The L 1157 protostellar outflow imaged with the Submillimeter Array[★]

A. I. Gómez-Ruiz^{1,2,★★}, N. Hirano³, S. Leurini², and S.-Y. Liu³

¹ INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
 e-mail: arturogr@arcetri.astro.it

² Max-Planck-Institut für Radioastronomie (MPIfR), Auf dem Hügel 69, 53121 Bonn, Germany

³ Academia Sinica, Institute of Astronomy & Astrophysics, PO Box 23–141, 106 Taipei, Taiwan

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ABSTRACT

Context. The outflow driven by the class 0 low-mass protostar L1157-mm stands out because of its peculiar chemical richness. However, its complex spatial/velocity structure makes it difficult to interpret observations of different molecular tracers.

Aims. We aim to map at high spatial resolution different molecular tracers that are important tools for studying shocks and/or thermal-density structures in outflows.

Methods. We used the Submillimeter Array at 1.4 mm to observe the blue lobe of the L1157 outflow at high spatial resolution ($\sim 3''$).

Results. We detected SiO, H₂CO, and CH₃OH lines from several molecular clumps that constitute the outflow. All three molecules were detected along the wall of the inner cavity that is thought to be related to the later ejection event. On the other hand, no emission was detected toward positions related to an old ejection episode, which is very likely due to space filtering from the interferometer. The H₂CO and CH₃OH emission is detected only at velocities close to the systemic velocity. The spatial distributions of the H₂CO and CH₃OH are similar. These emission lines trace the U-shaped structure seen in the mid-infrared image. In contrast, the SiO emission is detected in a wider velocity range with a peak at $\sim 14 \text{ km s}^{-1}$ blueshifted from the systemic velocity. The SiO emission is brightest at the B1 position, which corresponds to the apex of the U-shaped structure. There are two compact SiO clumps along the faint arc-like feature to the east of the U-shaped structure. At the B1 position, there are two velocity components; one is a compact clump with a size of $\sim 1500 \text{ AU}$ seen at high velocity, the other is an extended component with lower velocities. The kinematic structure at the B1 position is different from that expected in a single bow shock. Most likely the high-velocity SiO clump at the B1 position is kinetically independent of the low-velocity gas. The line ratio between SiO (5–4) and SiO (2–1) suggests that the high-velocity SiO clumps consist of high-density gas of $n \sim 10^5\text{--}10^6 \text{ cm}^{-3}$, which is similar to the density of the bullets in extremely high velocity (EHV) jets. The high-velocity SiO clumps in L1157 probably have the same origin as the EHV bullets.

Key words. shock waves – ISM: jets and outflows – stars: formation – ISM: individual objects: L1157

1. Introduction

There is now increasing evidence that extremely young outflows driven by class 0 low-mass protostars interact with surrounding ambient gas and produce strong shock waves. One prototypical and well-studied example of an outflow with strong shocks is the well-collimated bipolar outflow driven by the class 0 source of $L_{\text{bol}} \sim 11 L_{\odot}$, IRAS 20386+6751, in the L1157 dark cloud at 440 pc from the Sun, also known as L1157-mm (e.g., Umemoto et al. 1992; Gueth et al. 1997). This outflow has been extensively studied with various molecular lines. The spatial-kinematic structure of the CO (1–0) was reproduced by a model of two limb-brightened cavities with slightly different axes (Gueth et al. 1996). The locations of the two cavities are indicated by the yellow and green lines in Fig. 1. At the tips of these two cavities, labeled B2 and B1, respectively, strong SiO and NH₃ (3, 3) emission lines, which are considered to be

good tracers of shocked molecular gas, are observed (Gueth et al. 1998; Zhang et al. 1995, 2000; Tafalla & Bachiller 1995). Based on observations of the highly excited (J, K) = (5, 5) and (6, 6) NH₃ emission lines, as well as on the CO (6–5), (3–2), and (1–0) lines, the gas kinetic temperature in the shocked region at the B1 position was estimated to be $\sim 170 \text{ K}$, which is a factor of ~ 10 higher than that of the quiescent gas (Umemoto et al. 1999; Hirano & Taniguchi 2001). A remarkable correlation between the kinetic temperature and velocity dispersion of the CO $J = 3\text{--}2$ emission along the lobe suggests that the molecular gas at the head of the bow-shock is indeed heated kinetically (Hirano & Taniguchi 2001).

In the shocked region, where the gas is significantly heated and compressed, various chemical reactions that cannot proceed in the cold and quiescent dark clouds are expected to be triggered. Bachiller & Perez Gutierrez (1997) and Bachiller et al. (2001) surveyed molecular lines in the L1157 outflow and found that molecules such as SiO, CH₃OH, H₂CO, HCN, CN, SO, and SO₂ are enhanced by at least an order of magnitude at the shocked region. In the blue lobe, molecular lines such as SiO, CH₃OH, and H₂CO mainly come from three regions labeled B2, B1, and B0 (Fig. 1). Furthermore, the spatial distributions of these shock-enhanced molecules differ from species to species;

[★] The molecular line maps in Figs. 4 and 8 as FITS files are available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/558/A94>

^{★★} Member of the International Max-Planck Research School for Astronomy and Astrophysics at the Universities of Bonn and Cologne.

Fig. 1. Half-power primary beams of the four fields observed with the SMA (circles) superposed on the integrated CO (1–0) emission in grayscale and the SiO (2–1) emission as white contours (from Gueth et al. 1998). The cross indicates the position of the protostar L1157-mm, $\alpha = 20^{\text{h}}39^{\text{m}}06.19^{\text{s}}$, $\delta = 68^{\circ}02'15''.9$ (J2000.0) given by Gueth et al. (1997). The bottom-right corner shows the HPBW of the Gueth et al. (1998) observations. Yellow and green ellipses indicate the location of the two cavities proposed by Gueth et al. (1997).

the SiO is remarkably enhanced at the B1 position, the CH₃OH is equally enhanced at both B1 and B2, whereas HCO⁺ and CN are enhanced in the region between the driving source and B1. This suggests that there is a stratification in the chemical composition of the shocked gas.

