PARSEC-SCALE SiO EMISSION IN AN INFRARED DARK CLOUD

I. Jiménez-Serra1,2*, P. Caselli1, J. C. Tan3, A. K. Hernandez3, F. Fontani4, M. J. Butler3 and S. van Loo1

1 School of Physics & Astronomy, E.C. Stoner Building, University of Leeds, Leeds, LS2 9JT, UK
2 Harvard-Smithsonian Center for Astrophysics, 60 Garden St., 02138, Cambridge, MA, USA
3 Department of Astronomy, University of Florida, Gainesville, FL 32611, USA
4 Institut de Radioastronomie Millimétrique, 300 rue de la Piscine, 38406 St. Martin d’Hères, France

Accepted 1988 December 15. Received 1988 December 14; in original form 1988 October 11

ABSTRACT

We present high-sensitivity 2′×4′ maps of the J=2→1 rotational lines of SiO, CO, 13CO and C18O, observed toward the filamentary Infrared Dark Cloud (IRDC) G035.39-00.33. Single-pointing spectra of the SiO J=2→1 and J=3→2 lines toward several regions in the filament, are also reported. The SiO images reveal that SiO is widespread along the IRDC (size ≥2pc), showing two different components: one bright and compact arising from three condensations (N, E and S), and the other weak and extended along the filament. While the first component shows broad lines (linewidths of ∼4–7 km s⁻¹) in both SiO J=2→1 and SiO J=3→2, the second one is only detected in SiO J=2→1 and has narrow lines (∼0.8 km s⁻¹). The maps of CO and its isotopologues show that low-density filaments are intersecting the IRDC and appear to merge toward the densest portion of the cloud. This resembles the molecular structures predicted by flow-driven, shock-induced and magnetically-regulated cloud formation models. As in outflows associated with low-mass star formation, the excitation temperatures and fractional abundances of SiO toward N, E and S, increase with velocity from ∼6 to 40 K, and from ∼10⁻¹⁰ to ∼10⁻⁸ respectively, over a velocity range of ∼7 km s⁻¹. Since 8 µm sources, 24 µm sources and/or extended 4.5 µm emission are detected in N, E and S, broad SiO is likely produced in outflows associated with high-mass protostars. The excitation temperatures and fractional abundances of the narrow SiO lines, however, are very low (∼9 K and ∼10⁻¹¹, respectively), and consistent with the processing of interstellar grains by the passage of a shock with vₜ∼12 km s⁻¹. This emission could be generated i) by a large-scale shock, perhaps remnant of the IRDC formation process; ii) by decelerated or recently processed gas in large-scale outflows driven by 8 µm and 24 µm sources; or iii) by an undetected and widespread population of lower mass protostars. High-angular resolution observations are needed to disentangle between these three scenarios.

Key words: stars: formation — ISM: individual (G035.39-00.33) — ISM: molecules

1 INTRODUCTION

Infrared Dark Clouds (IRDCs) are high-extinction regions viewed against the diffuse mid-IR Galactic background (Pérault et al. 1996; Egan et al. 1998). These clouds are cold (T <25 K; Pillai et al. 2007) and exhibit a range of densities from n(H)=10⁷ cm⁻³ to ≥10⁷–10⁸ cm⁻³ in their clumps and cores (Leveson, Hennebelle & Pérault 2002; Butler & Tan 2004). Since these structures have masses and mass surface densities similar to regions that are known to be forming massive protostars and star clusters, they may represent the initial conditions for massive star and star cluster formation (Rathborne, Jackson & Simon 2006; Zhang et al. 2008; Ragan, Bergin & Gutermuth 2009).

It is well-known that silicon monoxide (SiO) is an excellent tracer of molecular gas processed by shocks. While SiO is heavily depleted onto dust grains in the quiescent gas of dark clouds such as L183 (upper limits of the SiO fractional abundance of ≤10⁻¹²; Ziurys, Friberg & Irvine 1989; Requena-Torres et al. 2007), this molecule is enhanced by large factors (in some cases by >10⁶) toward molecular outflows (Martín-Pintado et al. 1992). This is due to the injec-

* E-mail: i.jimenez-serra@cfa.harvard.edu
Table 1. Observed molecular transitions and line frequencies, telescope beam sizes and beam efficiencies for the EMIR and HERA receivers at the IRAM 30 m telescope.

| Transition | Frequency (MHz) | Beam size (") | Beam Eff. |
|------------|----------------|---------------|-----------|
| SiO $J=2\rightarrow1$ | 86846.96 | 28 | 0.81 |
| SiO $J=3\rightarrow2$ | 130268.61 | 19 | 0.74 |
| CO $J=2\rightarrow1$ | 230538.00 | 11 | 0.63 |
| $^{13}$CO $J=2\rightarrow1$ | 220398.68 | 11 | 0.52 |
| C$^{18}$O $J=2\rightarrow1$ | 219560.36 | 11 | 0.52 |

