The L 1157 protostellar outflow imaged with the Submillimeter Array

A. I. Gómez-Ruiz1,2,⋆⋆, 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

Received 17 November 2011 / Accepted 13 August 2013

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 (\textasciitilde 3\arcsec).

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 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 \textasciitilde 1500 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 \( n \sim 10^6 \)–\( 10^8 \) 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 \( \text{L}_\text{bol} \sim 11 \text{L}_\odot \), 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)) \( \text{NH}_3 \) 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 \( \sim 170 \) K, which is a factor of \( \sim 10 \) 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 \( J = 3–2 \) 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 location of the two cavities proposed by Gueth et al. (1997). The cross indicates the position of the protostar L1157-mm, α = 20h39m06.19s, δ = 68°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 spatial and kinematic structure of the shocked gas at high 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 ∼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 SMA\(^2\). 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′×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), CH\(_3\)OH 4(2, 2)–3(1, 2)E, H\(_2\)CO 3(0, 3)–2(0, 2), and H\(_2\)CO 3(2, 2)–2(2, 1) were detected above a 4\(\sigma\) 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″×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 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 spatial resolution, we have mapped the blue lobe of the L1157 outflow at 1.4 mm using the Submillimeter Array (SMA).

Table 1. List of the detected transitions.

| Transition | Rest frequency GHz | \(E_u\) K | Vel. range km s\(^{-1}\) |
|-----------|--------------------|---------|----------------------|
| SiO(5–4)  | 217.3098            | 13.1    | −16.7 to +4.1        |
| H\(_2\)CO 3(0, 3)–2(0, 2) | 218.2218          | 21.0    | −3.7 to +4.1         |
| H\(_2\)CO 3(2, 2)–2(2, 1) | 218.47561           | 68.1    | −11.1 to +4.1        |
| CH\(_3\)OH 4(2, 2)–3(1, 2)E | 218.44400          | 37.6    | −3.7 to +1.5         |

\(^1\) 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
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 ~27σ. 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″ × 1.4″ (1200 × 600 AU) with a position angle of 88 deg. 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 ~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 H2 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 H2 molecule at these two regions is low because of the lower temperature and/or density. This is indeed confirmed by H2 rotational line studies: the temperature derived from the H2 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 km s\(^{-1}\). Most of the SiO 5–4 emission observed with the SMA is blueshifted with respect to the cloud systemic velocity (\(V_{\text{sys}}\)) 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 kλ were not able to recover structures larger than ~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 ~4.6 K km s\(^{-1}\), which is not sensitive enough to detect the SiO (5–4) emission at the B2 position, whose peak intensity is ~6 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 \(V_{\text{sys}}\) 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 km s\(^{-1}\) to −2.5 km s\(^{-1}\).
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 $V_{\text{LSR}}$ 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.

The list of clumps is shown in decreasing order of declination. 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.

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 3$\sigma$ ($\sigma$ = 1.40 Jy beam$^{-1}$ km s$^{-1}$) and are then separated by steps of 1$\sigma$.

### 3.3.2. H$_2$CO and CH$_3$OH

Two formaldehyde (H$_2$CO) lines were detected in the LSB (see Table 1). The H$_2$CO 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$_2$CO 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$_2$CO transitions overlaid on the IRAC 4.5 μm emission. To improve the sensitivity, we convolved both maps to 5″ x 5″. As for SiO, there is no significant H$_2$CO emission from B2 position. The spatial distribution of the H$_2$CO 3(0, 3)–2(0, 2) emission is similar to that of the H$_2$CO 3(2, 2)–2(2, 1), except for the elongated structure along the eastern wall that is barely seen in the H$_2$CO 3(2, 2)–2(2, 1). The energy level in the upper state of the H$_2$CO 3(0, 3)–2(0, 2) transition is 21 K, while for the H$_2$CO 3(2, 2)–2(2, 1) it is 68 K. Therefore, difference in the spatial distribution between the two transitions of H$_2$CO
suggests that the excitation of the elongated structure in the eastern wall is lower than that of the B0d clump.

The H$_2$CO emission clumps detected above the 4$\sigma$ 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$_2$CO 3(0, 3)–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$_3$N (11–10) map of Benedettini et al. (2007) and in the CH$_3$CN map of Codella et al. (2009). The brightest H$_2$CO 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$_3$OH (2–1) maps of Benedettini et al. (2007). The H$_2$CO clump at ∼15$''$ northwest of B0d is considered to be the counterpart of the B0b clump in the CH$_3$OH (2–1).