Millimeter-interferometric observations by Benedettini et al. (2007) have resolved each emission structure (B0, B1, and B2) into a group of smaller-scale clumps with a size of 0.02–0.04 pc. In addition, each emission structure also has its internal chemical stratification. At the B1 position, the HC₃N, HCN, CS, NH₃, and SiO lines are brighter in the eastern clumps, while the CH₃OH, OCS, and ³⁴SO lines are brighter in the western clumps. Interferometric observations have also suggested a temperature stratification within the B1 position, with the highest temperatures found toward the apex of the B1 bow-shock (Codella et al. 2009).

Understanding the internal structure of the shocks in L1157 outflow is of particular interest in the context of current chemical studies that are undertaken using several facilities to investigate this remarkable object, for example the *Herschel* key-program observations (Codella et al. 2010; Lefloch et al. 2010). To study the spatial and kinematic structure of the shocked gas at high

Table 1. List of the detected transitions.

Transition	Rest frequency GHz	E_u K	Vel. range km s ⁻¹
SiO (5–4)	217.10498	31.3	–16.7 to +4.1
H ₂ CO 3(0, 3)–2(0, 2)	218.22218	21.0	–3.7 to +4.1
H ₂ CO 3(2, 2)–2(2, 1)	218.47561	68.1	–1.1 to +4.1
CH ₃ OH 4(2, 2)–3(1, 2)E	218.44000	37.6	–3.7 to +1.5

angular resolution, we have mapped the blue lobe of the L1157 outflow at 1.4 mm using the Submillimeter Array (SMA).

2. Observations

2.1. SMA observations

The observations were carried out on 2004 August 10 with the SMA¹ on Mauna Kea, Hawaii (Ho et al. 2004). We used the compact-north configuration that provided baselines ranging from 12.9 m to 109.5 m. The primary-beam size (HPBW) of the 6-m diameter antennas at 217 GHz was measured to be $\sim 54''$. The entire region of the southern blue lobe was covered by four pointings separated by $30''$ (Fig. 1). The spectral correlator covers 2 GHz bandwidth in each of the two sidebands separated by 10 GHz. The frequency coverage ranged from 216.6 to 218.6 GHz in the lower sideband (LSB) and from 226.6 to 228.6 GHz in the upper sideband (USB). Each band was divided into 24 “chunks” of 104 MHz width. We used a uniform spectral resolution of 406.25 kHz across an entire 2 GHz band. The corresponding velocity resolution was 0.561 km s⁻¹. The visibility data were calibrated using the MIR software package, which was originally developed for Owens Valley Radio Observatory (Scoville et al. 1993) and adapted for the SMA². The absolute flux density scale was determined from observations of Uranus. A pair of nearby compact radio sources, 1927+739 and 1806+698, were used to calibrate relative amplitude and phase. We used Uranus to calibrate the bandpass.

The calibrated visibility data were imaged using MIRIAD, followed by a nonlinear joint deconvolution using the CLEAN-based algorithm, MOSSDI (Sault et al. 1996). We used natural weighting, which provided a synthesized beam of $3''.4 \times 2''.3$ with a position angle of 63° . The rms noise level of the line data was 265 mJy beam⁻¹ at 1.3 km s⁻¹ spectral resolution. Four molecular lines, SiO(5–4), CH₃OH 4(2, 2)–3(1, 2)E, H₂CO 3(0, 3)–2(0, 2), and H₂CO 3(2, 2)–2(2, 1) were detected above a 4σ level (see Table 1). All these lines were in the LSB, while no significant lines were detected in the USB. The continuum map was obtained by averaging the line-free chunks of the two sidebands. To improve the signal-to-noise ratio, the upper and lower sidebands were combined after the consistency of the images of two sidebands was confirmed. With natural weighting, the synthesized beam size was $3''.4 \times 2''.2$ with a position angle of 63° . The rms noise level of the 1.4 mm continuum map was 4.82 mJy beam⁻¹.

2.2. Spitzer/IRAC observations

Archival data of all four IRAC bands (3.6 μm , 4.5 μm , 5.8 μm , and 8.0 μm) were retrieved from the *Spitzer* data base through

¹ The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica.

² <http://cfa-www.harvard.edu/~cqi/mircook.html>

Fig. 2. 1.4 mm continuum emission from L1157-mm. The first contour and the contour spacing is 3σ ($\sigma = 4.82 \text{ mJy beam}^{-1}$), with the highest contour at 27σ . The black ellipse shows the synthesized beam size (natural weighting). The parameters of the Gaussian fit to this image are presented in Table 2.

Table 2. Parameters of the 1.4 mm continuum source.

Peak intensity (Jy/beam)	0.13 ± 0.01
Total integrated flux (Jy)	0.21
RA (J2000)	$20^{\text{h}}39^{\text{m}}06.24^{\text{s}}$
Dec (J2000)	$68^{\circ}02'15.8''$
Deconvolved major axis (arcsec)	2.7
Deconvolved minor axis (arcsec)	1.4
Deconvolved position angle (degrees)	88 ± 4

Leopard. We used the post-basic calibrated data (BCD) images for our analysis. The mean full width at half maximum of the point-response functions are $1''.66$, $1''.72$, $1''.88$, and $1''.98$ for bands 1, 2, 3, and 4, respectively. The details of the IRAC observations of L1157 are described in Looney et al. (2007).

3. Results

3.1. Millimeter continuum emission

The continuum emission map is shown in Fig. 2. The continuum emission from the central source was detected at a level of $\sim 27\sigma$. The parameters of the continuum source, obtained through an elliptical Gaussian fit, are listed in Table 2. The beam-deconvolved size of the source is $2.7'' \times 1.4''$ ($1200 \times 600 \text{ AU}$) with a position angle of 88° . Previous observations at the same wavelength have been presented by Beltrán et al. (2004) and Jørgensen et al. (2007). However, a comparison with these previous works is not always straightforward because of the different uv-coverage of the observations. The continuum map of Beltrán et al. (2004), shows a spatially extended component with a size of $\sim 8''$ around the compact component. On the other hand, the spatially extended component is not clearly detectable in our map. This is probably because our map does not include the short-spacing data, which were added to the map of Beltrán et al. (2004).

