Early Results of the 3 mm Spectral Line Survey toward the Lynds 1157 B1 Shocked Region


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Abstract

We have conducted a sensitive 3 mm observation toward the shocked region, Lynds 1157 B1, which is an interaction spot between a molecular outflow and its ambient gas. We have successfully detected the CH$_3$CHO, HCOOH, and HCOOH lines, as well as the CH$_2$DOH line. The abundances of these molecules relative to CH$_3$OH are found to be lower than those in the low-mass star-forming core, IRAS 16293–2422. Since these molecules are thought to evaporate from grain mantles, the observational results mean that complex molecules are less abundant in grain mantles residing in the ambient cloud surrounding a prestellar/protostellar core. Instead, efficient formation of the complex organic species and deuterated species should take place in a prestellar/protostellar core. The present result verifies the importance of an unbiased line survey of this source.

Key words: ISM: abundances — ISM: individual (Lynds 1157) — ISM: jets and outflows — ISM: molecules

1. Introduction

Since shock waves are ubiquitous in interstellar space, a thorough understanding of shock chemistry is essential to interpreting observed chemical compositions of interstellar gas. This is particularly true for star-forming regions, where shocks due to outflows from a protostar and/or accretion motions onto a protostar would cause substantial chemical processing. Although observational and theoretical studies on shock chemistry have extensively been made since the early years of interstellar chemistry (e.g., Michell 1984; Flower et al. 1985; Bachiller & Pérez Gutiérrez 1997; Jørgensen et al. 2004; Wakelam et al. 2005; Jiménez-Serra et al. 2008), our understanding is not yet satisfactory. The shock chemistry is, for instance, explored with spectral line surveys in the radio wavelength toward several massive star-forming regions such as Orion KL (e.g., Lee et al. 2001; Schilke et al. 2001; Comito et al. 2005), W 3(OH) (e.g., Helmich & van Dishoeck 1997; Kim et al. 2006), and Sgr B2 (e.g., Nummelin et al. 1998), as well as the low-mass star-forming region IRAS 16293–2422 (Blake et al. 1994; van Dishoeck et al. 1995; Castets et al. 2005). However, the physical and chemical complexities of these sources always hamper extraction of a pure nature of the shock chemistry, as often pointed out in the Orion KL case (e.g., Beuther et al. 2005).

The first step to overcome this situation is to observe the chemical composition of a well-defined shocked region in an unbiased way by a line survey. One of the best objects for this purpose is Lynds 1157 B1. The L 1157 dark cloud ($D = 440$ pc: Viotti 1969) harbors a low-luminosity (11 $L_\odot$) Class 0 protostar (IRAS 20386+6751), which drives a well-collimated molecular outflow with a dynamical age of 1.8 $\times$ 10$^5$ yr (Umemoto et al. 1992). The blue lobe of the L 1157 outflow consists of two cavities, and the B1 position is just on the tip of the inner cavity. L 1157 B1 is a shocked region formed by an apparent interaction between the molecular outflow and an ambient cloud. Mikami et al. (1992) detected the SiO ($J = 2–1$) emission with a prominent blue shifted feature, and proposed that SiO is produced by the disruption of silicate grains in the shocked region. A direct evidence of the shock was presented by the detection of near-infrared H$_2$ emission toward the B1 position (Davis & Eisloffel 1995; Nisini et al. 2010b). Very recently, the strong H$_2$O emission was detected toward L 1157 B1 with Herschel (Nisini et al. 2010a). The physical condition of the shocked gas was investigated by Bachiller and Pérez Gutiérrez (1997), Umemoto et al. (1999), and Hirano and Taniguchi (2001). The kinetic temperature is in a range of 50 to 170 K, reflecting the shock heating. The H$_2$ density is reported to be at an order of 10$^5$ cm$^{-3}$ on the basis of high density tracers (Mikami et al. 1992; Bachiller & Pérez Gutiérrez 1997). Since the B1 position is spatially apart from the protostar by 1‘, the “pure” shock
chemistry can be investigated even by using a single-dish telescope without being complicated by possible complex structures around the protostar itself.

Abundances of simple molecules have previously been reported by Avery and Chiao (1996) and Bachiller and Pérez Gutiérrez (1997). Interferometric observations were conducted to explore detailed distribution of molecules in the shocked region (e.g., Benedettini et al. 2007). These results indicate that the abundances of some molecules such as SiO, CH3OH, H2CO, and SO are significantly enhanced at the B1 position. Very recently, Arce et al. (2008) reported detections of complex organic molecules, HCOOCH3, HCOOH, and C2H3OH, and Codella et al. (2009) detected CH3CN. These indicate rich organic chemistry in the shocked region. However, all these studies are targeted at specific molecular lines of interest. For a full understanding of the chemical composition of L 1157 B1, an unbiased line survey is essential. Although such an unbiased survey has recently been carried out with Herschel HIFI in the 500 GHz band, the detected molecules are mostly limited to fundamental species such as CO, H2O, HCN, H2CO, and CH3OH (Lefloch et al. 2010; Codella et al. 2010).