2 OBSERVATIONS AND RESULTS

The $J=2\rightarrow1$ lines of SiO, CO, $^{13}$CO and C$^{18}$O, were mapped with the IRAM (Instituto de Radioastronomía Millimétrica) 30 m telescope at Pico Veleta (Spain) over an area of $2' \times 4'$ toward G035.39-00.33. These observations were carried out in August 2008, and in January and February 2009. The large-scale molecular images were obtained in the On-The-Fly (OTF) mode using the offsets $(1830'',658'')$ for SiO, $^{13}$CO and C$^{18}$O, and $(4995'',2828'')$ for CO, as off-positions. The central coordinates of the map were $\alpha(J2000)=18^h 57^m 08^s$, $\delta(J2000)=02^o 10' 39''$ ($=35.51''$, b=-0.274'). The SiO $J=2\rightarrow1$ emission was mapped with the old SIS receivers, while the HERA multibeam receivers simultaneously observed the $J=2\rightarrow1$ transitions of $^{13}$CO and C$^{18}$O. The CO $J=2\rightarrow1$ emission was mapped with the new generation EMIR receivers. In addition, we carried out single-pointing observations of the SiO $J=2\rightarrow1$ and $J=3\rightarrow2$ emission with EMIR toward the offsets (0.20), (30.30), (0.80), (-10.70) and (-37.37). The former three positions correspond to the brightest SiO emission peaks observed toward the IRDC (Section 2.1). The latter two offsets show the regions where we have detected narrow SiO lines (Section 2.3). All receivers were tuned to single sideband (SSB) with rejections of $\geq10$ dB. The beam sizes were $28''$ at 90 GHz for the SiO $J=2\rightarrow1$ line, $19''$ at 130 GHz for the SiO $J=3\rightarrow2$ emission, and $11''$ at 230 GHz for the CO, $^{13}$CO and C$^{18}$O $J=2\rightarrow1$ lines. The VESPA spectrometer provided spectral resolutions of 40 and 80 kHz, which correspond to velocity resolutions of $\sim0.14$ and $0.1$ km s$^{-1}$ at 90 and 230 GHz, respectively. Saturn was used to calculate the focus, and pointing was checked every two hours on G34.3+0.2. Typical system temperatures ranged from 100 to 300 K. All intensities were calibrated in units of antenna temperature, $T_A^*$. To convert these intensities into units of main-beam temperature, $T_{mb}$, we have used efficiencies of 0.81, 0.74 and 0.63 for the EMIR data at $\sim$90, 130 and 230 GHz, and of 0.52 for the HERA data at $\sim$230 GHz. All this information is summarized in Table 1.

Figure 1 (central panel) presents the high-sensitivity map of the SiO $J=2\rightarrow1$ emission integrated from 36 to 51.5 km s$^{-1}$ (blue contours), and superimposed on the mass surface density map, with an angular resolution of $2''$, reported by Butler & Tan (2009). The SiO $J=2\rightarrow1$ map has been obtained by averaging the OTF dumps in the SiO beam of $28''$, and by using a Nyquist-sampled grid with a pixel size of $14''$. The 2$\sigma$ intensity level of SiO is shown in dashed contours. The location of the massive cores (crosses; Rathborne et al. 2006; Butler & Tan 2009), 24 $\mu$m sources (red open triangles; extracted from MIPSGAL images; Carey et al. 2009), 8 $\mu$m sources (red open circles), and 4.5 $\mu$m extended emission (green squares; called green fuzzies in Chambers et al. 2009) in this IRDC, are also shown. The flux lower limits of the $8\mu$m and $24\mu$m sources reported in Figure 4 are $\geq3.5$ mJy and $\geq2$ mJy, respectively. We note that the cavity-like structures seen around the $8\mu$m sources, are produced by the fact that the extinction mapping technique of Butler & Tan (2009) cannot be applied in the vicinity of IR-bright sources.

From Figure 1, we find that the SiO $J=2\rightarrow1$ emission is widespread across the filament with a spatial extent of $\geq150'' \times 50''$. This corresponds to $\geq2.1$ pc$\times$0.7 pc at a dis-
Figure 1. Central panel: Integrated intensity map of the SiO J=2→1 line toward G035.39-00.33 for the velocity range from 36 to 51.5 km s$^{-1}$ (blue contours), overlapped on the mass surface density map of Butler & Tan (2009, gray scale). The contour levels of the SiO emission are 10 (2σ; dashed contour), 15, 20, 30 and 40 mK km s$^{-1}$. For the mass surface density map, contours are 0.014 (2σ), 0.021, 0.035, 0.049, 0.07, 0.105 and 0.14 g cm$^{-2}$, respectively. Crosses indicate the cores reported in the cloud by Rathborne et al. (2006) and Butler & Tan (2009). Red open circles, red open triangles and green squares show the location of the 8 µm sources, 24 µm sources (Carey et al. 2009) and 4.5 µm extended emission (Chambers et al. 2009) detected in G035.39-00.33, respectively. The marker sizes used for the 8 µm and 24 µm sources, have been scaled by the source flux. Red dashed lines show the directions of the P - V diagrams of Figure 2. Red numbers indicate the distance (in arcseconds) along the cuts made for these diagrams. The SiO J=2→1 beam size is plotted at the upper right corner.

Left and right panels: Sample of spectra of SiO J=2→1 and J=3→2, and of CO, 13CO and C$^{18}$O J=2→1 lines, measured toward several positions in the IRDC. The CO, 13CO, and C$^{18}$O spectra were obtained by averaging the OTF data within the 28″-beam of the IRAM 30 m telescope at 90 GHz. The spectra of CO and of its isotopologues shown in Figure 1, have also been obtained following this procedure. From the SiO spectra, we find that SiO shows a wide variety of line profiles, from broad emission with red- and/or blue-shifted line wings [see offsets (0,20), (30, 30) and (0, 80)], to narrow lines peaking at the ambient cloud velocity $v_{LSR}$≈45 km s$^{-1}$ [offsets (10, 10), (-10, 70) and (-37, 37)]. The CO, 13CO and C$^{18}$O lines show three different velocity components centred at $v_{LSR}$≈44, 45 and 47 km s$^{-1}$ (see Section 2.3).

In Table 2 we report the observed parameters (central radial velocity, $v_{LSR}$, linewidth, $\Delta v$, and peak intensity, $T_A^*$) of the different velocity components measured in SiO J=2→1, SiO J=3→2 and C$^{18}$O J=2→1 (representative of the low-density CO gas) toward (0,20), (10,10), (30,30), (-10,70), (-37,37) and (0,80). These parameters were obtained by fitting the molecular line emission with three gaussian line profiles simultaneously. Although this method works better for the C$^{18}$O J=2→1 emission, the gaussian linewidths derived from the SiO J=2→1 line profiles provide a rough estimate of the velocity range extent and terminal velocities of the shocked SiO emission. In Table 2 we...
Table 2. Observed parameters of the SiO $J=2\rightarrow1$ and $J=3\rightarrow2$ lines, and of the $J=2\rightarrow1$ emission of C$^{18}$O, toward several offsets in IRDC G039.35-00.33.