3.2. Mid-IR emission from the shocked gas

The detailed analysis by Takami et al. (2010) has shown that the mid-infrared (mid-IR) emission from this outflow is well explained by thermal H_2 emission excited by shocks. Figure 2

shows a three color image of IRAC bands 1, 2, and 4 of the blue lobe of the L1157 outflow together with contours of the SiO (5–4) emission, which is described in the next section. The mid-IR emission delineates a U-shaped structure with an apex near the position of B1. The eastern and western walls of the U-shaped structure are connected by an emission ridge. To the east of the U-shaped structure there is another fainter arc-like feature. The mid-IR emission from the B2 position is much fainter than that of the B1 position.

The U-shaped structure in the mid-IR is confined inside the CO (1–0) cavity whose tip is B1. The blurred emission at B2 also has its counterpart in the CO (1–0) map. The location of the arc-like feature coincides with that of the B0 position. A comparison between the images of mid-IR and CO (1–0) implies that the arc-like feature corresponds to the eastern wall of the outer cavity produced by the B2 shock.

The difference in the mid-IR color is considered to be due to the different excitation conditions (Takami et al. 2010). The mid-IR emission at the B2 position and the arc-like feature is dominated by the longer wavelength component seen in red excess. This suggest that the excitation of the H_2 molecule at these two regions is low because of the lower temperature and/or density. This is indeed confirmed by H_2 rotational line studies: the temperature derived from the H_2 line is lower than 300 K toward the arc-like feature, which is significantly lower than 1400 K at the tip of the U-shaped structure (Nisini et al. 2010).

3.3. Molecular line emission observed with the SMA

3.3.1. SiO (5–4)

The SiO 5–4 emission was detected in the velocity range from -16.7 km s^{-1} to $+4.1 \text{ km s}^{-1}$. Most of the SiO 5–4 emission observed with the SMA is blueshifted with respect to the cloud systemic velocity (V_{sys}) of $V_{\text{LSR}} \sim +2.7 \text{ km s}^{-1}$. The total integrated intensity map is shown in Fig. 3, and velocity channel maps at 2.6 km s^{-1} intervals are presented in Fig. 4. The total integrated intensity map shows that the SiO (5–4) emission is brightest at the B1 position, which corresponds to the apex of the U-shaped structure seen in the mid-IR. There are two compact SiO clumps along the faint arc-like feature to the east of the B0 position. Notably, no significant emission was detected at the position of B2, although the SiO (5–4) emission at this position was detected in the single-dish telescope observations of Bachiller et al. (2001). Our observations with the shortest projected baseline of $9.3 \text{ k}\lambda$ were not able to recover structures larger than $\sim 27''$, while the emission component at the B2 position in the single-dish map is extended to more than $20''$. Furthermore, the rms noise level of our map is $\sim 4.6 \text{ K km s}^{-1}$, which is not sensitive enough to detect the SiO (5–4) emission at the B2 position, whose peak intensity is $\sim 6 \text{ K km s}^{-1}$ in the single-dish map. Therefore this indicates that the SiO (5–4) emission from the B2 position is spatially extended with low surface brightness and thus filtered out in our data.

The velocity-channel maps reveals that the most prominent clump at the B1 position appears in the velocity channels from -15.4 km s^{-1} to -7.6 km s^{-1} (the corresponding velocity offset from V_{sys} is -18.1 km s^{-1} to -10.3 km s^{-1}). On the other hand, the SiO (5–4) emission from the B1 position is more extended in the channels of -2.4 km s^{-1} and 0.2 km s^{-1} (the velocity offset is from -5.1 km s^{-1} to -2.5 km s^{-1}). In Fig. 5, we display the spatial distributions of the SiO emission in the velocity ranges from -16.7 km s^{-1} to -6.3 km s^{-1} and from -6.3

Fig. 3. Overlay of SiO (5–4)-integrated emission (integrated from -16.7 to $+4.1$ km s^{-1} ; magenta contours) and IRAC three color image (blue: 3.6 μm , green: 4.5 μm , red: 8.0 μm). White and cyan dashed lines indicate the arc-like feature and the U-shaped structure, respectively, delineated by the mid-IR emission. SiO contours start at 3σ ($\sigma = 1.40$ $\text{Jy beam}^{-1} \text{ km s}^{-1}$) and are then separated by steps of 1σ .

to $+4.1$ km s^{-1} . In these maps, all SiO clumps detected above the 4-sigma level are labeled. The clumps B0d and B0g are visible only at the V_{LSR} of -2.4 km s^{-1} in the channel maps. Therefore, these clumps are labeled in Fig. 4. In Table 3 we list the clumps and their positions obtained by a two-dimensional Gaussian fit. The list of clumps is shown in decreasing order of declination. We used the same notation as Benedettini et al. (2007) when our clumps were coincident within $4''$ of their positions. Otherwise we named the clumps by following the sequence of letters for either B0 or B1. All clump positions reported in Table 3 are summarized graphically in Fig. 6. Three clumps shown in the map of the total integrated intensity (Fig. 3) appear in the high-velocity range (labeled B0f, B0i, and B1a). In the low-velocity range, the most prominent feature is the C-shaped structure that consist of three clumps labeled B1c, B1g, and B1h. This C-shaped feature surrounds the brightest clump B1a seen in the high-velocity range.

The SiO (5–4) emission from the B1 position was also observed by Gueth et al. (1998) using the PdBI with a similar angular resolution ($3.4'' \times 2.9''$). The overall features observed with the SMA at the B1 position are consistent with those of the PdBI map. The SMA and PdBI maps show a compact clump in the velocity channels of -10.2 and -12.8 km s^{-1} and the spatially extended feature in the lower velocity channels. In particular, the SMA and PdBI maps agree well in the peak flux of the compact component (B1a) at the $V_{\text{LSR}} = -12.8$ km s^{-1} channel (~ 1.5 Jy beam^{-1}), although B1a was located outside of the primary beam of the PdBI. In the low-velocity channels, the SMA map does not show the linear structure ahead of B1c. This is probably because the surface brightness of this linear feature (~ 300 mJy beam^{-1}) is lower than our detection limit ($3\sigma = 570$ mJy beam^{-1}). The B1c clump in the PdBI map is more extended to the west than the same component in the SMA map. Since the surface brightness of the extended part is beyond our detection limit, the SMA probably was unable to detect the western part of B1c because of the limited $u-v$ sampling.