The CH$_3$OH 4(2, 2)–3(1, 2)E line emission was found in the velocity range from ∼−3.7 km s$^{-1}$ to +1.5 km s$^{-1}$. The CH$_3$OH total integrated intensity map shown in Fig. 8c was also convolved to the 5$''$ × 5$''$ resolution to improve the signal-to-noise ratio. The overall distribution of the CH$_3$OH 4(2, 2)–3(1, 2)E emission is similar to that of the H$_2$CO 3(0, 3)–2(0, 2). The CH$_3$OH emission is brightest in the B0d clump, but also shows emission at B0h and B1f. No CH$_3$OH emission was detected at the B2 position. The clumps detected above the 4$\sigma$ level in the CH$_3$OH 4(2, 2)–3(1, 2)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 × 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 5$\sigma$ 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 ∼27$''$ for SiO (2–1) and ∼11$''$ for SiO (5–4). In addition, the line ratios used the total integrated intensity, including the low-velocity component, where as 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 × 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 ∼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 ± 0.1 K km s$^{-1}$ at B0i, and 7.7 ± 0.6 and 4.4 ± 0.1 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...
Table 3. Clump positions.

| Clump | RA J2000 | Dec J2000 | Molecular tracer | 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 |                  | N   | N      | N       |
| B0g   | 20:39:09.8 | 68:01:39 |                  | Y   | N      | N       |
| B0d   | 20:39:07.9 | 68:01:30 |                  | Y   | N      | Y       |
| B0h   | 20:39:10.4 | 68:01:27 |                  | N   | Y      | Y       |
| B0i   | 20:39:11.5 | 68:01:27 |                  | N   | Y      | 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      | N       |
| B1a   | 20:39:10.0 | 68:01:12 |                  | Y   | N      | N       |
| B1h   | 20:39:10.6 | 68:01:11 |                  | N   | N      | Y       |
| B1c   | 20:39:09.9 | 68:01:06 |                  | Y   | N      | N       |

Notes. (a) Detections above $4\sigma$ are marked Y, non-detections are marked N. (∗) Reported also by Benedettini et al. (2007). (+) Reported also by Codella et al. (2009).

the (2–1)/(5–4) ratios. Using the RADEX offline distribution\(^3\), we estimated the kinetic temperature ($T_{\text{kin}}$) 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 $10^6.5$ cm\(^{-3}\). On the other hand, the (2–1)/(5–4) ratio becomes sensitive to the temperature if the density is higher than $10^6.5$ 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 $3 \times 10^5$ 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 gas; the (8–7)/(5–4) ratio at $V_{\text{LSR}} \approx -15$ km s\(^{-1}\) required either a higher density of $5 \times 10^5$ cm\(^{-3}\) or a higher temperature of $T_K > 500$ K. Although our results do not support the high density of $>10^6.5$ 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/
tracers such as high-$J$ transitions of CO, H$_2$, and H$_2$O also support the presence of warm gas component with ~500 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, $n \sim 10^5$–$10^6$ cm$^{-3}$, and $T_K \geq 300$ 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$_2$CO emission

The H$_2$CO 3(0, 3)–2(0, 2) 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 $2.3 \pm 0.8$ in B0h, $2.0 \pm 0.4$ in B0d, and $1.1 \pm 0.4$ 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$_2$CO 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$_2$CO 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$_2$CO case, Fig. 12 presents the temperature-versus-density plot for different N(H$_2$CO)/$\Delta v$ parameters. As seen from the figure, the ratio is sensitive to temperatures for N(H$_2$CO)/$\Delta v$ of between $10^{13}$ and $10^{14}$ cm$^{-3}$ km$^{-1}$ s. On the other hand, the line ratio is sensitive to densities for N(H$_2$CO)/$\Delta v$ of between $10^{15}$ and $10^{16}$ cm$^{-3}$ km$^{-1}$ s. Assuming a value of about $10^{14}$ cm$^{-2}$ for N(H$_2$CO) (e.g. Bachiller & Perez Gutierrez 1997) and a linewidth of 4 km s$^{-1}$ (the linewidth measured at these positions), the N(H$_2$CO)/$\Delta v$ becomes $2.5 \times 10^{13}$ cm$^{-2}$ km$^{-1}$ s (bottom-left panel in Fig. 12). In this case, the H$_2$CO line ratios suggest that the gas temperatures in B0d and B0h are >350 K and >160 K, respectively. On the other hand, the line ratio at the B1a position has solutions only in the extreme model with N(H$_2$CO)/$\Delta v$ of $10^{16}$ cm$^{-3}$ km$^{-1}$ s (top-right panel of Fig. 12), which then turns into a value of N(H$_2$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 ~20″ beam). To explain the difference

