}\rightarrow 5_{2,5}$, and $J_{K_aK_c}=9_{5,9}\rightarrow 8_{1,8}$ lines of C$_2$H$_5$OH toward the GC were carried out simultaneously with the IRAM 30 m telescope. To estimate the H$_2$ column density we also observed simultaneously the $J=1\rightarrow 0$ line of $^{13}$CO and C$^{18}$O, the $J=2\rightarrow 1$ line of C$^{13}$O, and the $J=3\rightarrow 2$ line of CS. The half-power beam width of the telescope was 24", 17", and 12" for the 3, 2, and 1.3 mm bands. The receivers, equipped with SIS mixers, were tuned to single sideband with image rejections of $\approx 10$ dB. The typical system temperatures were 300, 500, and 900 K for the 3, 2, and 1.3 mm lines, respectively. We used two filter banks of 256 x 1 MHz and one of 512 x 1 MHz as spectrometers. The velocity resolutions provided by the filter banks were 3, 2, and 1.3 km s$^{-1}$ for the 3, 2, and 1.3 mm bands, respectively. The calibration was achieved by observing hot and cold loads. The line intensities are given in units of $T_A^*$. The observed molecular clouds were selected from the SiO maps of Martín-Pintado et al. (1997), and their locations are shown in the upper panel of Figure 1. The typical line profiles of C$_2$H$_5$OH, $^{13}$CO, and CS toward selected clouds in Sgr A ($M=0.11\pm0.08$), in Sgr B2 ($M=0.76\pm0.05$), and associated with the Sickle (M$=0.20\pm0.03$) and the NTRA (M$=0.17\pm0.01$) are shown in the lower panels of Figure 1. Table 1 summarizes the results obtained for all molecular clouds. The emission in the $J_{K_aK_c}=4_{1,4}\rightarrow 3_{0,3}$ line of C$_2$H$_5$OH is widespread in Sgr A and Sgr B2. However, the line profiles of C$_2$H$_5$OH are different from those of CS, $^{13}$CO, and C$^{18}$O. This is illustrated in Figure 1 for M$=0.76\pm0.06$. The CS and the $^{13}$CO emission appears from $\approx 20$ to 120 km s$^{-1}$. However, like the SiO emission in Sgr A and Sgr B2 (Martín-Pintado et al. 2000), the C$_2$H$_5$OH emission mainly appears for radial velocities between 10 and 70 km s$^{-1}$. This indicates variations in the abundance of C$_2$H$_5$OH in the molecular clouds along the line of sight with different radial velocities. Column (4) in Table 1 gives the radial velocity...
of the peak intensity of the $J_{\text{ex, e}} = 4_1 - 3_2 \text{C}_2\text{H}_5\text{OH}$ line and the velocity range where the C$_2$H$_5$OH emission is detected.

The morphology of the C$_2$H$_5$OH emission in the GC is also different from those of CS, $^{13}$CO, and C$^{18}$O. C$_2$H$_5$OH emission is not detected toward M$-0.08 - 0.06$ in Sgr A. Furthermore, the C$_2$H$_5$OH emission shows different behavior toward the different kind of filaments in the GC. In general, the molecular clouds associated with the thermal features such as the Sickle (Serabyn & Güsten 1991; M$+0.18 - 0.04$ and M$+0.20 - 0.03$) and the TAFs E1 and E2 (Serabyn & Güsten 1987; M$+0.13 + 0.02$ and M$+0.17 + 0.01$) do not show C$_2$H$_5$OH emission. An interesting exception is the detection of C$_2$H$_5$OH emission.