Given the above motivation, we are conducting a line survey of L 1157 B1 in the 3 mm band with the Nobeyama 45 m telescope (NRO 45 m), as a part of the legacy project of Nobeyama Radio Observatory. In contrast to the previous line surveys toward star-forming regions, we observe the shock region which is well apart from the protostar. In this paper, we report the early result of the line survey covering the 88.6–91.0 GHz range and 96.3–97.5 GHz ranges. In spite of small frequency coverage, we have detected the lines of complex organic molecules such as acetaldehyde (CH3CHO) and methylformate (HCOOCH3), and a line of mono-deuterated methanol (CH2DOH). We compare our results with those reported for low- and high-mass star-forming regions with a particular emphasis on the abundances of complex organic molecules.

2. Observations

We observed L 1157 B1 with NRO 45 m from 2008 January to June. L 1157 B1 is the brightest CO clump in the southern lobe of the L 1157 outflow at α(J2000.0) = 20h30m09s75, δ(J2000.0) = 68°01′15″9, located at an offset of Δα = 20″, Δδ = −60″ (0.14 pc) from the L 1157 protostar (IRAS 20386+6751). This observation covers the frequency range of 3.6 GHz (88.6–91.0 GHz and 96.3–97.5 GHz) to test the feasibility of a line survey in this source. In the observation, we used the dual-polarization sideband-separating SIS receiver newly installed on NRO 45 m (Nakajima et al. 2008). Typical system temperatures were 150 K and 250 K for the two orthogonal polarizations in winter, and 250 K and 350 K in spring. The intensity scale was calibrated by the chopper-wheel method. Since the image rejection ratio of the new receiver was not well calibrated, the intensity scale was finally corrected on the base of the intensity of a strong line (e.g., HCO+, J = 1–0, 89.188523 GHz) measured with the standard SSB receiver, S100. The main beam efficiency and beam size are 0.44 and 20″, respectively. The telescope pointing was checked by observing the nearby SiO maser source (T Cep) every hour. The pointing accuracy was kept to be better than 10″. The position-switching mode was employed for all observations, where the off position was taken at Δα = 0″, Δδ = 20″. The backend was a bank of autocorrelators (AC), whose bandwidth and channel spacing are 512 MHz and 0.5 MHz, respectively. Two successive frequency channels of AC are averaged to improve the signal-to-noise ratio of the spectral lines. The resultant frequency resolution is 1 MHz, which corresponds to a velocity resolution of 3 km s⁻¹. Since the lines are typically as broad as 10 km s⁻¹, this resolution is enough for line detection. Although the sideband-separating SIS receiver provides the IF output range of 2 GHz for both the lower sideband and the upper side-band, the actual instantaneous bandwidth for observations was 1.2 GHz, because of the limitation of the backend.

3. Results

3.1. Overall Results

Figure 1 shows the observed spectra in the 88.6–91.0 GHz and 96.3–97.5 GHz regions. The rms noise level ranging from 4 mK to 10 mK in TMB was achieved at the frequency resolution of 1 MHz, so that many weak spectral line features were detected in addition to the intense spectral features of HCO+, CH3OH, and C34S. Observed lines were identified on the basis of the spectral line databases (CDMS and JPL), and the results are summarized in table 1. A detection criterion is that a line appears at the 6σ confidence level at its expected frequency. The line parameters are determined by Gaussian fitting. The observed lines show broad line widths (~10 km s⁻¹), indicating that the lines arise from the shocked region, not from the ambient gas. The systemic velocity of the quiescent gas is ~2.7 km s⁻¹, and hence, the most of the peak velocities are blue shifted. A slight scatter of the peak velocities is due to a limited signal-to-noise ratio, and also to the difference in distributions in the shocked region.

3.2. Organic Molecules

In the present observation, we detected the lines of CH3CHO, HCOOCH3, and HCOOH (formic acid). For CH3CHO, three lines were detected in the 96.5 GHz region. CH3CHO is the most stable geometrical isomer of C2H4O; ethylene oxide and CH2CHOH (vinyl alcohol) are less stable than CH3CHO. This molecule was first discovered in Sgr B2 by Gottlieb (1973), and then in cold dark clouds such as TMC-1 and L 134 N by Matthews, Friberg, and Irvine (1985). It is now known to exist in many massive star-forming regions (e.g., Ikeda et al. 2001), and in a hot corino of the low-mass star-forming region IRAS 16293–2422 as well (Cazaux et al. 2003). CH3CHO is often recognized as a member of complex organic molecules, whose abundances are much enhanced in hot cores and/or hot corinos around protostars. In the present study, we have shown that this molecule also exists in the L 1157 B1 shocked region. In contrast, the lines of ethylene oxide and the s and a forms of vinyl alcohol were not detected in the present observation.