| Molecule          | (20,20) | (10,10) | (30,30) |
|-------------------|---------|---------|---------|
|                   | $v_{LSR}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $T_A^*$ (K) | $v_{LSR}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $T_A^*$ (K) | $v_{LSR}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $T_A^*$ (K) |
| SiO(2→1)          | ~44.0   | ...     | <0.03   | 44.73(8) | 0.7(2)   | 0.07(1) | 42.9(4) | 7.0(8)   | 0.06(1) |
|                   | 45.56(6) | 1.3(2) | 0.13(1) | 45.7(1) | 0.8(3)   | 0.06(1) | 44.73(7) | 1.9(2)   | 0.12(1) |
|                   | 47.30(8) | 1.0(2) | 0.07(1) | ~46.8(2) | ...     | <0.04   | ~46.4   | ...     | <0.04   |
| SiO(3→2)          | ~43     | ...     | <0.04   | ...     | ...     | ...     | ~42.9(3) | 3(1)     | ~0.06(2) |
|                   | 45.51(1) | 1.7(4) | 0.07(1) | ...     | ...     | ...     | ~44.9(2) | 2(3)     | ~0.08(2) |
|                   | 47.8(2)  | 0.8(3) | 0.05(1) | ...     | ...     | ...     | ~46.4   | ...     | <0.05   |
| C$^{18}$O(2→1)    | 44.0(2) | 2.3(3)  | 0.34(3) | 44.500(1) | 3.0(4) | 0.25(4) | 43.1(2) | 1.7(4) | 0.08(3) |
|                   | 45.41(1) | 1.08(4) | 1.30(3) | 45.38(1) | 1.07(3) | 1.36(4) | 45.21(2) | 1.30(3) | 0.87(3) |
|                   | 46.77(2) | 1.26(5) | 0.78(3) | 46.78(8) | 1.4(1)  | 0.36(4) | 46.4(1) | 1.4(3) | 0.09(3) |
|                   | (-10,70) | ...     | ...     | (-37,37) | ...     | ...     | (-80,80) | ...     | ...     |

2.1 The broad SiO emission toward condensations N, E, and S

Figure 1 shows that the brightest SiO $J=2\rightarrow1$ and $J=3\rightarrow2$ emission in the IRDC arises from three major condensations toward (0,20) [N], (30,-30) [E] and (0,-80) [S]. The N and S condensations peak at the densest cores reported in the filament (MM7/H6 and MM6/H5; Rathborne et al. 2008; Butler & Tani 2009), and harbor not only several 8 $\mu$m and 24 $\mu$m sources, but 4.5 $\mu$m extended emission (likely related to H$_2$ shocked gas; Noriega-Crespo et al. 2004). This suggests that these condensations are active sites of star formation.

Condensation E, however, is located east of the IRDC and slightly off the high extinction region (see Figure 1). Although small amounts of gas are present, no local maxima is seen toward E in either extinction (Butler & Tani 2009), or in other high-density molecular tracers such as N$_2$H$^+$ or H$^{13}$CO$^+$ (Caselli et al. 2010, in preparation). Like N and S, several 8 $\mu$m sources are detected toward this condensation, but only one is seen at 24 $\mu$m and this is about 15$''$ north of the peak SiO position (see Figure 1). The Spitzer IRAC (3-8 $\mu$m) and MIPS 24 $\mu$m fluxes of this source are consistent with a protostellar model with a luminosity of $\sim 2 \times 10^3 L_{\odot}$, negligible circumstellar material, and a foreground extinction of $A_V \sim 15$ mag. This corresponds to a 15 M$_{\odot}$ star on the zero age main sequence (ZAMS). This is the best fit model returned from the SED fitting program of Robitaille et al. (2007). However, this result is not unique and the determination of protostellar properties from a relatively poorly constrained SED is quite uncertain. For example, the observed luminosity across the IRAC bands is only $\sim$20 L$_{\odot}$, and the above estimate of a much higher luminosity relies on the reality of the large foreground extinction. The source in condensation E could be responsible for the SiO broad feature observed toward this condensation. However, one would not expect strong outflow activity from such an evolved star. Alternatively, this source could be of much lower luminosity and mass and has more active accretion and outflow activity. There may also be other low-luminosity protostars in the vicinity, although the lack of high enough angular resolution in our SiO images prevents to establish if this is the origin of the broad SiO emission in this condensation (see below).

In Figure 2, we show the $P-V$ diagrams of the SiO $J=2\rightarrow1$ emission observed between the N and E, and the E and S condensations, for the velocity range from 40 to 50 km s$^{-1}$. Outside this velocity range, the emission of SiO $J=2\rightarrow1$ is below the 2$\sigma$ rms level in the spectra. From Figure 2, we find that the typical SiO line profiles toward condensations N, E, and S have a central component peaking at $v_{LSR} \sim 45$ km s$^{-1}$, with broader line wing emission. The linewidths of the central component are $\sim 4-7$ km s$^{-1}$, and those of the broad SiO emission are $\sim 4-7$ km s$^{-1}$ (Table 3). The blue- and red-shifted terminal velocities are $\sim 40$ and 50 km s$^{-1}$, respectively (i.e. $\pm 5$ km s$^{-1}$ with respect to the central velocity $v_{LSR} \sim 45$ km s$^{-1}$; Figure 1). While the broad SiO emission toward condensation E is blue-shifted, the SiO line wings toward N and S mainly appear at red-shifted velocities. Broad line profiles have previously been reported in SiO and other molecular species such as H$_2$CO and CH$_3$OH...
2.2 The extended and narrow SiO components

In addition to the broad SiO condensation N, E and S, the \( P-V \) diagrams of Figure 2 show that very narrow SiO emission [with linewidths of \( \leq 1 \) km s\(^{-1} \)] offset (10,10) in Figure 1 arises from regions linking these condensations. This is more clearly seen in Figure 3 (central panel), where the narrow SiO lines arising from ambient gas (at \( v_{LSR} \sim 45 \) km s\(^{-1} \)), form a large-scale and extended ridge that follows the filament. We note that the SiO emission associated with the ridge shows narrower line profiles than \(^{18}\)O \( J=2\rightarrow1 \) [0.8 km s\(^{-1} \) vs. \( \sim 1-3 \) km s\(^{-1} \); offset (10,10) in Table 2]. The peak intensity of narrow SiO toward this position is relatively weak (0.06 K; Table 2) and is at the \( \sim 5\sigma \) level (the \( \sigma_{rms} \) of the SiO \( J=2\rightarrow1 \) spectrum is 0.012 K; Figure 1).