**TABLE 1**

**DERIVED PHYSICAL CONDITIONS**

| Source  | $a$ (B1950) | $b$ (B1950) | $V_e$ ($V_s$, $V_p$) | $T_{ex}$ | $N(^{13}\text{CO})$ | $N(\text{CS})$ | $N(\text{eth.})$ | $[\text{CS}]$ |
|---------|-------------|-------------|---------------------|---------|-----------------|----------------|----------------|------------|
| M$-0.11 - 0.08$ | 28.0 | 62.9 | 19.8 (5, 32) | 11 | 5 | 3 | 15 | 2 | 7 | 0.4 | 4.7 | 2.2 |
| M$-0.08 - 0.06$ | 30.0 | 61.0 | 29.7 (19, 42) | 8 | 5 | 5 | 6 | 3 | 2 | 0.8 | 2.8 | 2.4 |
| M$-0.04 - 0.03$ | 29.1 | 58.1 | ($-20$, 103) | 14 | 4 | 4 | 2 | 2 | 11 | 4.7 |
| M$-0.02 - 0.01$ | 40.0 | 58.0 | 47.4 (36, 67) | 14 | 4 | 4 | 2 | 2 | 11 | 4.7 |
| M$+0.04 + 0.03$ | 26.2 | 51.8 | $30.6 (-38, -25)$ | 10 | 4 | 4 | 8 | 1 | 0.6 | 2.8 | 0.7 |
| M$+0.07 + 0.06$ | 54.2 | 53.5 | 52.8 (37, 67) | 12 | 10 | 7 | 12 | 5 | 5 | 0.6 | 3.9 | 1.1 |
| M$+0.13 + 0.02$ | 41.4 | 47.6 | ($-39$, 95) | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 | 17 |
| M$+0.17 + 0.01$ | 50.0 | 45.8 | 59.8 (52, 69) | 13 | 9 | 7 | 7 | 1 | 0.8 |
| M$+0.18 + 0.04$ | 61.0 | 47.3 | 59.9 (5, 90) | 13 | 13 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| M$+0.20 + 0.03$ | 63.6 | 45.7 | 3 (3, 100) | 19 | 19 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| M$+0.24 + 0.01$ | 59.6 | 42.6 | 34.1 (23, 53) | 12 | 10 | 8 | 10 | 4 | 8 | 0.4 | 8.4 | <1.1 |
| M$+0.59 + 0.02$ | 116.4 | 25.3 | 73.5 (50, 94) | 11 | 6 | 4 | 6 | 1 | 3 | 0.3 | 5.9 | <2.1 |
| M$+0.62 + 0.10$ | 137.0 | 26.5 | 56.5 (42, 72) | 10 | 6 | 6 | 6 | 1 | 3 | 0.3 | 5.9 | <2.1 |
| M$+0.64 + 0.08$ | 137.5 | 24.5 | 60.8 (42, 72) | 10 | 6 | 6 | 6 | 4 | 4 | 0.5 | 3.3 | <1.3 |
| M$+0.67 + 0.06$ | 137.0 | 22.5 | 50.6 (31, 78) | 10 | 10 | 3 | 14 | 2 | 3 | 0.4 | 1.9 | <1.9 |
| M$+0.68 + 0.10$ | 147.2 | 23.3 | 22.1 (0, 40) | 9 | 10 | 3 | 13 | 1 | 3 | 0.5 | 3.7 | <3.4 |
| M$+0.70 + 0.01$ | 130.0 | 19.5 | 62.2 (52, 74) | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| M$+0.70 + 0.09$ | 147.2 | 22.1 | 43.0 (29, 62) | 10 | 8 | 5 | 5 | 2 | 1.0 | 3.3 | <2.2 |
| M$+0.71 + 0.13$ | 158.4 | 22.4 | 42.0 (13, 74) | 9 | 13 | 6 | 9 | 4 | 2 | 1.2 | 2.7 | <3.1 |
| M$+0.76 + 0.05$ | 147.2 | 17.6 | 32.4 (14, 59) | 8 | 13 | 10 | 13 | 10 | 6 | 0.4 | 5.0 | <0.4 |
emission toward M+0.04+0.03, a molecular cloud located south of the TAF W1. However, the rather narrow radial velocity range of the $^{13}$CO emission as compared with those of the CS and 12CO emission (Serabyn & Güsten 1987) suggests that the bulk of the molecular gas associated with thermal features does not show $^{13}$CO emission. Mapping of the $^{13}$CO emission in this region will tell the possible association of this velocity component with the thermal features. In contrast to the lack of $^{13}$CO emission from the molecular clouds associated with the thermal features, weak $^{13}$CO emission is detected toward M+0.17+0.01 in the NTRA.

