COMPLEX MOLECULES IN THE L1157 MOLECULAR OUTFLOW

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ABSTRACT

We report the detection of complex organic molecules in the young protostellar outflow L1157. We identify lines from HCOOCH3, CH3CN, HCOOH, and C2H5OH at the position of the B1 shock in the blueshifted lobe, making it the first time that complex species have been detected toward a molecular outflow powered by a young low-mass protostar. The timescales associated with the warm outflow gas ($<2 \times 10^3$ yr) are too short for the complex molecules to have formed in the gas phase after the shock-induced sputtering of the grain mantles. It is more likely that the complex species formed in the surface of grains and were then ejected from the grain mantles by the shock. The formation of complex molecules in the grains of low-mass star forming regions must be relatively efficient, and our results show the importance of considering the impact of outflows when studying complex molecules around protostars. The relative abundance with respect to methanol of most of the detected complex molecules is similar to that of hot cores and molecular clouds in the Galactic center region, which suggests that the mantle composition of the dust in the L1157 dark cloud is similar to dust in those regions.

Subject headings: ISM: individual (L1157) — ISM: jets and outflows — ISM: molecules — stars: formation

1. INTRODUCTION

Shocks from protostellar outflows heat and compress the surrounding medium thereby triggering different processes (e.g., grain disruption, ice grain mantle sublimation) that can release molecules trapped in the grains into the gas phase. In this way, outflows contribute to the chemical enrichment of the gaseous environment surrounding young stars. This is clearly demonstrated by multimolecular line observations reflecting enhanced molecular abundances either in shocks associated with the outflows or in the outflow cavity walls in the protostellar envelopes (e.g., Garay et al. 1998; Bachiller et al. 2001; Arce & Sargent 2006; Jørgensen et al. 2007). In most cases these molecules have similar velocity and structure as the CO lines that trace the outflows, and it is clear that the outflow is responsible for their overabundance.

The limited outflow chemistry studies show shock-triggered overabundance of parent (or “first generation”) species—molecules that are released directly into the gas phase from the icy dust mantles, such as H2CO and CH3OH—as well as other simple molecules presumably formed in the warm gas (e.g., SO, HCO+). Chemical models indicate that larger organic molecules (made of seven atoms or more) can form on grain surfaces (e.g., Garrod & Herbst 2006) and should be present in the gas phase along with the other simpler molecules observed near outflow shocks, as suggested by Chandler et al. (2005) and Remijan & Hollis (2006). Yet, to date, conclusive evidence for shock-triggered overabundances in molecular outflows from low-mass stars ($M < 2 M_\odot$) exists only for species with six atoms or less. Here we report the first detection of HCOOH, CH3CN, HCOOCH3, and C2H5OH in the L1157 molecular outflow.

The L1157 dark cloud (at a distance of about 440 pc) harbors an embedded low-mass stellar object, L1157-mm (IRAS 20386+6751), that powers a young molecular outflow (Ume moto et al. 1992). The powerful L1157 outflow is composed of several shocks seen as bright knots in near- and mid-infrared images (Davis & Eisloffel 1995; Cabrit et al. 1998; Looney et al. 2007). Millimeter observations of many molecular emission lines show that L1157 is a chemically rich outflow exhibiting an overabundance of SiO, CH3OH, H2CO, CN, HCN, SO, and a number of other species by a factor of a few tens to more than 103, depending on the molecule (Bachiller & Pérez Güiterrez 1997, hereafter BP97). In the blue (southern) lobe, the emission from these species is brightest toward two to three clumps (Bachiller et al. 2001), and high-resolution interferometer observations reveal the clumps are associated with shell-like structures created by two jet-driven bow shocks (Zhang et al. 1995; Gueth et al. 1996). These results indicate that the observed chemical enhancements are induced by the outflow shocks.