A number of observations have proven the particular chemical richness of the B1 position in L1157. Thus, the physical characterization at this position is important to account for kinematic effects in the chemical models that aim to explain the emission from different molecular species (e.g. Viti et al. 2011). Therefore, most of the analysis of the SiO emission presented in the following sections are mainly focused on the B1 position. With the aim of estimating the missing flux at the B1 position, we compared the single-dish spectrum taken with the IRAM-30 m (provided by M. Tafalla) with our SMA spectrum convolved to the same angular resolution ($11''$). As shown in Fig. 7, the single-dish spectrum in B1 peaks at $V_{\text{LSR}} \sim -2$ km s^{-1} . On the other hand, the spectrum obtained with the SMA peaks at $V_{\text{LSR}} \sim -11$ km s^{-1} , which is also seen as a bump in the single-dish spectrum. It is found that the SiO flux recovered by the SMA was only $\sim 10\%$ in the velocity range from -10.3 to $+2.6$ km s^{-1} , suggesting that most of the SiO emission in this velocity range comes from a spatially extended region and is filtered out in the current SMA map. In contrast, the SMA recovered up to $\sim 80\%$ of the SiO flux in the velocity range from -16.0 to -10.8 km s^{-1} . This implies that most of the SiO emission in this velocity range arises from the compact clump, B1a. Therefore, our SMA observations peaks at -11 km s^{-1} instead of ~ -2 km s^{-1} , as the IRAM-30 m observations, because most of the low-velocity emission is filtered out in the SMA map.

3.3.2. H_2CO and CH_3OH

Two formaldehyde (H_2CO) lines were detected in the LSB (see Table 1). The H_2CO $3(0, 3)-2(0, 2)$ line was detected in the velocity range from -3.7 km s^{-1} to $+4.1$ km s^{-1} , while the H_2CO $3(2, 2)-2(2, 1)$ line was detected from -1.1 to $+4.1$ km s^{-1} . In Fig. 8a and b we show the total integrated emission of the two H_2CO transitions overlaid on the IRAC 4.5 μm emission. To improve the sensitivity, we convolved both maps to $5'' \times 5''$. As for SiO, there is no significant H_2CO emission from B2 position. The spatial distribution of the H_2CO $3(0, 3)-2(0, 2)$ emission is similar to that of the H_2CO $3(2, 2)-2(2, 1)$, except for the elongated structure along the eastern wall that is barely seen in the H_2CO $3(2, 2)-2(2, 1)$. The energy level in the upper state of the H_2CO $3(0, 3)-2(0, 2)$ transition is 21 K, while for the H_2CO $3(2, 2)-2(2, 1)$ it is 68 K. Therefore, difference in the spatial distribution between the two transitions of H_2CO

Fig. 4. SiO (5–4) emission (contours) in channel maps of 2.6 km s^{-1} width, overlaid on the $4.5 \mu\text{m}$ emission from *Spitzer*/IRAC. SiO contours start at 3σ ($\sigma = 0.188 \text{ Jy beam}^{-1}$) and are then separated by steps of 1σ up to a value of 8σ . The central velocity of each channel map is indicated in the upper left corner, while the ellipse in the lower right corner shows the synthesized beam.

suggests that the excitation of the elongated structure in the eastern wall is lower than that of the B0d clump.

The H_2CO emission clumps detected above the 4σ level are labeled in Fig. 8, and their positions are listed in Table 3 (see also Fig. 6 for the distribution of all the clumps reported in Table 3). We again used the same notation as Benedettini et al. (2007) and Codella et al. (2009) when our clumps were coincident within $4''$ of their positions, otherwise we defined the new clumps in the same way as we adopted for the SiO clumps. As shown in Figs. 8a and 9, an elongated H_2CO $3(0, 3) \rightarrow 2(0, 2)$ emission feature clearly traces the eastern wall (clumps B0g and B0h) of the mid-IR U-shaped structure. A similar elongated feature was also seen in the HC_3N (11–10) map of Benedettini et al. (2007) and in the CH_3CN map of Codella et al. (2009). The brightest H_2CO emission component is seen in the western wall. This component is probably the counterpart of the B0d clump seen in the HCN (1–0) and CH_3OH ($2_K - 1_K$) maps of Benedettini et al. (2007). The H_2CO clump at $\sim 15''$ northwest of B0d is considered to be the counterpart of the B0b clump in the CH_3OH ($2_K - 1_K$).

The CH_3OH $4(2, 2) \rightarrow 3(1, 2)\text{E}$ line emission was found in the velocity range from $\sim -3.7 \text{ km s}^{-1}$ to $+1.5 \text{ km s}^{-1}$. The CH_3OH total integrated intensity map shown in Fig. 8c was also convolved to the $5'' \times 5''$ resolution to improve the signal-to-noise ratio. The overall distribution of the CH_3OH $4(2, 2) \rightarrow 3(1, 2)\text{E}$ emission is similar to that of the H_2CO $3(2, 2) \rightarrow 2(2, 1)$. The CH_3OH emission is brightest in the B0d clump, but also shows emission at B0h and B1f. No CH_3OH emission was detected at the B2 position. The clumps detected above the 4σ level in the CH_3OH $4(2, 2) \rightarrow 3(1, 2)\text{E}$ line are also listed in Table 3 (see also Fig. 6 for the distribution of all the clumps reported in Table 3).

Using the line ratio between the SiO (5–4) and the SiO (2–1) observed by Zhang et al. (2000) with a synthesized beam of $9'.5 \times 8'.0$, we derived the physical conditions of the gas in the high-velocity clumps. For our analysis we selected the portion of the high-velocity range that is less affected by the missing

flux. The analysis was performed at the B0i and B1a positions, at which the SiO (5–4) emission was detected above the 5σ level. We note that an analysis using several SiO lines observed with a single-dish telescope has been made by Nisini et al. (2007). However, they used single-pointing observations, which means that the data were taken with different beam sizes, for instance $\sim 27''$ for SiO (2–1) and $\sim 11''$ for SiO (5–4). In addition, the line ratios used the total integrated intensity, including the low-velocity component, whereas we used higher-resolution data and focused on the high-velocity component.