In summary, $^{13}$CO emission in the GC molecular clouds is widespread, but it shows substantial differences between the different features in the GC. Furthermore, the $^{13}$CO emission is mainly restricted to molecular clouds with radial velocities between 10 and 70 km s$^{-1}$.

3. EXCITATION AND ABUNDANCE OF C$_2$H$_5$OH IN THE GC

The lack of C$_2$H$_5$OH emission toward some molecular clouds in the GC with CS emission cannot be due to excitation effects since the $J_{4_{1,3}}-J_{3_{0,2}}$ line of C$_2$H$_5$OH and the CS $J=3-2$ line have similar critical densities. The difference between CS and C$_2$H$_5$OH emissions must be due to changes in the abundance of these molecules. The three C$_2$H$_5$OH lines can be combined to estimate the H$_2$ densities and the C$_2$H$_5$OH column densities. The excitation temperature, $T_e$, derived from the column densities of the $J_{4_{1,3}}-J_{3_{0,2}}$, and $J_{4_{1,4}}-9_{0,8}$ lines are given in column (5) of Table 1. For the sources detected in both lines, the derived $T_e$ ranges from 9 to 14 K. Considering a collisional cross section of C$_2$H$_5$OH similar to that of CH$_3$OH, the $T_e$ derived from the C$_2$H$_5$OH lines indicates H$_2$ densities of a few times $10^{4}$ cm$^{-3}$. These densities are in good agreement with those obtained from SiO and CS for the GC clouds (Martin-Pintado et al. 1997; Hüttemeister et al. 1998; Serabyn & Güsten 1987, 1991). For the other sources, the upper limits are between 8 and 13 K. In the following we will assume a $T_e$ of 7 K for these sources.

The total C$_2$H$_5$OH column densities have been derived by assuming optically thin emission and using the three substates partition function given by Pearson et al. (1997) for the $T_e$ in Table 1. Since the gauche$^+$ and gauche$^-$ torsional substates are not excited, only the trans substate has been considered. Since the C$_2$H$_5$OH profiles are, in general, different from those of CS and $^{13}$CO, in Table 1 we give two different column densities for C$_2$H$_5$OH: the first one derived for the velocity range (col. [4] in Table 1) where the C$_2$H$_5$OH line has been detected ("yes" column) and the second one the upper limit derived for the velocity range with CS and $^{13}$CO but without C$_2$H$_5$OH emission ("no" column). Table 1 also gives the column densities of $^{13}$CO and CS derived for the two velocity ranges using the typical conditions in the GC, an H$_2$ density of $3 \times 10^{4}$ cm$^{-3}$ and a kinetic temperature of $\sim 80$ K.

The ratio between CS and $^{13}$CO column densities for all sources and the two velocity ranges is fairly constant, with a value of $\sim 10^{-2}$. This indicates that the CS abundance in the GC molecular clouds is roughly constant. For the typical $^{13}$CO to H$_2$ abundance ratio in the GC of $5 \times 10^{-6}$, we derive a CS abundance of $\sim 5 \times 10^{-8}$. For this CS abundance we derive a C$_2$H$_5$OH abundance (see col. [10] of Table 1) of $(0.4-5) \times 10^{-8}$ for the clouds with C$_2$H$_5$OH emission. For the other clouds such as those associated with the thermal features, the C$_2$H$_5$OH abundance decreases by at least more than 1 order of magnitude. We conclude that large C$_2$H$_5$OH abundance of a few times $10^{-8}$ is found in most of the GC molecular clouds in the Sgr A and Sgr B2 complexes with radial velocities between 10 and 70 km s$^{-1}$ and the NTRA. However, the C$_2$H$_5$OH abundance is not uniform and drops by more than 1 order of magnitude toward some molecular clouds in both complexes and the material associated with the thermal features in the GC.