![Fig. 8. Total integrated emission (see Table 1 for the velocity ranges) of the a) H$_2$CO 3(0, 3)–2(0, 2); b) H$_2$CO 3(2, 2)–2(2, 1), and c) CH$_3$OH 4(2, 2)–3(1, 2E) transitions. In all panels, contours start at 3$\sigma$ ($\sigma = 1.35, 0.50, 0.55$ Jy beam$^{-1}$ km s$^{-1}$, respectively) and are then separated by steps of 1$\sigma$. The grayscale represents the 4.5 μm emission from Spitzer/IRAC. All maps are convolved to 5″ × 5″ (beam is shown at the bottom-right corner of each panel).]

![Fig. 9. Total integrated H$_2$CO 3(0, 3)–2(0, 2) emission (cyan; from −3.7 to +4.1 km s$^{-1}$) and the SiO (5–4) emission (red; from −16.7 to +4.1 km s$^{-1}$). Contours start at 3$\sigma$ ($\sigma = 1.35, 2.60$ Jy beam$^{-1}$ km s$^{-1}$, respectively) and are then separated by steps of 1$\sigma$. The maps are convolved to 5″ × 5″ (beam shown at the bottom-right corner). The grayscale represents the 4.5 μm emission from Spitzer/IRAC.]
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 \(T_{\text{kin}}\) and \(n(H_2)\) 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)–2(0, 2) transition. It is natural that the 3(0, 3)–2(0, 2) transition in the lower-energy level is more spatially extended than the 3(2, 2)–2(2, 1) transition. In this case, most of the 3(0, 3)–2(0, 2) emission is resolved out, resulting in the low flux of the 3(3,2)–2(0, 2) line and very low line ratio.

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...
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 ~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 ~2000 × 1000 AU. Thus assuming an H2 density of 10^5−10^6 cm^-3 (as derived from the LVG analysis), the corresponding mass is ~6 × 10^{-5}−6 × 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, H2CO, and CH3OH spatial distribution

H2CO and CH3OH 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, H2CO and CH3OH 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 H2CO transitions and the CH3OH 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 CH3OH and H2CO lines with similar energy levels (i.e., CH3OH 4(2, 2)–3(1, 2) with \(E_u \approx 38\) K and H2CO 3(0, 3)–2(0, 2) with \(E_u \approx 21\) K), the CH3OH clump (B1f) is located to the west of the apex, while the H2CO clump (B1a) is located to the east of the apex. The east-west asymmetry of the CH3OH was also reported in the western half of the cavity and the apex, is consistent with that observed in the 2K−1K lines by Benedettini et al. (2007). The trend observed in CH3OH 4(2, 2)–3(1, 2), which is brighter in the western part of the cavity and the apex, is consistent with that observed in the 2K−1K lines, supporting the idea of higher CH3OH abundance in the western part of the cavity. On the other hand, a comparison between two transitions of H2CO 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 H2CO and CH3OH 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 H2CO and CH3OH 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 H$_2$CO and CH$_3$OH 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, SiO$_2$, or SiH$_4$ (Schilke et al. 1997; Gusdorf et al. 2008). In Fig. 9 we show the total integrated emission of the SiO (5–4) and H$_2$CO 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 H$_2$CO (and therefore from that of CH$_3$OH, since its distribution is similar to H$_2$CO). 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 H$_2$CO or CH$_3$OH 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 H$_2$CO clump, H$_2$CO being systematically closer to the protostar. In addition, at the positions of the H$_2$CO clumps, the low-velocity SiO is also detected (although B0h is only 3$\sigma$ in the SiO). These results imply the possibility that the H$_2$CO 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 H$_2$CO in the B1a clump. However, it is unlikely for the B0g and B0h clumps, because the spatial distribution of the H$_2$CO 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 H$_2$CO emission at B0g and B0h delineate the wall of the U-shaped cavity, as for the CH$_3$OH (2$_x$–1$_x$) 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), H$_2$CO 3(0, 3)–2(0, 2), H$_2$CO 3(2, 2)–2(2, 1), and CH$_3$OH 4(2, 2)–3(1, 2) 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 H$_2$CO and CH$_3$OH lines trace (or delineate) the U-shaped structure seen in the mid-IR. The overall distribution of the two species is similar.

- The spatial distribution of the SiO 5–4 is significantly different from that of H$_2$CO and CH$_3$OH. 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$10$^6$–10$^7$ 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.