Since the interferometric SiO (2–1) observations agreed to better than 20% with the single-dish results, Zhang et al. (2000) concluded that most of the SiO (2–1) flux was recovered with the interferometer. Therefore we did not take into account the effect of the missing flux in this transition. Our SiO (5–4) observations were convolved to the angular resolution of the SiO (2–1) data (i.e. $9'.5 \times 8'.0$). In Fig. 10 we show the SiO (5–4) and (2–1) spectra at the position of clumps B0i and B1a in a brightness-temperature scale. The portion of the high-velocity range in which most of the single-dish SiO (5–4) emission at the B1a position is recovered by our SMA observations is -16.0 to -10.8 km s^{-1} . We assumed the velocity range for the B0i clump to be the same as that of the B1a clump. The linewidth was assumed to be 5 km s^{-1} for both B1a and B0i. Since smoothing the SMA maps to $\sim 9''$ beam averaged the emission of adjacent clumps, the spectrum at B1a includes the emission from B1g, B1h, B1c, and B1f. However, the emission from adjacent clumps appears only in the low-velocity range and does not affect the analysis. The integrated line intensities of SiO (2–1) and (5–4) in this velocity range are 1.5 ± 0.6 and $1.5 \pm 0.1 \text{ K km s}^{-1}$ at B0i, and 7.7 ± 0.6 and $4.4 \pm 0.1 \text{ K km s}^{-1}$ at B1a. The derived (2–1)/(5–4) ratios are therefore 1.0 ± 0.4 for B0i and 1.7 ± 0.1 for B1a.

We used the non-local thermodynamic equilibrium program RADEX (van der Tak et al. 2007) in the low-velocity gas (LVG) approximation and plane-parallel geometry to model

Fig. 5. SiO(5–4) emission in the blue lobe of the L1157 outflow integrated in two velocity ranges. The high-velocity range (*left panel*) is integrated from -16.7 to -6.3 km s^{-1} , the low-velocity range (*right panel*) from -6.3 to $+4.1$ km s^{-1} . The velocity range is indicated in the upper left corner of each panel. Contours start at 3σ and are then separated by steps of 1σ ($\sigma = 0.985$ $\text{Jy beam}^{-1} \text{ km s}^{-1}$). The grayscale represents the 4.5 μm emission from *Spitzer*/IRAC.

Table 3. Clump positions.

Clump	RA J2000	Dec J2000	Molecular tracer ^a		
			SiO	H ₂ CO	CH ₃ OH
B0b*	20:39:05.5	68:01:40	N	Y	N
B0f	20:39:10.9	68:01:40	Y	N	N
B0g	20:39:09.8	68:01:39	Y	Y	N
B0d*	20:39:07.9	68:01:30	Y	Y	Y
B0h	20:39:10.4	68:01:27	N	Y	Y
B0i	20:39:11.5	68:01:27	Y	N	N
B0j	20:39:07.7	68:01:22	Y	N	N
B1g	20:39:10.3	68:01:13	Y	N	N
B1f*	20:39:09.0	68:01:13	N	N	Y
B1a*	20:39:10.0	68:01:12	Y	Y	Y
B1h	20:39:10.6	68:01:11	Y	N	N
B1c*	20:39:09.9	68:01:06	Y	N	N

Notes. (^a) Detections above 4σ are marked Y, non-detections are marked N. (^{*}) Reported also by [Benedettini et al. \(2007\)](#). (⁺) Reported also by [Codella et al. \(2009\)](#).

Fig. 6. Summary of all the clumps found in the SiO, H₂CO, and CH₃OH transitions reported in this paper. The crosses indicate the positions reported in Table 3, overlaid on the 4.5 μm emission.

the (2–1)/(5–4) ratios. Using the RADEX offline distribution³, we estimated the kinetic temperature (T_{kin}) and/or the volume density (n) from the observed line ratio. The input parameters were the background radiation field (the CMB temperature of 2.73 K) and the line width (5 km s^{-1}). To constrain the SiO column density, $N(\text{SiO})$, we used the observed integrated line intensity of the SiO (5–4) emission (1.5 and 4.4 K km s^{-1} for B0i and B1a, respectively). Then, by running the LVG for different $N(\text{SiO})$, we found the best $N(\text{SiO})$ that matches better the SiO (5–4) brightness temperature and the (2–1)/(5–4) ratio.

In Fig. 11 we show the LVG results for the two cases of interest. The LVG results (Fig. 11) show that the (2–1)/(5–4) ratio depends on the density and is less sensitive to the temperature if the density is lower than $10^{6.5} \text{ cm}^{-3}$. On the other hand, the (2–1)/(5–4) ratio becomes sensitive to the temperature if the density is higher than $10^{6.5} \text{ cm}^{-3}$. We found that the observed ratios yield similar solutions for the two positions, with a density of $n \sim 10^5$ to 10^6 cm^{-3} . Although the uncertainties on the line intensity and ratio are larger at B0i, these uncertainties do not affect the solution significantly (less than a factor of three). It should be noted that the $N(\text{SiO})$ at B1a is twice as high as that at B0i. The density obtained here is similar to the $3 \times 10^5 \text{ cm}^{-3}$ derived by [Nisini et al. \(2007\)](#) as an averaged density that included the low-velocity component. Nisini et al. also found that the physical parameters of the high-velocity component are different from those averaged over all the emitting

Fig. 7. SiO (5–4) spectra at the B1 position observed by IRAM 30 m telescope (thin solid line) and the SMA (dashed line). The cloud velocity is indicated by a thick vertical line ($V_{\text{LSR}} = 2.7 \text{ km s}^{-1}$). The SMA observations were convolved to the $11''$ resolution to match the beam of the IRAM 30 m telescope. The spectral resolution is 1.3 km s^{-1} in both cases.