Second, we detected at least three lines of HCOOCH3. This molecule is characteristic of the hot core and/or hot corino chemistry (e.g., Cazaux et al. 2003; Kuan et al. 2004; Bottinelli
et al. 2004; Sakai et al. 2006), but it is absent in cold dark clouds (Requena-Torres et al. 2007). In our survey, the 81.8–
71.7 line of HCOOCH$_3$ is clearly seen at 89.3 GHz, where the A and E state lines overlap with each other, giving a twice
stronger line. The doublet lines of the 71.6–61.5 transition can be marginally recog-
nized at 90.15 GHz in spite of the low signal-to-noise ratio. Therefore, our detection of this species is reliable. After we
detected these lines, we came to know that Arce et al. (2008) also detected the HCOOCH$_3$ lines toward almost the same
position of L 1157 with the IRAM 30 m telescope. They
observed 10 lines of HCOOCH$_3$ in the A and E states in the
3 mm and 1.3 mm regions including the 72.5–62.4 lines at
90.15 GHz. Since the signal-to-noise ratio of the 72.5–62.4 line is poor in our observation, we compare the line intensity of
the 81.8–71.7 line observed with the NRO 45 m telescope to that of the 80.8–70.7 line with the IRAM 30 m telescope. These
two lines have similar upper state energies and line strengths, and hence, they are useful for the mutual comparison. Note
that the 80.8–70.7 line was not detected in our survey, probably because the signal-to-noise ratio at the line frequency is
worse by a factor of 2 than that at the frequency of the 81.8–
71.7 line. The integrated intensity ratio between the 81.8–71.7
line (NRO 45 m) and the 80.8–70.7 line (IRAM 30 m) is \( \sim 3 \),
being much higher than the ratio of the intrinsic line strengths of
1.0 (Oesterling et al. 1999). This means a significant beam
dilution effect for the HCOOCH$_3$ lines; the ratio is close to the
upper limit expected for a pointlike source (2.25). A size of
the evaporation region of CH$_2$OH is reported to be only 10.5
according to the interferometric observation (Benedettini et al.
2007). The emitting region of HCOOCH$_3$ should be similar to
or smaller than this, considering that the adsorption energy of
HCOOCH$_3$ is slightly higher than that of CH$_2$OH (Cuppen &
Herbst 2007). The observed intensity ratio thus seems consist-
ent with the source size.

In addition to CH$_3$CHO and HCOOCH$_3$, we also detected
the 404–303 line of HCOOH at 89.579 GHz. For this molecule,
Arce et al. (2008) also detected two lines (422–321 at
90.165 GHz and 624–523 at 135.738 GHz). This molecule is
known to exist in massive star-forming regions such as Orion
KL with a different distribution from HCOOCH$_3$ (e.g.,
Liu et al. 2002). It is also seen in the low-mass star-forming
region IRAS 16293–2422 (Cazaux et al. 2003) and cold dark
clouds such as L 183 (Requena-Torres et al. 2007).