Acknowledgements. We wish to thank the whole SMA staff in Hawaii, Cambridge, and Taipei for their enthusiastic help during these observations. We are grateful to the anonymous referee for the detailed comments which improved this paper. We also thank Mario Tafalla for providing us with the single-dish SiO(5–4) spectra and for his useful comments. A.G.R. acknowledges ASIAA, UNAM, MPIfR, and INAF/ASI for their support during this research project. N. Hirano is supported by NSC grant 99-2112-M-001-009-M3y3. S.-Y. Liu is supported by NSC grant 99-2112-M-001-025-MY2.

References

Avery, L. W., & Chiao, M. 1996, ApJ, 463, 642
Bachiller, R., & Perez Gutierrez, M. 1997, ApJ, 487, L93
Bachiller, R., Liechti, S., Walmsley, C. M., & Colomer, F. 1995, A&A, 295, L51
Bachiller, R., Perez Gutierrez, M., Kumar, M. S. N., & Tafalla, M. 2001, A&A, 372, 1049
Beltrán, M. T., Gueth, F., Guilloteau, S., & Dutrey, A. 2004, A&A, 416, 631
Benedettini, M., Viti, S., Codella, C., et al. 2007, MNras, 381, 1127
Charnley, S. B., Tielens, A. G. G. M., & Rodgers, S. D. 1997, ApJ, L203
Codella, C., Benedettini, M., Beltrán, M. T., et al. 2009, A&A, 507, L25
Codella, C., Leefoch, B., Ceccarelli, C., et al. 2010, A&A, 518, L112
Gueth, F., Guilloteau, S., & Bachiller, R. 1996, A&A, 307, 891
Gueth, F., Guilloteau, S., Dutrey, A., & Bachiller, R. 1997, A&A, 323, 943
Gueth, F., Guilloteau, S., & Bachiller, R. 1998, A&A, 333, 287
Gusdorf, A., Cabrit, S., Flower, D. R., & Pineau Des Forêts, G. 2008, A&A, 482, 809
Hirano, N., & Taniguchi, Y. 2001, ApJ, 550, L219
Hirano, N., Liu, S.-Y., Shang, H., et al. 2006, ApJ, 636, L141
Ho, P. T. P., Moran, J. M., & Lo, K. Y. 2004, ApJ, 616, L1
Jiménez-Serra, I., Martín-Pintado, J., Caselli, P., Viti, S., & Rodríguez-Franco, A. 2009, ApJ, 695, 149
Jørgensen, J. K., Bourke, T. L., Myers, P. C., et al. 2007, ApJ, 659, 479
Lee, C.-F., Mundy, L. G., Reipurth, B., Ostriker, E. C., & Stone, J. M. 2000, ApJ, 542, 925
Leefoch, B., Cabrit, S., Codella, C., et al. 2010, A&A, 518, L113
Looney, L. W., Tobin, J. J., & Kwon, W. 2007, ApJ, 670, L131
Mangum, J. G., & Wootten, A. 1993, ApJS, 89, 123
Nisini, B., Giannini, T., Neufeld, D. A., et al. 2010, ApJ, 724, 69
Palau, A., Ho, P. T. P., Zhang, Q., et al. 2006, ApJ, 636, L137
Santiago-García, J., Tafalla, M., Johnstone, D., & Bachiller, R. 2009, A&A, 495, 169
Sault, R. J., Staveley-Smith, L., & Brouw, W. N. 1996, A&AS, 120, 375
Schilke, P., Walmsley, C. M., Pineau des Forêts, G., & Flower, D. R. 1997, A&A, 321, 293
Schöier, F. L., Jørgensen, J. K., van Dishoeck, E. F., & Blake, G. A. 2004, A&A, 418, 185
Scoville, N. Z., Carlstrom, J. E., Chandler, C. J., et al. 1993, PASP, 105, 1482
Tielens, A. G. G. M., & Whittet, D. C. B. 1997, in IAU Symp. 178, ed. A. G. G. M. Tielens, A. G. G. M., & Rodgers, S. D. 1997, ApJ, 571, L173
Viti, S., Jimenez-Serra, I., Yates, J. A., et al. 2011, ApJ, 740, L3
Watanabe, N., & Kouchi, A. 2002, ApJ, 571, L173
Zhang, Q., Ho, P. T. P., Wright, M. C. H., & Wilner, D. J. 1995, ApJ, 451, L71
Zhang, Q., Ho, P. T. P., & Wright, M. C. H. 2000, AJ, 119, 1345