gas; the (8–7)/(5–4) ratio at $V_{\text{LSR}} \sim -15 \text{ km s}^{-1}$ required either a higher density of $\sim 5 \times 10^6 \text{ cm}^{-3}$ or a higher temperature of $T_K > 500 \text{ K}$. Although our results do not support the high density of $>10^{6.5} \text{ cm}^{-3}$, they do not exclude the high-temperature solution. The kinetic temperatures derived from other warm gas

³ <http://www.sron.rug.nl/~vdtak/radex/>

Fig. 8. Total integrated emission (see Table 1 for the velocity ranges) of the **a)** H_2CO 3(0, 3)–2(0, 2); **b)** H_2CO 3(2, 2)–2(2, 1), and **c)** CH_3OH 4(2, 2)–3(1, 2)E transitions. In all panels, contours start at 3σ ($\sigma = 1.35, 0.50, 0.55 \text{ Jy beam}^{-1} \text{ km s}^{-1}$, respectively) and are then separated by steps of 1σ . The grayscale represents the $4.5 \mu\text{m}$ emission from *Spitzer*/IRAC. All maps are convolved to $5'' \times 5''$ (beam is shown at the bottom-right corner of each panel).

tracers such as high- J transitions of CO, H_2 , and H_2O also support the presence of warm gas component with $\sim 500 \text{ K}$ (e.g. Nisini et al. 2007, 2010). We note that the density and temperature of the high-velocity clump are similar to those of the EHV bullets in highly collimated outflows such as HH211 and L1448C, $n \sim 10^5\text{--}10^6 \text{ cm}^{-3}$, and $T_K \geq 300 \text{ K}$ (Nisini et al. 2002, 2007; Hirano et al. 2006; Palau et al. 2006). This implies that the high-velocity emission in the B1a and B0i clumps has an origin common with that of the EHV bullets.

4. Discussion

4.1. Physical conditions of the clumps

4.1.1. SiO high-velocity clumps

4.1.2. H_2CO emission

The H_2CO 3(0, 3)–2(0, 2)/3(2, 2)–2(2, 1) ratio is sensitive to temperatures in the range of 50–200 K (van Dishoeck et al. 1993; Mangum & Wootten 1993). These two transitions were detected in the clumps B0h, B0d, and B1a. The line ratios, 3(0, 3)–2(0, 2)/3(2, 2)–2(2, 1), averaged over the $5''$ beam and measured at the center of these clumps, are 2.3 ± 0.8 in B0h, 2.0 ± 0.4 in B0d, and 1.1 ± 0.4 in B1a. The two transitions probably miss a significant amount of flux. Since there are no single-dish data available for these transitions, it is difficult to estimate how much flux was missed. However, since the two line transitions were observed simultaneously with the same uv sampling, the line ratio probably is reliable for spatially compact components. In general, the missing flux in the lower excitation line is expected to be higher than that in the higher excitation line, because the lower excitation line is more extended than the higher excitation line. Therefore, the line ratio derived here can be the lower limit, if the source is extended. Despite these limitations, which prevent a proper LVG analysis of the H_2CO lines, we present below the general trend of such an analysis with the information available to us.

We ran LVG models to reproduce the H_2CO 3(0, 3)–2(0, 2)/3(2, 2)–2(2, 1) line ratios observed at these three clumps. To show the general trend of the results of the LVG for the H_2CO case, Fig. 12 presents the temperature-versus-density plot for different $N(\text{H}_2\text{CO})/\Delta v$ parameters. As seen from the figure, the ratio is sensitive to temperatures for $N(\text{H}_2\text{CO})/\Delta v$ of between 10^{13} and $10^{14} \text{ cm}^{-1} \text{ km}^{-1} \text{ s}$.

Fig. 9. Total integrated H_2CO 3(0, 3)–2(0, 2) emission (cyan; from -3.7 to $+4.1 \text{ km s}^{-1}$) and the SiO (5–4) emission (red; from -16.7 to $+4.1 \text{ km s}^{-1}$). Contours start at 3σ ($\sigma = 1.35$ and $2.60 \text{ Jy beam}^{-1} \text{ km s}^{-1}$, respectively) and are then separated by steps of 1σ . The maps are convolved to $5'' \times 5''$ (beam shown at the bottom-right corner). The grayscale represents the $4.5 \mu\text{m}$ emission from *Spitzer*/IRAC.

On the other hand, the line ratio is sensitive to densities for $N(\text{H}_2\text{CO})/\Delta v$ of between 10^{15} and $10^{16} \text{ cm}^{-1} \text{ km}^{-1} \text{ s}$. Assuming a value of about 10^{14} cm^{-2} for $N(\text{H}_2\text{CO})$ (e.g. Bachiller & Perez Gutierrez 1997) and a linewidth of 4 km s^{-1} (the linewidth measured at these positions), the $N(\text{H}_2\text{CO})/\Delta v$ becomes $2.5 \times 10^{13} \text{ cm}^{-2} \text{ km}^{-1} \text{ s}$ (bottom-left panel in Fig. 12). In this case, the H_2CO line ratios suggest that the gas temperatures in B0d and B0h are $>350 \text{ K}$ and $>160 \text{ K}$, respectively. On the other hand, the line ratio at the B1a position has solutions only in the extreme model with $N(\text{H}_2\text{CO})/\Delta v$ of $10^{16} \text{ cm}^{-2} \text{ km}^{-1} \text{ s}$ (top-right panel of Fig. 12), which then turns into a value of $N(\text{H}_2\text{CO})$ that is two orders of magnitude higher than the values derived from the single-dish observations. This large difference in the column density could be explained if the filling factor of the single-dish observations were very low (the emitting region is much smaller than the $\sim 20''$ beam). To explain the difference

Fig. 10. SiO (2–1) and (5–4) spectra at B0i and B1a in a brightness-temperature scale. SiO (5–4) has been convolved to the angular resolution of the SiO (2–1) observations (i.e., 9.5×8.0 arcsec). The thick vertical line indicates the high-velocity ranges in which the analysis has been made, from -16.0 to -10.8 km s $^{-1}$.