### Table 1. Observed line parameters.

<table>
<thead>
<tr>
<th>( v_{\text{rest}} ) (GHz)</th>
<th>Molecules</th>
<th>Transition</th>
<th>( E_{\text{u}} ) (cm$^{-1}$)</th>
<th>( T_{\text{MB}} ) (K)</th>
<th>( V_{\text{LSR}} ) (peak) (km s$^{-1}$)</th>
<th>( \int T_{\text{MB}}dv ) (K km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.631602</td>
<td>HCN</td>
<td>1–0</td>
<td>2.95</td>
<td>5.837(15)</td>
<td>-1.2</td>
<td>74.26(19)</td>
</tr>
<tr>
<td>88.843117</td>
<td>HCOOCH$_3$</td>
<td>7(1.6)–6(1.5) E</td>
<td>12.5</td>
<td>0.027(15)</td>
<td>0.6</td>
<td>0.12 (9)</td>
</tr>
<tr>
<td>88.851641</td>
<td>HCOOCH$_3$</td>
<td>7(1.6)–6(1.5) A</td>
<td>12.5</td>
<td>0.019(15)</td>
<td>-1.0</td>
<td>0.11 (9)</td>
</tr>
<tr>
<td>89.188523</td>
<td>HCO$^+$</td>
<td>1–0</td>
<td>2.97</td>
<td>2.276(19)</td>
<td>2.0</td>
<td>18.5 (2)</td>
</tr>
<tr>
<td>89.314589‡</td>
<td>HCOOCH$_3$</td>
<td>8(1.8)–7(1.7) E</td>
<td>14</td>
<td>0.034(19)</td>
<td>-4.6</td>
<td>0.28(13)</td>
</tr>
<tr>
<td>89.316668‡</td>
<td>HCOOCH$_3$</td>
<td>8(1.8)–7(1.7) A</td>
<td>14</td>
<td></td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>89.40791</td>
<td>CH$_2$DOH</td>
<td>2(0,2)–1(0,1) e$_0$</td>
<td>4.5</td>
<td>0.029(17)</td>
<td>-0.1</td>
<td>0.20(10)</td>
</tr>
<tr>
<td>89.579179</td>
<td>HCOOH</td>
<td>4(0.4)–3(0.3)</td>
<td>7.48</td>
<td>0.034(17)</td>
<td>0.8</td>
<td>0.18(10)</td>
</tr>
<tr>
<td>90.663568</td>
<td>HNC</td>
<td>1–0</td>
<td>3.02</td>
<td>1.27 (3)</td>
<td>2.1</td>
<td>7.0 (2)</td>
</tr>
<tr>
<td>90.979023</td>
<td>H$_2$N</td>
<td>10–9</td>
<td>16.7</td>
<td>0.70 (3)</td>
<td>0.4</td>
<td>5.0 (3)</td>
</tr>
<tr>
<td>96.412950</td>
<td>C$_3$S</td>
<td>2–1</td>
<td>4.82</td>
<td>0.255(19)</td>
<td>0.2</td>
<td>1.71(12)</td>
</tr>
<tr>
<td>96.42562</td>
<td>CH$_3$CHO</td>
<td>5(–2.4)–4(–2.3) E</td>
<td>15.9</td>
<td>0.034(19)</td>
<td>2.3</td>
<td>0.23(10)</td>
</tr>
<tr>
<td>96.475523</td>
<td>CH$_3$CHO</td>
<td>5(2.3)–4(2.2) E</td>
<td>16.0</td>
<td>0.037(19)</td>
<td>2.4</td>
<td>0.19(10)</td>
</tr>
<tr>
<td>96.632668</td>
<td>CH$_3$CHO</td>
<td>5(2.3)–4(2.2) A$^{++}$</td>
<td>16.0</td>
<td>0.037(19)</td>
<td>2.4</td>
<td>0.19(10)</td>
</tr>
<tr>
<td>96.739362‡</td>
<td>CH$_3$OH</td>
<td>2(–1,2)–1(–1,1) E</td>
<td>8.71</td>
<td>3.040(18)</td>
<td>1.5</td>
<td>51.85(17)</td>
</tr>
<tr>
<td>96.741375‡</td>
<td>CH$_3$OH</td>
<td>2(0,2)–1(0,1) A$^+$</td>
<td>4.84</td>
<td>4.373(18)</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>96.74455‡</td>
<td>CH$_3$OH</td>
<td>2(0,2)–1(0,1) E</td>
<td>14.0</td>
<td>0.852(18)</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>96.755511</td>
<td>CH$_2$OH</td>
<td>2(1.1)–1(1,0) E</td>
<td>19.5</td>
<td>0.214(18)</td>
<td>-1.1</td>
<td>1.47(10)</td>
</tr>
<tr>
<td>97.172064</td>
<td>C$_3$S</td>
<td>2–1</td>
<td>4.86</td>
<td>0.043(18)</td>
<td>0.6</td>
<td>0.29 (9)</td>
</tr>
<tr>
<td>97.301209</td>
<td>OCS</td>
<td>8–7</td>
<td>14.6</td>
<td>0.069(18)</td>
<td>1.0</td>
<td>0.41 (9)</td>
</tr>
</tbody>
</table>

| Tentative       | HCOOH     | 4(2.3)–3(2.2) | 16.3 | 0.02 (4) | -1.6 | 0.2 (2) |
| 89.861484       | HCOOCH$_3$| 7(2.5)–6(2.4) E | 13.7 | 0.02 (4) | 2.3  | 0.1 (2) |
| 90.156534       | HCOOCH$_3$| 7(2.5)–6(2.4) A | 13.7 | 0.02 (4) | 1.9  | 0.2 (2) |
| 90.771564       | SiS       | 5–4        | 9.08           | 0.03 (3)       | 5.5              | 0.2 (2)           |

‡ The numbers in parenthesis represent three times the standard deviations in units of the last significant digits.

d The velocity resolution is 3 km s$^{-1}$.

Blended.
Fig. 1. Spectrum of L157 Bl.
Fig. 1. (Continued)
Fig. 1. (Continued)
Fig. 1. (Continued)
databases (CDMS and JPL), and confirmed no accidental overlapping of other known lines including those in the image sideband. This is the first detection of deuterated methanol in this source. The two other CH$_3$OH lines, i.e., 2$_{0,2}$–1$_{0,1}$ e$_1$ and o$_1$, were both in the observed frequency range of our survey, but they were not detected probably because of the higher upper state energies (∼20 K) (Quade & Suenram 1980). The 2$_{0,10}$ A$^+$ line of CH$_3$OD (89.4079 GHz; Parise et al. 2002) was also in our observed frequency range, but it was not detected.

### 3.4. Other Molecules

In addition to the above molecules, we detected the lines of C$^{33}$S ($J = 2–1$), C$^{34}$S ($J = 2–1$), OCS ($J = 8–7$), HC$_3$N ($J = 10–9$ and $J = 12–11$), SO ($J_N = 2_3–1_2$ image), and possibly SiS ($J = 5–4$). The integrated intensity ratio of C$^{34}$S to C$^{33}$S is found to be 5.9. This ratio is consistent with the $^{34}$S/$^{33}$S ratio in the interstellar cloud (6.27: Chin et al. 1996), indicating that the C$^{33}$S and C$^{34}$S lines are optically thin. The OCS molecule was previously detected toward the B2 position of L 1157 by Bachiller and Pérez Gutiérrez (1997), but it was marginally detected toward the B1 position. In our survey, we confirmed this species in the B1 position. HC$_3$N and SO are both abundant species in L 1157 B1, giving intense spectral lines (Bachiller & Pérez Gutiérrez 1997). Because of the imperfect sideband rejection, the HC$_3$N ($J = 12–11$; 109.173634 GHz) and SO ($J_N = 2_3–1_2$: 109.252220 GHz) lines in the image sideband appear in the survey. Finally we found two candidates of unidentified lines at 96.605 GHz and 97.295 GHz, though their repeatability has to be examined by further observations.