4. DISCUSSION

The widespread large abundance of C$_2$H$_5$OH in most of the GC clouds is a clear signature that large-scale grain mantle erosion is taking place in this region of the Galaxy. The abundance of C$_2$H$_5$OH in the GC clouds is even larger than those measured in the hot cores in the Galactic disk (Nummelin et al. 1998). In hot cores, the high C$_2$H$_5$OH abundance is explained by grain surface chemistry and subsequent thermal evaporation from the grains when they are heated by recently formed massive stars (Millar, Herbst, & Charnley 1991; Charnley et al. 1995). In the GC clouds, most of the dust is cold, with dust temperatures of 20–30 K (Martin-Pintado et al. 1999b; Rodríguez-Fernández et al. 2000) that are too low to evaporate the icy mantle from the grains. Further support for the association of C$_2$H$_5$OH with the cold dust comes from the low C$_2$H$_5$OH abundance measured toward the thermal features such as the Sickle that show large column densities of warm dust (Simpson et al. 1997). This is likely due to the fact that the UV photons that heat the dust also photodissociate the thermal-evaporated C$_2$H$_5$OH. Thus, thermal evaporation of grain mantles in the GC clouds does not seem to account for the measured C$_2$H$_5$OH abundance in the GC.

Shock waves are thought to dominate the heating and the chemistry of refractory elements in the GC (Wilson et al. 1982; Martin-Pintado et al. 1997; Hüttemeister et al. 1998). C$_2$H$_5$OH sputtered off the grain mantles by shock waves can explain the observed widespread large abundance of this molecule associated with the cold dust in the GC. Continuous shocks with moderate velocities of 30–40 km s$^{-1}$ can produce substantial grain processing (Flower et al. 1996; Caselli, Hartquist, & Hames 1997; Charnley & Kaufman 2000), explaining the large abundance of SiO, C$_2$H$_5$OH, and HOCO$^+$ in the GC. The picture emerging from all the molecular data is that the chemistry in the GC is largely driven by widespread shocks with moderate velocities of $\leq 40$ km s$^{-1}$.

One interesting aspect of alcohol chemistry is its transient nature (Millar, Herbst, & Charnley 1991; Charnley et al. 1995). The typical timescale for ethanol destruction after the injection into the gas phase is $\sim 10^5$ yr for the hot-core conditions (Charnley et al. 1995). For the typical H$_2$ densities in the GC clouds, 1 order of magnitude smaller than those for the hot cores, the estimated timescale for destruction of C$_2$H$_5$OH would be $\sim 10^7$ yr. This indicates that the widespread shocks that drive the chemistry in the GC have occurred in the last $\sim 10^7$ yr. Similar timescales for the shocks have been derived from the nonequilibrium H$_2$ ortho-to-par ratios in two GC clouds (Rodríguez-Fernández et al. 2000).

Several possibilities have been proposed for the origin of the widespread shocks in the GC, including shocks due to cloud-cloud collisions associated with the large-scale dynamics in the context of a bar potential (Wilson et al. 1982; Hasegawa et al. 1994; Hüttemeister et al. 1998) and shocks produced by wind-blown bubbles driven by evolved massive stars (Martin-Pintado et al. 1999a). Both mechanisms seem to account for the timescales derived from the abundance of C$_2$H$_5$OH. The timescale derived for the cloud-cloud collisions would be less...
than the galactic rotation period of ~10^6 yr (Güsten 1989). This scenario is supported by the large SiO abundances found at the outer inner Lindblad resonance in the Milky Way (Hüttemeister et al. 1998) and in NGC 253 (Garcia-Burillo et al. 2000). The wind-blown bubbles driven by evolved massive stars have typical dynamical ages of ~10^5 yr, consistent with the lifetime derived from ethanol. Furthermore, evolved massive stars also explain the correlation between the large C_2H_5OH and SiO abundance in the molecular clouds with radial velocities between 10 and 70 km s^{-1} and the Fe 6.4 keV lines (Martín-Pintado et al. 2000). However, this scenario can explain the widespread large C_2H_5OH and SiO abundance only if a burst of massive star formation has occurred in the GC ~10^7 yr ago. Large-scale mapping of the GC in molecular species dominated by a different type of chemistry will help to establish the origin of the shocks. Furthermore, the strong C_2H_5OH line intensities toward many sources in the GC make these regions ideal targets to search for the large ether molecules predicted by Charnley et al. (1995).

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