The high-sensitivity single-pointing SiO spectra obtained with EMIR toward (-10,70) and (-37,37), also reveal that the narrow SiO component spreads north and northwest of Core MM7/H6 (Figure 1). The SiO data toward (-10,70) has been smoothed to a velocity resolution of 0.53 km s\(^{-1} \) to improve the signal-to-noise ratio of the spectrum. For the (-37,37) offset, however, we keep a velocity resolution of 0.26 km s\(^{-1} \), because the SiO line emission toward this position is a factor of 2 narrower than that reported toward (-10,70) (i.e. 0.8 km s\(^{-1} \) vs. 1.5 km s\(^{-1} \); see Table 2). The narrow SiO lines are very faint and have integrated line intensities of 0.038±0.005 K km s\(^{-1} \) and 0.030±0.005 K km s\(^{-1} \) toward (-10,70) and (-37,37), respectively. Since the SiO lines reported by Beuther & Sridharan (2007) in a sample of IRDCs have significantly larger linewidths (\( \geq 2.5 \) km s\(^{-1} \)) than those observed toward the ridge, toward (-10,70) or toward (-37,37), these lines are the narrowest features detected so far in a high-mass star forming region. The SiO \( J=3\rightarrow2 \) lines are not detected toward positions (-10,70) and (-37,37).

From the weak intensity and spatial distribution of narrow SiO, one could think that this emission could be due to some line emission contribution, within the large 30 m beam of our observations (\( \sim 28'' \)), arising from condensations N, E and S. However, the narrow SiO lines measured toward (10,10), (-10,70) and (-37,37) have profile lines different from those observed toward N, E, and S (see Figure 1) and their central radial velocities differ from those found toward these condensations. This is particularly clear toward (-10,70), where the line peak velocity of narrow SiO is redshifted by \( \sim 1 \) km s\(^{-1} \) with respect to that derived toward N. Therefore, the narrow SiO lines detected in G035.39-00.33 trace different molecular material from that seen in the SiO condensations N, E and S.

Finally, in Figure 1 we note that the narrow SiO emission toward (-10,70) and (-37,37) lies below the 2\( \sigma \) contour level of the integrated intensity SiO map. This is due to the fact that narrow SiO lines are diluted in the broad velocity range considered to create the map. In Figure 3 (central panel), the narrow SiO emission detected toward (-10,70) with the high-sensitivity EMIR receivers (Figure 1), also lies below the 3\( \sigma \) noise level of the SiO map at ambient velocities, because the observations with the old SIS receivers were not sensitive enough to detect such faint emission (see above). The narrow SiO lines toward (-10,70) are of particular interest because they do not show any clear association with a 8\( \mu \)m or a 24\( \mu \)m source. The narrow SiO emission toward several samples of IRDCs (see Carey et al. 1998; Beuther & Sridharan 2007; Leurini et al. 2007; Sakai et al. 2008), and are believed to trace material associated with molecular outflows.

The SiO \( P-V \) diagram of Figure 2 also shows that condensations N, E and S have several local maxima centered at different radial velocities. Due to the low angular resolution of our SiO observations, it is currently impossible to determine whether these maxima are produced by error fluctuations in the SiO line temperature, or whether they are associated with shocked gas high-velocity \textit{bullets}, or with different low-mass protostars (see Section 4).

The \( P-V \) diagrams of \(^{13}\)CO \( J=2\rightarrow1 \) (Figure 2) show that the terminal velocities of the \(^{13}\)CO lines are, in general, similar to those measured for SiO toward the condensations N, E and S. The \(^{18}\)O \( J=2\rightarrow1 \) emission does not reveal any significant broad line wing emission since it is mainly associated with the high-density gas seen in extinction toward G035.39-00.33 (see Section 2.3). The correlation between the CO molecular gas and the mass surface density map of Butler & Tan (2009), will be analysed in detail in the near future (Hernandez et al. 2010, in preparation).
detected toward (-37,37) is likely associated with the faint SiO condensation (intensity level of \(\sim 3\sigma\)) located at (-40,50) in the central panel of Figure 3.

2.3 The CO filaments in G035.39-00.33

The general kinematics of the low-density CO gas toward G035.39-00.33, as traced by \(^{18}\)CO \(J=2\rightarrow1\), are also shown in Figure 3. The CO gas is distributed along three different filaments with radial velocities \(v_{\text{LSR}}\approx44.1, 45.3\) and 46.6 km s\(^{-1}\). These values correspond to the averaged central radial velocities derived for every filament from the \(^{13}\)CO emission. While the central and brightest filament at \(v_{\text{LSR}}\approx45\) km s\(^{-1}\) bends east tightly following the densest material within the IRDC, the blue-shifted filament with \(v_{\text{LSR}}\approx44\) km s\(^{-1}\) intersects the former one in an arc-like structure pointing west (i.e. with the centre of curvature lying to the east of the IRDC). The two intersecting regions are coincident with the highest density cores reported in the IRDCs. 

3.1 LVG modelling and input parameters

In our LVG calculations, we have considered the first 15 rotational levels of SiO, and used the collisional coefficients of SiO with H\(_2\) derived by Turner et al. (1992) for temperatures up to \(T\approx300\) K. These collisional coefficients are well suited for our case of study, because the kinetic temperatures assumed for the SiO shocked gas in the IRDC are \(T<300\) K. As input parameters, we have considered the CMB (Cosmic Microwave Background) temperature (i.e. \(T_{\text{bg}}=2.7\) K), the linewidths of the SiO emission, and the kinetic temperature of the gas, \(T_{\text{kin}}\). The brightness temperature, \(T_B\), excitation temperature, \(T_{\text{ex}}\), and optical depth, \(\tau\), of every rotational line transition of SiO, are then calculated for a grid of models with different \(v\), (volumetric) gas densities and column densities of SiO. We note that \(T_{\text{ex}}\) may significantly differ from \(T_{\text{kin}}\), since the excitation conditions of the SiO shocked gas could be far away from the LTE (Local Thermodynamic Equilibrium).