Fig. 11. SiO (2–1)/(5–4) ratio as a function of T_{kin} and $n(\text{H}_2)$ from the LVG modeling (grayscale). The panels show B1a and B0i cases. The observed line ratios (1.7 at B1a and 1.0 at B0i) are shown as a dashed curve, while the SiO (5–4) intensities (4.4 and 1.5 K km s $^{-1}$, for B1a and B0i, respectively) are represented by the solid lines. The line ratios plotted in gray are 0.16, 0.17, 0.18, 0.2, 0.5, 1, 5, 10, 20 (some of them indicated with numbers).

of two orders of magnitude, the size of the emitting region should be $\sim 2''$ (in diameter). On the other hand, the observed low line ratio could be explained if the missing flux were more significant in the $3(0, 3) \rightarrow 2(0, 2)$ transition. It is natural that the $3(0, 3) \rightarrow 2(0, 2)$ transition in the lower-energy level is more spatially extended than the $3(2, 2) \rightarrow 2(2, 1)$ transition. In this case, most of the $3(0, 3) \rightarrow 2(0, 2)$ emission is resolved out, resulting in the low flux of the $3(3,2) \rightarrow 2(0, 2)$ line and very low line ratio.

Fig. 12. LVG for the H_2CO emission in L1157. The H_2CO $3(0, 3) \rightarrow 2(0, 2)/3(2, 2) \rightarrow 2(2, 1)$ observed ratios are 1.1 (solid), 2.0 (dashed), and 2.3 (dotted). Each panel shows the $N(\text{H}_2\text{CO})/\Delta v$ parameter used for the LVG calculation. The grayscale with numbers indicates the line ratios calculated from the LVG model.

4.2. The SiO emission at B1

Figure 13 displays a close-up view of the high- and low-velocity SiO emission at the B1 position, taken from Fig. 5. The high-velocity clump B1a is surrounded by three low-velocity clumps, two of which are B1c and B1h, located downstream of B1a. Indeed, the clumpy structure of the low-velocity SiO emission at the B1 position is a remarkable finding of our observations. The position-velocity (PV) diagram along the axis of the inner cavity (PA 161 deg.) also exhibits the higher velocity emission at the position closest to the protostar and the lower velocity in the downstream (Fig. 14). This velocity structure is different from that expected in a single bow shock, in which the highest velocity appears at the tip followed by a low-velocity wake or bow wing (e.g., Lee et al. 2000). If the jet axis is close to the plane of the sky (as is the case for the L1157 outflow), the velocity dispersion produced by a single bow shock decreases significantly in the post-shock region closer to the protostar (see Fig. 20 of Lee et al. 2000). However, the observed PV diagram exhibits the opposite trend, with the largest dispersion at the position closer to the protostar. The PV plot implies that the high-velocity clump B1a is decelerated at the interface with the low-velocity clump B1c. As discussed previously, the low-velocity clumps are probably the part of the spatially extended structure, that is shocked ambient gas. It is very likely that the momentum transfer from high-velocity component to the ambient gas occurs at their interface.

The line profile of the high-velocity component observed with the SMA shows the highest intensity close to the highest blueshifted velocity with a gradual wing toward the lower velocity (Fig. 7). This line profile is similar to those produced by the C-type shock models calculated by Schilke et al. (1997). The line profile also resembles the model calculations by Jiménez-Serra et al. (2009) for a single shock with an age of few hundred years. This type of line profile is observed in the extremely high velocity (EHV) bullets of jet sources such as L1448C and

Fig. 13. Low-velocity (red contours) and high-velocity (cyan contours) SiO(5–4) emission at the B1 position, overlaid on the $4.5\ \mu\text{m}$ emission from *Spitzer*/IRAC. The dashed line indicates the axis (PA of 161 degrees) of the inner cavity identified in the CO (1–0) by Gueth et al. (1996). The PV diagram in Fig. 14 was made along this cut. The black square shows the reference position (offset = 0) of the PV diagram in Fig. 14.

HH211 (e.g., Nisini et al. 2007). The similarity to the line profiles in EHV jets may suggest that the B1a clump is the possible counterpart of the EHV bullets seen in outflows such as L1448C. Additional support for this suggestion is the size and mass of the high-velocity clump. Because $\sim 80\%$ flux of the high-velocity SiO emission is recovered with the SMA at B1 position, the high-velocity emission is considered to come from a compact region with a size close to that of the B1a clump. The size of the B1a clump as measured by a two-dimensional Gaussian fit is $\sim 2000 \times 1000$ AU. Thus assuming an H_2 density of $10^5\text{--}10^6\ \text{cm}^{-3}$ (as derived from the LVG analysis), the corresponding mass is $\sim 6 \times 10^{-5}\text{--}6 \times 10^{-4}\ M_\odot$. This value is similar to the EHV bullets in IRAS 04166+2706 (see Table 1 of Santiago-García et al. 2009). In summary, the line profile and physical parameters (such as density and mass) of the B1a clump suggest that this compact and high-velocity clump has an origin common with the EHV bullets observed in the jet-like outflow sources. The PV diagram at the B1 position implies that the EHV bullet is running into the dense ambient material at this position. As shown in Sect. 4.1.1, the B0i clump also has similar physical properties to B1a. Therefore, the B0i clump is probably also an EHV bullet, although the amount of missing flux at this position is uncertain.

4.3. SiO, H_2CO , and CH_3OH spatial distribution

H_2CO and CH_3OH are known to be formed efficiently on grain surfaces through successive hydrogenation (e.g., Tielens & Whittet 1997; Charnley et al. 1997; Watanabe & Kouchi 2002). Observationally, H_2CO and CH_3OH show significant abundance enhancement in shocked gas, which is probably originated from evaporation of grain mantles (e.g., Bachiller et al. 1995; Avery & Chiao 1996; Schöier et al. 2004). As shown in Fig. 8, the two

Fig. 14. Position–velocity diagram of the SiO(5–4) emission at the B1 position. The offset is measured from the center of the B1a clump. The cut runs along the axis of the inner cavity (dashed line in Fig. 13). The vertical line indicates the cloud velocity ($V_{\text{LSR}} = 2.7\ \text{km s}^{-1}$), the horizontal line plots the reference position (offset = 0).