### 3.5. Important Nondetections

Although our observing frequency range is limited to 3.6 GHz, we report some important nondetections, which put strong constraints on abundances of particular species such as (CH$_3$)$_3$O, C$_2$H$_5$CN, and HOC$^+$. Since CH$_3$CHO and HCOOCH$_3$ are detected in this source, other organic molecules related to hot corino and/or hot core chemistry are expected. (CH$_3$)$_3$O is such a molecule, and its $J_{2,4}$–$J_{5,5}$ lines (96.85 GHz) fall in our observing range. However, they were not detected at an rms noise level of 6 mK in $T_{\text{MB}}$. Similarly, C$_2$H$_5$CN has the 11$_{0,11}$–10$_{0,10}$ line at 96.92 GHz, but it was not detected at the same rms noise level of 6 mK in $T_{\text{MB}}$. In addition, HOC$^+$ is considered to be an important species in a photodissociation region (Fuente et al. 2003), and its $J = 1–0$ line located at 89.49 GHz was not seen in the present study.

### 3.6. Column Densities and Upper Limits

We derived the beam-averaged column density of each detected species under the assumption of the local thermodynamic equilibrium (LTE) condition. We also assumed that all the lines are optically thin. We confirmed this for the lines of CH$_3$OH by observing $^{13}$CH$_3$OH (T. Yamaguchi et al. in preparation). In most cases, we detected one line for each species in this survey. Although we detected a few lines for CH$_3$OH, CH$_3$CHO, and HCOOCH$_3$ each, their upper state energies are similar to one another. For this reason, the excitation temperature cannot be determined from our observations. According to Arce et al. (2008), the rotation temperature for organic molecules is around 10–30 K, although the kinetic temperature is as high as 38–140 K (Umemo et al. 1999). Bachiller et al. (1995) reported the rotation temperature of CH$_3$OH to be 12 K. Considering these results, we here assumed the excitation temperature of 30 K in deriving the column densities. In order to see the dependence of the derived column densities on the assumed excitation temperature, we also calculated the column densities with the excitation temperatures of 12 K and 50 K. The results are summarized in table 2. The quoted errors are derived from three times the rms noise of the spectra, and do not include the absolute calibration error (∼20%).

An upper limit to the column density was also evaluated for (CH$_3$)$_3$O, C$_2$H$_5$CN, CH$_3$OD, CCS, and HOC$^+$ by the same method and assumptions as are described above. In this case, the velocity width was assumed to be 6.5 km s$^{-1}$ and three times the rms noise was used as the peak intensity in the evaluation. The results are summarized in table 3.
4. Discussion

4.1. Organic Molecules

As described above, a few organic species such as CH$_3$CHO, HCOOCH$_3$, and HCOOH are detected in our line survey. This result, along with that reported by Arce et al. (2008), demonstrates rich organic chemistry in L 1157 B1. It is well known that the CH$_3$OH lines are very intense and broad in L 1157 B1 (Avery & Chiao 1996; Bachiller & Pérez Gutiérrez 1997). Its blue-shifted profile directly indicates that CH$_3$OH exists in the shocked gas, and its extremely high abundance suggests evaporation of grain mantles as its origin (Avery & Chiao 1996). In this region, strong emission of SiO was also observed with a blue-shifted profile, which suggests that SiO originates from disruption of dust grains (Mikami et al. 1992). Considering these previous results, it seems likely that other organic species could also be supplied by the grain mantle evaporation due to the outflow shock. Evaporation processes are thermal desorption, sputtering by H$_2$O, and other molecules, and grain–grain collision, the latter two of which are considered as dominant processes in shocked regions (Caselli et al. 1997).

In this survey, we successfully detected CH$_3$CHO in L 1157 B1. The CH$_3$CHO molecule is known to exist in star-forming regions. According to Ikeda et al. (2001) and Charnley (2004), the column density of CH$_3$CHO in massive star-forming regions ranges from $4 \times 10^{12}$ to $10^{14}$ cm$^{-2}$, and the fractional abundance ranges from $10^{-11}$ to $10^{-9}$. On the other hand, Cazaux et al. (2003) reported that the fractional abundance of CH$_3$CHO is $5 \times 10^{-8}$ in the hot corino of the low-mass star-forming region IRAS 16293–2422. Charnley (2004) discussed possible production pathways of CH$_3$CHO, and concluded that the gas phase chemistry cannot account for its abundance in the physical conditions of hot cores. Alternatively Charnley (2004) suggested the production by grain-surface reactions starting from CO and/or C$_2$H$_2$.