Three different velocity regimes have been considered for the SiO emission observed in G035.39-00.33: the ambient component, which ranges from 44.5 to 45.5 km s\(^{-1}\); the moderate shocked gas, with 42.5 km s\(^{-1}\) \(< v_{\text{LSR}} < 44.5\) km s\(^{-1}\) or 45.5 km s\(^{-1}\) \(< v_{\text{LSR}} < 47.5\) km s\(^{-1}\); and the high-velocity regime, with \(v_{\text{LSR}} < 42.5\) km s\(^{-1}\) or \(v_{\text{LSR}} > 47.5\) km s\(^{-1}\).

Within every velocity regime, we perform the LVG calculations for velocity bins of 1 km s\(^{-1}\). We assume that \(T_{\text{kin}}=15\) K for the ambient component (similar to those derived in a sample of IRDCs; Pillai et al. 2007), and \(T_{\text{kin}}=25\) K and \(T_{\text{kin}}=45\) K for the moderate and high-velocity SiO gas, respectively. The latter two temperatures are consistent with those found in shocked gas of the L1448-mm outflow (Jiménez-Serra et al. 2003).

We would like to stress that the selection of these temperature regimes are expected not to be crucial in our calculations of \(N(\text{SiO})\), since the excitation of the SiO rotational lines with \(J_{\text{upp}}<5\) does not strongly depend on \(T_{\text{kin}}\) but on the H\(_2\) density of the gas (Nisini et al. 2007). Indeed, if we increase \(T_{\text{kin}}\) from 15 K to 50 K for the narrow SiO component, and from 25-45 K to 300 K for the moderate and high-velocity SiO shocked gas, the derived \(N(\text{SiO})\) change by less than a factor of 2.

The brightness temperatures, \(T_B\), derived with the LVG model for the SiO \(J=2\rightarrow1\) and \(J=3\rightarrow2\) lines, are finally compared with those observed toward G035.39-00.33, in units of \(T_{\text{mb}}\). We assume that the SiO emission is uniformly distributed and that the beam-filling factor of our SiO observations is \(\sim 1\) (only in this case \(T_B \approx T_{\text{mb}}\)). This is justified by the fact that the SiO emission is extended in the IRDC.

To derive the SiO fractional abundances, the H\(_2\) column densities were estimated from \(^{13}\)CO for the ambient gas, from \(^{12}\)CO for the moderate velocity regime, and from CO for the high-velocity gas. In contrast with the mass surface density map of Butler & Tari (2004), which gives an averaged value of the H\(_2\) column density of the gas toward a certain position, CO and its isotopologues provide estimates of the H\(_2\) column density as a function of velocity within the shock. We assume isotopic ratios \(^{12}\)C/\(^{13}\)C=53 and \(^{18}\)O/\(^{16}\)O=327 (Wilson & Rood 1994), and a CO fractional abundance of \(2\times10^{-4}\) across the IRDC. The uncertainty in the CO abundance is about a factor of two, considering its variations in different molecular cloud complexes (e.g. Frerking, Langer, & Wilson 1982) as well as within the same complex (Pineda, Caselli & Goodman 2008). The value adopted in this study is close to that directly measured towards another high mass star forming region (NGC2024; Lacy et al. 1994), which better represents the properties of IRDCs.
Figure 3. Integrated intensity maps (in units of $T_\ast^* A_{\text{km s}^{-1}}$) of the SiO $J=2\rightarrow1$ (black contours) and $^{18}$C$\text{O} J=2\rightarrow1$ lines (red contours) measured toward G035.39-00.33 from 40 to 44.5 km s$^{-1}$ (blue-shifted gas; left panel), 44.5 to 45.5 km s$^{-1}$ (ambient gas; central panel), and 45.5 to 50 km s$^{-1}$ (red-shifted gas; right panel). The mass surface density map (Butler & Tan 2009) is shown in greyscale (contour levels as in Figure 1). The contour levels of the SiO $J=2\rightarrow1$ maps are 24 (3$\sigma$), 32, 40, 48 and 56 mK km s$^{-1}$ for the blue-shifted emission, 51 (3$\sigma$), 68, 85, 102, 119 and 136 mK km s$^{-1}$ for the ambient velocity range, and 27 (3$\sigma$), 36, 45, 54, 63, 72 and 81 mK km s$^{-1}$ for the red-shifted gas. For clarity, we only plot the contours at the 5$\sigma$, 15$\sigma$ and 25$\sigma$ levels in the $^{18}$C$\text{O}$ maps, with first contours at 150, 350 and 200 mK km s$^{-1}$ for the blue-shifted (left), ambient (centre), and red-shifted (right) velocity ranges, respectively. Beam sizes of the SiO $J=2\rightarrow1$ (black circle) and $^{18}$C$\text{O} J=2\rightarrow1$ observations (filled red circle) are indicated in the upper left corner.

3.2 LVG results

The $T_{\text{ex}}$ and SiO fractional abundances, $\chi$(SiO), derived toward (-10,70), (-37,37), (0,20), (30,-30) and (0,-80) by means of the LVG approximation, are shown in Figure 5. Toward (10,10), $\chi$(SiO) was calculated assuming that $T_{\text{ex}}=9$ K [i.e. similar to those derived toward (-10,70) and (-37,37); see below] and that the SiO emission is optically thin.