2. OBSERVATIONS AND RESULTS

Observations of the lines shown in Table 1 were obtained using the IRAM 30 m telescope in Pico Veleta, Spain, in 2007 June. Our observations concentrated in the brightest CO clump in the blue lobe of the L1157 outflow (i.e., the B1 clump), located at an offset of $\Delta x = 22.5^\circ$, $\Delta y = -64.5^\circ$ from the L1157-mm protostar at $\alpha$(J2000.0) = 20$^h$39$^m$06.2$^s$, $\delta$(J2000.0) = 68$^\circ$02′16″ (Bachiller et al. 2001). The B1 clump is far enough from the source and the telescope beam is sufficiently small (see below) that any molecular line emission associated with the gas immediately surrounding L1157-mm (i.e., within $10^4$ AU) does not contaminate our observations. Two different spectral configurations were used in order to include as many line transitions as possible of HCOOH, CH3CN, CH2CN, and HCOOCH3 (A and E)—complex molecules that have been detected in the immediate surroundings of deeply embedded low-mass protostars (Cazaux et al. 2003; Bottinelli et al. 2007). Both spectral configurations included four receivers, each simultaneously connected to a 256 channel filter bank with a spectral resolution of 1 MHz and a unit of an autocorrelator, that provided simultaneous observations at four different frequencies ranging from 90.1 to 257.6 GHz. The autocorrelator was set to provide spectral resolutions of 40 and 320 kHz and bandwidths between 40 and 320 MHz. All observations were obtained in wobbler switching mode with a 90° throw—large
four HCOOCH$_3$- transitions, three CH$_3$CN transitions, two HCOOH transitions, and one C$_2$H$_5$OH transition. The emission arises from the L1157 outflow’s blue lobe as all lines are blueshifted by 1.5–4.0 km s$^{-1}$ with respect to the L1157 cloud central velocity (30 km s$^{-1}$). We are confident that the emission is optically thin and the gas is in local thermodynamic equilibrium. In Table 2 we show our results with a correction for beam dilution, assuming a source size of 10.5″. We base our assumption of the source size on the high-resolution interferometer CH$_3$OH observations of the L1157 blueshifted lobe by Benedettini et al. (2007) which show that B1 is mostly made of two subclumps. Taken together, the emission from these two subclumps extends about 10.5″ (estimated from the geometric mean of the minor and major axis of the emission; see Fig. 2 of Benedettini et al. 2007). Whether the complex molecules are formed as a by-product of methanol in the warm gas or are ejected from the grain mantle with the methanol (see below), we expect the emission from the ob-

We detect, at a 3σ level or higher, five HCOOCH$_3$-A transitions, four HCOOCH$_3$-E transitions, three CH$_3$CN transitions, two HCOOH transitions, and one C$_2$H$_5$OH transition (see Table 1). These were identified using the CDMS and JPL catalogs (Müller et al. 2001; Pickett et al. 1998). We are confident that the emission arises from the L1157 outflow’s blue lobe as all lines are blueshifted by 1.5–4.0 km s$^{-1}$ with respect to the L1157 cloud central velocity (30 km s$^{-1}$) and have a velocity width between 2 and 7 km s$^{-1}$ as expected from the velocity distribution of other species associated with the L1157 outflow, observed toward B1 by BP97. Figure 1 shows an example of our detected lines. We used the rotational diagram method to estimate the rotational temperature ($T_{rot}$) and column densities of the species for which we detect two or more transitions (Fig. 2; see, e.g., Bisschop et al. 2007). We only detect one transition of C$_2$H$_5$OH, so we estimate its column density assuming $T_{rot} \sim 25$ K (similar to that of HCOOCH$_3$) and follow Requena-Torres et al. (2006). For all lines we assume the emission is optically thin and the gas is in local thermodynamic equilibrium. In Table 2 we show our results with a correction for beam dilution, assuming a source size of 10.5″. We base our assumption of the source size on the high-resolution interferometer CH$_3$OH observations of the L1157 blueshifted lobe by Benedettini et al. (2007) which show that B1 is mostly made of two subclumps. Taken together, the emission from these two subclumps extends about 10.5″ (estimated from the geometric mean of the minor and major axis of the emission; see Fig. 2 of Benedettini et al. 2007). Whether the complex molecules are formed as a by-product of methanol in the warm gas or are ejected from the grain mantle with the methanol (see below), we expect the emission from the ob-

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**TABLE 1**

**Detected Emission Lines**

| Molecule       | Transition  | Frequency (MHz) | $E_J/k$ (K) | $\delta V$ (km s$^{-1}$) | $T_{mb}$ (mK) | $\Delta V$ (km s$^{-1}$) | $\int T_{mb}dV$ (K km s$^{-1}$) | rms (mK) |
|----------------|-------------|-----------------|-------------|--------------------------|--------------|--------------------------|---------------------------------|----------|
| HCOOCH$_3$-A  | $7_{2,0} \rightarrow 6_{1,1}$ | 90156.48        | 19.68       | 2.1                      | 11           | 5.0 ± 1.5                | 0.06 ± 0.02                       | 2        |
| HCOOCH$_3$-A  | $8_{1,0} \rightarrow 7_{0,1}$ | 90229.63        | 20.07       | 1.0                      | 12           | 3.7 ± 1.5                | 0.05 ± 0.02                       | 3        |
| HCOOCH$_3$-A  | $8_{1,0} \rightarrow 7_{0,1}$ | 98611.15        | 27.26       | 1.0                      | 15           | 4.5 ± 0.9                | 0.07 ± 0.02                       | 3        |
| HCOOCH$_3$-A  | $8_{1,0} \rightarrow 7_{0,1}$ | 98682.60        | 31.90       | 3.0                      | 7            | 3.3 ± 2.5                | 0.03 ± 0.03                       | 3        |
| HCOOCH$_3$-A  | $8_{1,0} \rightarrow 7_{0,1}$ | 226718.70       | 120.27      | 0.8                      | 26           | 2.3 ± 0.5                | 0.07 ± 0.03                       | 8        |
| CH$_3$CN       | $14_{1,13} \rightarrow 13_{0,13}$ | 257482.80      | 156.77      | 1.2                      | 26           | 4.7 ± 1.5                | 0.13 ± 0.04                       | 7        |
| HCOOH          | $4_{1,3} \rightarrow 3_{0,3}$ | 90164.63        | 23.54       | 3.3                      | 8            | 7.3 ± 1.8                | 0.06 ± 0.02                       | 2        |
| C$_2$H$_5$OH   | $6_{1,5} \rightarrow 5_{0,5}$ | 135737.76      | 35.48       | 1.4                      | 17           | 5.8 ± 1.4                | 0.11 ± 0.03                       | 3        |