In TMC-1, the column density of CH$_3$CHO is $6 \times 10^{12}$ cm$^{-2}$ (Matthews et al. 1985), corresponding to the fractional abundance of $6 \times 10^{-10}$. The beam-averaged column density of CH$_3$CHO derived from L 1157 B1 is $(1.8-3.6) \times 10^{13}$ cm$^{-2}$, assuming that the excitation temperature ranges from 12 K to 50 K. This value is slightly higher than that in TMC-1. However, the fractional abundance of CH$_3$CHO in L 1157 B1 is evaluated to be $(1.3-2.6) \times 10^{-8}$, which is higher than that in TMC-1 by more than an order of magnitude. Here, we assume a beam-averaged H$_2$ column density of $1.4 \times 10^{13}$ cm$^{-2}$ (Bachiller & Pérez Gutiérrez 1997). This indicates that formation of CH$_3$CHO in L 1157 B1 is shock-related rather than an originally ambient component simply compressed by the shock.

In order to compare the molecular abundances in L 1157 B1 with those derived from the chemical model for shocked regions, we employ the abundance ratios relative to CH$_3$OH. The column density of the H$_2$ molecule, which is necessary for the derivation of the fractional abundances, usually has large systematic uncertainties depending on observation and analysis methods. We can minimize these uncertainties by the use of the relative abundance to CH$_3$OH. Furthermore, the uncertainty of the beam-dilution factor can also be eliminated by taking the ratio of the column densities measured with almost the same beam size. We used CH$_3$OH as a reference molecule, because this species can be regarded as a representative molecule formed on dust grains (e.g., Watanabe & Kouchi 2002).

The abundances of CH$_3$CHO, HCOOCH$_3$, and HCOOH relative to CH$_3$OH are listed in table 4. These results are compared with the shock chemistry models by Nomura and Millar (2009). A comparison of two models is made; model 1 assumes that CH$_3$CHO and HCOOCH$_3$ are formed only in the gas phase and HCOOH and CH$_3$OH on grain mantles, while model 2 assumes that all of CH$_3$CHO, HCOOCH$_3$, HCOOH, and CH$_3$OH are formed on grain mantles and then evaporate into the gas phase. In model 1, CH$_3$CHO is produced in the gas phase mainly by a reaction between the oxygen atom and C$_2$H$_2$, where C$_2$H$_2$ is formed from a grain surface molecule, C$_2$H$_6$. HCOOCH$_3$ is mainly produced from protonated methanol via a reaction as CH$_3$OH$^+ +$ H$_2$CO $\rightarrow$ HCOOCH$_3^+$ + H$_2$ and the subsequent dissociative electron recombination of HCOOCH$_3^+$. In our model, we do not consider detailed mechanisms of evaporation. Abundances of evaporated molecules (or molecules on grain surface) are simply set as initial conditions, and chemical reactions in the gas phase after evaporation of icy grain mantles are just calculated. Since the time scale for evaporation is as short as 10 yr, this treatment would not affect the result significantly.

The result of the chemical model calculation is shown in figure 2. In model 1, the [CH$_3$CHO]/[CH$_3$OH] ratio gradually increases with time due to the gas-phase production of CH$_3$CHO and it reaches at the observed value in $2 \times 10^3$ yr after the shock. Since the dynamical time scale of the outflow is $10^4$ yr, it may be possible that CH$_3$CHO is produced in the post-shocked gas by gas-phase reactions. In contrast, the [HCOOCH$_3$]/[CH$_3$OH] ratio in model 1 is much lower than the observed value. On the other hand, the [CH$_3$CHO]/[CH$_3$OH] and [HCOOCH$_3$]/[CH$_3$OH] ratios in model 2 are almost comparable to the observed

<table>
<thead>
<tr>
<th>Molecules</th>
<th>$N(T_{\text{rot}} = 12 \text{ K})^*$ (cm$^{-2}$)</th>
<th>$N(T_{\text{rot}} = 30 \text{ K})^*$ (cm$^{-2}$)</th>
<th>$N(T_{\text{rot}} = 50 \text{ K})^*$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCS</td>
<td>$&lt;1.7 \times 10^{12}$</td>
<td>$&lt;1.1 \times 10^{12}$</td>
<td>$&lt;1.3 \times 10^{12}$</td>
</tr>
<tr>
<td>HOC$^+$</td>
<td>$&lt;1.5 \times 10^{11}$</td>
<td>$&lt;3 \times 10^{11}$</td>
<td>$&lt;5 \times 10^{11}$</td>
</tr>
<tr>
<td>C$_2$H$_5$CN</td>
<td>$&lt;3 \times 10^{12}$</td>
<td>$&lt;3 \times 10^{12}$</td>
<td>$&lt;4 \times 10^{12}$</td>
</tr>
<tr>
<td>CH$_3$OCH$_3$</td>
<td>$&lt;2 \times 10^{13}$</td>
<td>$&lt;3 \times 10^{13}$</td>
<td>$&lt;5 \times 10^{13}$</td>
</tr>
<tr>
<td>CH$_3$OD (E + A)</td>
<td>$&lt;3 \times 10^{13}$</td>
<td>$&lt;7 \times 10^{13}$</td>
<td>$&lt;1.4 \times 10^{14}$</td>
</tr>
</tbody>
</table>

* Upper limits evaluated from three times the rms noise.
Table 4. Abundance ratios.