For the narrow SiO emission toward (-10,70) and (-37,37), we obtain $T_{\text{ex}}\sim9$ K, optical depths $\tau$(SiO)$\leq0.01$, and SiO column densities ranging from $5\times10^{10}$ cm$^{-2}$ to $10^{11}$ cm$^{-2}$. This implies SiO fractional abundances $\chi$(SiO)$\sim6\times10^{-11}$ (Figure 5). The derived $H_2$ gas densities are $\leq6\times10^4$ cm$^{-3}$. Toward (10,10), the derived SiO fractional abundance is $\sim5\times10^{-11}$. These abundances are a factor of 10 larger than the upper limits found in dark clouds ($\leq10^{-12}$; Ziurys et al. 1989, Requena-Torres et al. 2007), and are similar to those measured from narrow SiO toward the molecular outflows in the low-mass star forming regions NGC1333 and L1448-mm (Leffloch et al. 1998, Jiménez-Serra et al. 2004).

Toward the N, E and S condensations, $T_{\text{ex}}$ and $\chi$(SiO) tend to increase from the ambient to the moderate and the high-velocity regimes (Figure 5). The typical optical depths derived for the SiO emission in these condensations are $\tau$(SiO)$\leq0.06$. The derived $H_2$ gas densities and SiO column densities range from $10^5$ cm$^{-3}$ to $10^6$ cm$^{-3}$, and from $5\times10^{10}$ cm$^{-3}$ to $4\times10^{11}$ cm$^{-3}$, respectively. For $T_{\text{ex}}$, a similar behavior for the excitation of the SiO shocked gas has been reported toward the L1157-mm and L1448-mm outflows (Nisini et al. 2007), where the SiO $J=8\rightarrow7/J=5\rightarrow4$ ratio is known to increase as a function of velocity within the shock (Nisini et al. 2007). In the case of the SiO fractional abundances, $\chi$(SiO) is progressively enhanced from $\sim10^{-10}$ in the ambient gas, to $\sim10^{-9}$ in the moderate velocity component, and to $\geq10^{-8}$ in the high-velocity shocked gas. This trend has also been observed toward the L1448-mm outflow (Jiménez-Serra et al. 2005).
3.3 Validity of the LVG approximation

As shown in Section 3.2, the typical optical depths derived for the SiO emission toward G035.39-00.33, are \( \tau(\text{SiO}) < 1 \). In molecular outflows, the SiO line emission is expected to be optically thin for ratios \( N(\text{SiO})/\Delta v < 5 \times 10^{13} \text{ cm}^{-2} \text{ km}^{-1} \text{s}^{-1} \), where \( N(\text{SiO}) \) is the derived SiO column density and \( \Delta v \), the linewidth of the SiO line profiles (Nisini et al. 2007). The derived SiO column densities, \( N(\text{SiO}) \), toward the IRDC are relatively low and range from \( 5 \times 10^{10} \text{ cm}^{-2} \) to \( 4 \times 10^{13} \text{ cm}^{-2} \) (Section 3.2). Considering that the velocity bins used in our calculations are 1 km s\(^{-1}\)-wide, the ratio \( N(\text{SiO})/\Delta v \) is \( 5 \times 10^{10} - 10^{11} \text{ cm}^{-2} \text{ km}^{-1} \text{s}^{-1} \), i.e. well below the upper limit established by Nisini et al. (2007). Therefore, the use of the LVG approximation in our case is fully justified.

4 ON THE ORIGIN OF THE PARSEC-SCALE SIO EMISSION IN G035.39-00.33

Theoretical models of flow-driven (Hennebelle & Pérault 1999; Heitsch et al. 2000, 2006; Hennebelle et al. 2008; Heitsch et al. 2009), shock-induced (Koyama & Inutsuka 2000; 2002; van Loo et al. 2007), and magnetically-regulated formation of clouds (Field & Pudritz 2000a,b), predict that these regions have a very filamentary structure at their early stages of evolution. Consistent with this idea, the filamentary IRDC G035.39-00.33 shows a relatively high number of quiescent cores (without \( H_2 \) shocked gas or 24\,$\mu$M sources), which are believed to be at a pre-stellar/cluster core phase (Chambers et al. 2004). As a consequence, one should not expect to find a significant impact of outflow interaction within the cores and on their surroundings (see e.g. Martín-Pintado et al. 1992; Beuther et al. 2002).

The high-sensitivity maps of the SiO emission toward G035.39-00.33, however, reveal for the first time that SiO is widespread along an IRDC. Large-scale SiO emission (with sizes ranging from 4 to 20\,pc) has also been reported across the molecular clouds in the Galactic Centre (Martin-Pintado et al. 1997; Amo-Baladrón et al. 2009). In this case, the origin of these lines is different from that in G035.39-00.33, because the SiO gas is highly turbulent (linewidths of \( \sim 60-90 \text{ km}^{-1} \text{s}^{-1} \)). The large SiO fractional abundances \( \sim 10^{-10} \) derived toward these regions are likely generated in fast shocks of supernova explosions, HII regions and Wolf-Rayet stellar winds (Martin-Pintado et al. 1997), and/or associated with X-ray or cosmic ray induced chemistry (Amo-Baladrón et al. 2009). Besides the GC, the large-scale SiO emission observed toward this IRDC constitutes the largest SiO feature detected so far in a star forming region.

In Section 2, we have shown that the SiO line profiles measured toward G035.39-00.33 have two different components with different spatial distributions, kinematics and excitation. The first one consists of bright and compact SiO condensations (N, E and S) with broad line profiles in both SiO \( J=2\rightarrow1 \) and \( J=3\rightarrow2 \) transitions. From our excitation and fractional abundance analysis of the SiO lines, \( T_{ex} \) and \( \chi(\text{SiO}) \) tend to progressively increase for larger velocities within the shock (from 6 to 40\,K, and from \( \sim 10^{-10} \) to \( \geq 10^{-8} \), respectively), as expected for shocked gas in molecu-
Figure 5. Excitation temperatures, $T_{\text{ex}}$ (color lines), and SiO fractional abundances, $\chi$(SiO) (symbols), derived for the ambient, moderate and high-velocity regimes (vertical dotted lines) observed toward several offsets in G035.39-00.33. We consider $v_0=45.0 \text{ km s}^{-1}$. The errors associated with $T_{\text{ex}}$ are estimated to range from 15% to 35%.

Figure 6. The SiO fractional abundances derived toward G035.39-00.33 for different velocity offsets. The error bars are estimated to range from 15% to 35%.