H_2CO transitions and the CH_3OH 4(2, 2)–3(1, 2)E line exhibit a similar spatial distribution, that is, the walls of the U-shaped feature, suggesting that the chemistry of the two molecular species are linked. However, the detailed structure within this cavity shows differences from one molecular tracer to the other. For example, if we compare the spatial distribution of the CH_3OH and H_2CO lines with similar energy levels (i.e., CH_3OH 4(2, 2)–3(1, 2) with $E_u \sim 38$ K and H_2CO 3(0, 3)–2(0, 2) with $E_u = 21$ K), the CH_3OH clump (B1f) is located to the west of the apex, while the H_2CO clump (B1a) is located to the east of the apex. The east–west asymmetry of the CH_3OH was also reported in the $(2_K\text{--}1_K)$ lines by Benedettini et al. (2007). The trend observed in CH_3OH 4(2, 2)–3(1, 2), which is brighter in the western parts of the cavity and the apex, is consistent with that observed in the $2_K\text{--}1_K$ lines, supporting the idea of higher CH_3OH abundance in the western part of the cavity. On the other hand, a comparison between two transitions of H_2CO implies a difference in physical condition between the eastern and western parts of the cavity. As shown in Sect. 4.1.2, the temperature of the western cavity is probably higher than that of the western cavity.

The H_2CO and CH_3OH lines trace the mid-IR U-shaped structure closely. This U-shaped structure might be a wing of the bow shock whose tip is a bright SiO clump, B1a. On the other hand, the U-shaped structure could be formed by means of multiple shocks. As shown in Fig. 5 of Takami et al. (2011), the northern lobe of the L1157 outflow contains a number of mid-IR knots along the S-shaped emission ridge. This implies that the multiple ejection events, whose directions have varied by means of precession, have contributed to form the lobe. On the other hand, only two bright knots are identified in the southern lobe. If the ejection events themselves were symmetric, the counterparts of the knots five and six in the northern lobe (A2 and A3 groups in Takami et al. 2011) might have contributed to form the U-shaped cavity in the southern lobe. The B0d clump, which is bright in H_2CO and CH_3OH lines, probably originates

from the interaction between the ejecta and ambient material. The lack of SiO in B0d clump is probably due to the low shock velocity, which is also supported by the low velocity of the H₂CO and CH₃OH emission.

The abundance of SiO is also known to be enhanced in shocked gas. The gas-phase SiO is considered to originate from silicon-bearing species that are sputtered from grains (cores or mantles) and are injected into the gas phase in the form of neutral Si, SiO, SiO₂, or SiH₄ (Schilke et al. 1997; Gusdorf et al. 2008). In Fig. 9 we show the total integrated emission of the SiO (5–4) and H₂CO 3(0, 3)–2(0, 2) transitions convolved to the same angular resolution of 5''. It is obvious that the spatial distribution of the SiO is different from that of the H₂CO (and therefore from that of CH₃OH, since its distribution is similar to H₂CO). The most prominent SiO clumps are located at the apex of the U-shaped structure and along the faint mid-IR arc-like feature outside of the U-shaped structure. In addition, these major SiO features appear in the high-velocity range in which no H₂CO or CH₃OH emission has been detected. If the arc-like feature seen in the mid-IR corresponds to the wall of an outer cavity, the B0f and B0i clumps might be interacting with the wall of the outer cavity.

Figure 9 also shows that each of the three SiO clumps is associated with a H₂CO clump, H₂CO being systematically closer to the protostar. In addition, at the positions of the H₂CO clumps, the low-velocity SiO is also detected (although B0h is only 3 σ in the SiO). These results imply the possibility that the H₂CO and the low-velocity SiO trace the wakes of the shocks whose tips are the high-velocity SiO clumps. This is very likely for the H₂CO in the B1a clump. However, it is unlikely for the B0g and B0h clumps, because the spatial distribution of the H₂CO 3(0, 3)–2(0, 2) emission is elongated along the eastern wall of the U-shaped cavity, and because B0g and B0h are not located on the lines between the high-velocity SiO clumps, B0f and B0i, and the protostar. Therefore, it is more natural to consider that the H₂CO emission at B0g and B0h delineate the wall of the U-shaped cavity, as for the CH₃OH (2_K–1_K) emission reported by Benedettini et al. (2007).

5. Summary and conclusions

The principal results of the SMA observations at 1.4 mm toward the blue lobe of the L1157 outflow are summarized as follows:

- Four molecular transitions, SiO (5–4), H₂CO 3(0, 3)–2(0, 2), H₂CO 3(2, 2)–2(2, 1), and CH₃OH 4(2, 2)–3(1, 2)_E were detected at B1 and B0 in the blue lobe. None of these lines shows significant emission at the protostellar position and at B2.
- The H₂CO and CH₃OH lines trace (or delineate) the U-shaped structure seen in the mid-IR. The overall distribution of the two species are similar.
- The spatial distribution of the SiO 5–4 is significantly different from those of H₂CO and CH₃OH. The SiO (5–4) emission is brightest at the B1 position, which corresponds to the apex of the U-shaped structure. There are two compact SiO clumps along the mid-IR arc-like feature to the east of the B0 position.
- At the B1 position, the SMA recovered 80% of the single-dish flux in the high-velocity range, suggesting that the high-velocity emission is confined in a compact clump with a size of $\sim 2000 \times 1000$ AU. The gas density of this clump derived from the SiO (2–1)/(5–4) line ratio is $\sim 10^5$ – 10^6 cm^{–3}, which

is similar to those of the EHV bullets. The line profile at this position is also similar to those seen in the EHV bullets; the line peaks at the highest blueshifted velocity with a gradual wing toward the lower velocity. The B1a clump probably has similar properties to the EHV bullets.

- On the other hand, the SMA recovered only $\sim 10\%$ of the flux in the low-velocity range. This indicates that the low-velocity SiO is spatially extended.
- The velocity structure around the B1 position is different from that expected in a single bow shock. Very likely the high-velocity clump B1a is an EHV bullet running into the dense ambient material and transferring its momentum.

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