<table>
<thead>
<tr>
<th></th>
<th>L 1157*</th>
<th>IRAS 16293–2422</th>
<th>Orion KL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>((T_{\text{rot}} = 12 \text{ K}))</td>
<td>((T_{\text{rot}} = 30 \text{ K}))</td>
<td>((T_{\text{rot}} = 50 \text{ K}))</td>
</tr>
<tr>
<td>HCOOH/CH$_3$OH</td>
<td>0.0026(14)</td>
<td>0.0028(15)</td>
<td>0.0028(15)</td>
</tr>
<tr>
<td>HCOOCH$_3$/CH$_3$OH</td>
<td>0.011(5)</td>
<td>0.007(3)</td>
<td>0.007(3)</td>
</tr>
<tr>
<td>CH$_3$CHO/CH$_3$OH</td>
<td>0.006(3)</td>
<td>0.0036(18)</td>
<td>0.0031(15)</td>
</tr>
<tr>
<td>((\text{CH}_3)_2\text{O}/\text{CH}_3\text{OH})</td>
<td>&lt; 0.007</td>
<td>&lt; 0.005</td>
<td>&lt; 0.004</td>
</tr>
<tr>
<td>C$_2$H$_2$CN/CH$_3$OH</td>
<td>&lt; 0.007</td>
<td>&lt; 0.010</td>
<td>&lt; 0.009</td>
</tr>
<tr>
<td>CH$_3$DOH/CH$_3$OH</td>
<td>0.013(7)</td>
<td>0.024(12)</td>
<td>0.029(15)</td>
</tr>
<tr>
<td>CH$_3$OD/CH$_3$OH</td>
<td>&lt; 0.011</td>
<td>&lt; 0.012</td>
<td>&lt; 0.012</td>
</tr>
</tbody>
</table>

$^*$ The numbers in parenthesis represent three times the standard deviations in units of the last significant digits. Upper limits are evaluated from three times the rms noise.

$^\dagger$ Blake et al. (1987) — compact ridge.

$^\ddagger$ Ikeda et al. (2001) — compact ridge.

$^\ddagger$ Parise et al. (2002).

$^\ddagger$ Calculated from the \([\text{CH}_3\text{DOH}]/[\text{CH}_3\text{OD}]\) ratio by Jacq et al. (1993) and the \([\text{CH}_3\text{OD}]/[\text{CH}_3\text{OH}]\) ratio by Mauersberger et al. (1988).

$^*\ddagger$ Mauersberger et al. (1988).

values. Therefore, the mantle evaporation seems essential to explaining the both ratios. Although the gas-phase reactions in the postshock gas may contribute to the CH$_3$CHO production, the mantle evaporation would be responsible for the rich organic chemistry in L 1157 B1.

Next we compare the observed ratios with the corresponding values of the low-mass star-forming region IRAS 16293–2422 and the massive star-forming region, Orion KL. Upper limits to the abundances of (CH$_3$)$_2$O and C$_2$H$_2$CN relative to CH$_3$OH are also calculated for comparison and listed in table 4. A comparison of molecular abundances among the sources is not straightforward, because different sources have different distributions of molecules within the observed beam, as mentioned later. Even the abundance ratios relative to CH$_3$OH differ by an order of magnitude among observations toward the same source (e.g., Herbst & van Dishoeck 2009). For instance, the CH$_3$CHO abundance relative to CH$_3$OH toward IRAS 16293–2422 is reported to be less than 0.02 by van Dishoeck et al. (1995), whereas it is reported to be 0.17 by Cazaux et al. (2003). Nevertheless, it seems evident that the abundances of organic molecules relative to CH$_3$OH in L 1157 B1 are lower than those in IRAS 16293–2422. The differences are so large that this trend would not be changed, even if uncertainties caused by different telescopes directed at IRAS 16293–2422 are taken into account. Although L 1157 is a low-mass star-forming region, the chemical composition in the B1 position is significantly different from that of hot corinos. Conversely, the chemical composition of Orion KL (compact ridge) looks similar to that of L 1157 B1. This may imply that the compact ridge chemistry is related to the shock chemistry caused by an interaction between the outflow and the ridge cloud (e.g., Liu et al. 2002). However, the similarity may be fortuitous. According to Liu et al. (2002) and Beuther et al. (2005), the distribution of molecular emission in the compact ridge is different from molecule to molecule on a small scale (~ a few arcsec), and hence the abundances may be higher at their peak positions. A similar situation may be expected.