In the collision of two flows (Hennebelle & Pérault 1999; Heitsch et al. 2006; van Loo et al. 2007; Hennebelle et al. 2008; Heitsch et al. 2009), in G035.39-00.33, this collision could have been produced by the interaction between the main filament (as seen in the mass surface density map of Butler & Tan 2009), and the lower density filaments traced by C$^{18}$O (see Figure 3). Since the time-scales required for SiO to freeze-out onto dust grains are relatively short (i.e. from $5 \times 10^5$ yr to $5 \times 10^4$ yr for volume densities from $10^3$ to $10^5$ cm$^{-3}$; see Section 6.2 in Martín-Pintado et al. 1992), the dust grain processing event associated with this interaction would be relatively recent. The narrow feature would then constitute a signature of the filament-filament collision or of previous accretion events produced onto the main IRDC filament.

This scenario is supported not only by the extended morphology of narrow SiO, but also by the fact that the coherent CO filaments observed toward G035.39-00.33 resemble the molecular structures predicted in these models (van Loo et al. 2007; Hennebelle et al. 2008; Heitsch et al. 2009). In addition, the narrow SiO lines, specially toward the north and northeast of Core MM7/H6, do not show any clear association with 8$\mu$m or 24$\mu$m sources (Section 2.2). However, we note that the relatively small ($2-4 \text{ km s}^{-1}$) velocity difference between the CO filaments compared to the shock velocity of $\sim 12 \text{ km s}^{-1}$ required to produce the low SiO fractional abundances of $\sim 10^{-11}$, does place constraints on this scenario. This would require either that much of the relative velocity between the colliding molecular gas is in the plane of the sky or that much of the gas has already been decelerated in the interaction. Detailed comparison with the results of numerical simulations are required to assess the likelihood of these possibilities.

As proposed by Lefloch et al. (1998) for the NGC1333 low-mass star forming region, the narrow SiO emission in G035.39-00.33 could arise from decelerated shocked gas associated with large-scale outflows driven by the 8$\mu$m and 24$\mu$m sources seen in the IRDC. This gas would have been decelerated by its interaction with a dense and clumpy surrounding medium (Lefloch et al. 1998). It is also possible that narrow SiO is produced by material recently processed in the magnetic precursor of MHD shocks, as proposed for the L1448-mm outflow (Jiménez-Serra et al. 2004). This idea is similar to that suggested by Beuther & Sridhara (2007), for which narrow SiO would be linked to the youngest jet/outflow objects present in their sample of IRDCs. As discussed by these authors, narrow SiO lines are unlikely to be produced by an effect of outflow inclination with respect to the line-of-sight, because this would lead to the detection of fewer outflows with broad line emission than outflows with narrow SiO (see Section 3.2 in Beuther & Sridhara 2007). Although any of the previous mechanisms could explain the narrow SiO lines in the ridge between condensations N, E and S, it seems unlikely for offsets (-10,70) and (-37,37), where the narrow SiO lines do not show a clear association with 8$\mu$m or 24$\mu$m sources (Section 2.2).

Alternatively, the extended and narrow SiO emission toward G035.39-00.33 could be produced by a widespread and lower-mass population of protostars, compared to those powering condensations N, E and S. Some of these distributed protostars may be visible as the 8$\mu$m sources in...
Figure 1 although we do see SiO emission from regions apparently devoid of such sources. In this scenario, beam dilution would then prevent us from detecting the broad SiO line wings expected to arise from these objects. Interferometric observations are thus needed to discriminate between i) the large-scale shock scenario, remnant of the IRDC formation process; ii) decelerated or recently processed gas in the precursor of MHD shocks in large-scale outflows driven by the 8 $\mu$m and 24 $\mu$m sources; and iii) an undetected and widespread lower mass protostar population, as an origin of the widespread SiO emission in G035.39-00.33.

Extended narrow SiO emission could also be produced by the UV photo-evaporation of the mantles of dust grains in photon dominated regions (PDRs) such as the Orion bar (Schilke et al. 2001). However, this mechanism seems unlikely in G035.39-00.33, because of the relatively low luminosity of the region (it is observed as an infrared dark rather than bright cloud), and because the UV radiation field required to produce SiO fractional abundances similar to those observed in this cloud (of $\sim 10^{-11}$), should be at least few hundred times the Galactic UV field (Schilke et al. 2001). There is no evidence for sources capable of producing such an intense FUV field in this region, and even propagation of the much lower-intensity Galactic FUV radiation field into this cloud, would be strongly impeded by its high extinction. Nor are cosmic ray induced UV photons (Gredel et al. 1989) expected to play a key role in the formation of narrow SiO since the same UV field is generated in nearby quiescent dark clouds, where no SiO is detected.

In summary, we report the detection of widespread (size of $\geq 2$ pc) SiO emission toward a very filamentary IRDC. This emission presents two different components with different kinematics, excitation and spatial distributions. The compact morphology, large SiO fractional abundances, and broad SiO line profiles observed toward N, E and S, indicate that these condensations are shocked gas in outflows associated with high-mass star formation. The second SiO component is extended along the filament and shows very narrow line profiles, low SiO abundances, and lower excitation than the gas detected toward N, E and S. Although interferometric images are needed to clearly establish the origin of this emission, the properties of narrow SiO are consistent with i) a large-scale shock, remnant of the IRDC formation processes; ii) decelerated or recently shocked material in the precursor of shocks in large-scale outflows powered by 8 $\mu$m and 24 $\mu$m sources; or iii) an undetected and widespread population of lower mass protostars.

ACKNOWLEDGMENTS

We acknowledge the IRAM staff, and in particular H. Wiesemeyer, for the help provided during the observations. We also thank Prof. J. Martín-Pintado for helpful discussions on the different mechanisms that can produce widespread SiO in star forming regions, and an anonymous referee for his/her careful reading of the manuscript. J.C.T. acknowledges support from NSF CAREER grant AST-0654142. FF acknowledges support by Swiss National Science Foundation grant (PP002 – 110504). This effort/activity is supported by the European Community Framework Programme 7, Advanced Radio Astronomy in Europe, grant agreement no.: 227290.

REFERENCES

Amo-Baladrón, M. A., Martín-Pintado, J., Morris, M. R., Muno, M. P., & Rodríguez-Fernández, N. J. 2009, ApJ, 694, 943
Beuther, H., Schilke, P., Sridharan, T. K., Menten, K. M., Walmsley, C. M., & Wyrowski, F. 2002, A&A, 383, 892
Beuther, H., & Sridharan, T. K. 2007, ApJ, 668, 348
Butler, Michael J., & Tan, J. C. 2009, ApJ, 696, 484
Carey, S. J., Clark, F. O., Egan, M. P., Price, S. D., Shipman, R. F., & Kuchar, T. A. 1998, ApJ, 508, 721
Carey, S. J., et al. 2009, PASP, 121, 76
Caselli, P., Hartquist, T. W., & Haynes, O. 1997, A&A, 322, 296
Chambers, E. T., Jackson, J. M., Rathborne, J. M., & Simon, R. 2009, ApJS, 181, 360
Egan, M. P., Shipman, R. F., Price, S. D., Carey, S. J., Clark, F. O., & Cohen, M. 1998, ApJ, 494, L199
Fallscheer, C., Beuther, H., Zhang, Q., Kato, E., & Sridharan, T. K. 2009, arXiv:0907.2232
Fiege, J. D., & Pudritz, R. E. 2000, MNRAS, 311, 85
Fiege, J. D., & Pudritz, R. E. 2000, MNRAS, 311, 105
Ferking, M. A.; Langer, W. D. & Wilson, R. W. 1982, ApJ, 262, 590
Gredel, R., Lepp, S., Dalgarno, A., & Herbst, E. 1989, ApJ, 347, 289
Guillet, V., Pineau des Forêts, G., & Jones, A. P. 2007, A&A, 476, 263
Guillet, V., Jones, A. P., & Pineau des Forêts, G. 2009, A&A, 497, 145
Heitsch, F., Slyz, A. D., Devriendt, J. E. G., Hartmann, L. W., & Burkert, A. 2006, ApJ, 648, 1052
Heitsch, F., Stone, J. M., Hartmann, L. W. 2009, ApJ, 695, 248
Hennebelle, P., & Pétruit, M. 1999, A&A, 351, 309
Hennebelle, P., Banerjee, R., Vázquez-Semadeni, E., Klessen, R. S., & Audit, E. 2008, A&A, 486, L43
Jiménez-Serra, I., Martín-Pintado, J., Rodríguez-Franco, A., & Marcelino, N. 2004, ApJ, 603, L49
Jiménez-Serra, I., Martín-Pintado, J., Rodríguez-Franco, A., & Martin, S. 2005, ApJ, 627, L121
Jiménez-Serra, I., Caselli, P., Martín-Pintado, J., & Hartquist, T. W. 2008, A&A, 482, 549
Koyama H., Inutsuka S.-i., 2000, ApJ, 532, 980
Koyama H., Inutsuka S.-i., 2002, ApJ, 564, L97
Lacy, J. H., Knacke, R., Geballe, T. R., & Tokunaga, A. T. 1994, ApJ, 428, L69
Lefloch, B., Castets, A., Cernicharo, J., & Loinard, L. 1998, ApJ, 504, L109
Leurini, S., Schilke, P., Wyrowski, F., & Menten, K. M. 2007, A&A, 466, 215
Martín-Pintado, J., Bachiller, R., & Fuente, A. 1992, A&A, 254, 315
Martín-Pintado, J., de Vicente, P., Fuente, A., & Planesas, P. 1997, ApJ, 482, L45
Motte, F., Bontemps, S., Schilke, P., Schneider, N., Menten, K. M., & Broguiere, D. 2007, A&A, 476, 1243
Nisini, B., Codella, C., Giannini, T., Santiago García, J.,
Richer, J. S., Bachiller, R., & Tafalla, M. 2007, A&A, 462, 163
Noriega-Crespo, A., et al. 2004, ApJS, 154, 352
Pérault, M., et al. 1996, A&A, 315, L165
Pillai, T., Wyrowski, F., Hatchell, J., Gibb, A. G., & Thompson, M. A. 2007, A&A, 467, 207
Pineda, J. E., Caselli, P., & Goodman, A. A. 2008, ApJ, 679, 481
Ragan, S. E., Bergin, E. A., Gutermuth, R. A. 2009, ApJ, 698, 324
Rathborne, J. M., Jackson, J. M., & Simon, R. 2006, ApJ, 641, 389
Requena-Torres, M. A., Marcelino, N., Jiménez-Serra, I., Martín-Pintado, J., Martín, S., & Mauersberger, R. 2007, ApJ, 655, L37
Robitaille, T. P., Whitney, B. A., Indebetouw, R., & Wood, K. 2007, ApJS, 169, 328
Sakai, T., Sakai, N., Kamegai, K., Hirota, T., Yamaguchi, N., Shiba, S., & Yamamoto, S. 2008, ApJ, 678, 1049
Schilke, P., Walmsley, C. M., Pineau des Forêts, G., & Flower, D. R. 1997, A&A, 321, 293
Schilke, P., Pineau des Forêts, G., Walmsley, C. M., & Martin-Pintado, J. 2001, A&A, 372, 291
Su, Y.-N., Liu, S.-Y., Chen, H.-R., Zhang, Q., & Cesaroni, R. 2007, ApJ, 671, 571
Teyssier, D., Hennebelle, P., & Péralt, M. 2002, A&A, 382, 624
Turner, B. E., Chan, K.-W., Green, S., & Lubowich, D. A. 1992, ApJ, 399, 114
van Loo S., Falle S. A. E. G., Hartquist T. W., Moore T. J. T., 2007, A&A, 471, 213
Wilson, T. L., & Rood, R. 1994, ARA&A, 32, 191
Zhang, Q., Wang, Y., Pillai, T., & Rathborne, J. 2009, ApJ, 696, 268
Ziurys, L. M., Friberg, P., & Irvine, W. M. 1989, ApJ, 343, 301