![Fig. 2. Chemical model simulations for a shocked region. The H$_2$ density and the kinetic temperature of the preshock gas are 10$^7$ cm$^{-3}$ and 10 K, respectively, and the shock velocity is 20 km s$^{-1}$. The shock model by Jiménez-Serra et al. (2008) is employed. About reaction rate coefficients, the UMIST database (Rate06) is used. See Nomura and Millar (2009) for details. The upper panel assumes that CH$_3$CHO and HCOOCH$_3$ are formed only in the gas phase (model 1). The lower panel assumes that all of CH$_3$CHO, HCOOCH$_3$, HCOOH, and CH$_3$OH are evaporated from grain mantles (model 2). Note that the observed [HCOOH]/[CH$_3$OH], [HCOOCH$_3$]/[CH$_3$OH], and [CH$_3$CHO]/[CH$_3$OH] ratios are 0.0026–0.0028, 0.007–0.011, and 0.003–0.006, respectively. See table 4.](image-url)
in L 1157 B1. A detailed and careful comparison between the two sources requires higher angular resolution resolving small-scale chemical differentiation.

4.2. Deuterated Molecules

In our survey, we detected one CH$_3$DOH line. The [CH$_3$DOH]/[CH$_3$OH] ratio is consequently found to be 0.013–0.029. This ratio is much lower than the corresponding ratio in IRAS 16293–2422 (0.9: Parise et al. 2002), and is almost comparable to the ratio in Orion KL (0.01–0.08: Mauersberger et al. 1988; Jacq et al. 1993). High deuterium fractionation of CH$_3$DOH in several low-mass star-forming regions including IRAS 16293–2422 is reported (e.g., Parise et al. 2002), and such high fractionation is thought to originate from heavy depletion of CO onto dust grains. Since CO is the main destroyer of the H$_2$D$^+$ ion, which is responsible for the deuterium fractionation in the gas phase, the removal of CO extends the lifetime of the H$_2$D$^+$ ion, realizing heavy deuterium fractionation in the gas phase. High fractionation of H$_2$D$^+$ causes high abundance of the D atom by the electron recombination reaction, which promotes the deuterium fractionation on grain surface. For these reasons, even triply deuterated methanol is detected in IRAS 16293–2422 (Parise et al. 2004). In view of such mechanisms of the deuterium fractionation, a rather low ratio of [CH$_3$DOH]/[CH$_3$OH] in L 1157 B1 may be reasonable, because the degree of depletion is expected to be lower in the ambient cloud than in the prestellar and protostellar cores. Note that the deuterium fractionation ratio is not affected seriously by the shock, as pointed out by the chemical model of Pineau des Forêts, Roueff, and Flower (1989), because the time scale for exchange of H and D is longer than the typical dynamical time scale of the outflow.

We have found an upper limit to the [CH$_3$OD]/[CH$_3$OH] ratio of 0.012. Since the [CH$_3$OD]/[CH$_3$OH] ratio in IRAS 16293–2422 is only 1/20 of the [CH$_3$DOH]/[CH$_3$OH] ratio (Parise et al. 2004), our nondetection of CH$_3$OD is not surprising. Here, we note that observations of deuterated molecules have been limited in L 1157 B1. Even fundamental deuterated molecules such as DCO$^+$ and DCN are not detected toward L 1157 B1, although they are detected toward the protostar position of L 1157 (Bachiller & Pérez Gutiérrez 1997). A sensitive search for other deuterated molecules would be very important for the understanding of deuterium fractionation in grain mantles.

4.3. Implications for Grain-Surface Chemistry

We have confirmed rich organic chemistry in L 1157 B1, which is revealed by the evaporation of grain mantles due to the outflow shock. As pointed out by Arce et al. (2008), the gas-phase chemical composition in L 1157 B1 reflects the chemical composition of grain mantles in an ambient cloud, although chemical processing after the evaporation would be effective for some molecules such as CH$_3$CHO (figure 2). In L 1157 B1, we can learn chemical composition of grain mantles from observations of gaseous molecules.

Abundant CH$_3$OH in L 1157 B1 means that the CO molecule, which is used in the production of CH$_3$OH on the grain, has already been depleted to some extent. More complex molecules such as HCOOCH$_3$, however, do not seem to be produced efficiently in these grain mantles, and the molecular D/H ratio is of the order of a few percent. These features would represent the nature of grain mantles existing in an ambient cloud. Formation of complex organic molecules such as HCOOCH$_3$ as well as heavy deuterium fractionation may take place in a denser region of a prestellar core. In addition, complex organic molecules would further be produced efficiently during a warm-up phase of protostellar cores (Garrod & Herbst 2006). In other words, the chemical processing in the vicinity of the protostar is different from that occurring in the outflow shock. These seem to be the reasons why the chemical composition of L 1157 B1 is different from that in hot corino sources such as IRAS 16293–2422, even though both belong to low-mass star-forming regions.

Based on these preliminary results, a complete survey of L 1157 B1 in the 3 mm band is important, not only as a great help in understanding the shock chemistry but also as a new tool to explore the chemical composition of grain mantles. Further survey observations are now in progress to unveil a complete view of the chemical compositions of molecular gas in a shocked region.

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