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Fig. 1.—Sample spectrum from our observations of the B1 position in the L1157 outflow. The spectrum shown here is centered around 90.17 GHz, spans about 0.15 GHz, and has a spectral resolution of 0.625 MHz (~2 km s$^{-1}$) and an rms of 2 mK.

Fig. 2.—Rotational diagrams of molecules for which we detect two or more transitional lines. Errors shown are derived from the errors in the integrated intensity (see Table 1).
low temperatures. Further observations are needed to distin-
guish these two scenarios. The two main competing scenarios propose that com-
plex organic molecules can be found in outflows from low-mass stars. The interesting
question that follows is, how are these complex molecules formed? The two main competing scenarios propose that com-
plex organic molecules mainly form either in the warm gas phase or on grain surfaces. The gas phase models were orig-
inally conceived to explain the chemical richness of hot cores. In these objects the radiation from a massive protostar is
believed to heat the dense ($n \sim 10^6-10^7$ cm$^{-3}$) inner core to temperatures higher than 100 K where the icy grain mantles
evaporate injecting molecules such as H$_2$O, H$_2$CO, and CH$_3$OH into the gas phase (e.g., Kurtz et al. 2000). The gas-phase models indicate that subsequent chemical ion-molecule re-
actions in the warm gas can result in the formation of other, more complex, molecules, such as HCCOCH$_3$ and C$_2$H$_5$OH (the so
called daughter or “second generation” species) (Charnley et al. 1992; Caselli et al. 1993). Alternatively, in the grain surface
model, the observed complex organic molecules are formed on the grain surface and are later released into the gas phase (with
H$_2$CO and CH$_3$OH) when the grain mantles evaporate (e.g., Hasegawa et al. 1992; Hasegawa & Herbst 1993).

In both models, a heat source is necessary to evaporate the icy grain mantle. At the position of B1, the outflow shock is
the only source that can trigger the ejection of molecules from the grain surface. Using the known characteristics of the L1157
outflow shocks, we can deduce which of the two mechanisms is most likely responsible for the formation of the detected
complex molecules. Multitransition millimeter observations of NH$_3$, CO, and SiO indicate that the gas associated with B1 has a
temperature between 80 and 300 K and a density of about $3 \times 10^5$ cm$^{-3}$ (Tafalla & Bachiller 1995; Umemoto et al. 1999;
Hirano & Taniguchi 2001; Nisini et al. 2007). The shocked region associated with B1 extends no more than 20" along
the outflow axis (see H$_2$ image in Zhang et al. 2000), and Nisini et al. (2007) indicate that shocks in L1157 have velocities larger
than $\sim$30 km s$^{-1}$. We therefore estimate the time it took the shock to transverse the area associated with B1 to be no more
than about 1400 yr. Molecular gas heated by a shock with a velocity of about 30 km s$^{-1}$ takes a few hundred years to cool
down below 100 K (Bergin et al. 1998). Hence, the gas in the B1 region has been above 100 K for no more than 2000 yr.

The B1 region is hot enough for grain mantles to evaporate and it is dense enough for gas-phase chemical reactions that result in complex molecules to occur (e.g., Millar et al. 1991). However, gas-phase models predict the maximum abundance of complex molecules in the gas to occur between a few $10^4$ and a few $10^5$ yr after the parent molecules are released into the gas phase (see Millar et al. 1991)—considerably longer than the timescale estimated above—and the maximum abun-
dance of HCOOCH$_3$, predicted by these models is a factor of 10 less than our observed abundance. Moreover, recent results by
Horn et al. (2004) indicate that gas-phase production of HCOOCH$_3$ is much less efficient than previously considered by
gas-phase models. It is highly improbable that most of the observed complex molecules in the L1157 outflow are pro-
duced in the gas phase. We therefore conclude that the relatively high abundance of complex molecules in the L1157 outflow is
better explained by the formation of these species on the grain surface and their subsequent release into the gas phase
caused by the outflow shock. We note that our results do not discard the possibility of small differences in the formation
mechanism of these molecules, and that a small fraction of some of the species may exist in the gas phase independent of
outflow shocks. For example, HCOOH has been observed in a quiescent dark cloud, yet HCOOCH$_3$, has only been observed
in active regions (Turner et al. 1999; Requena-Torres et al. 2007). The derived HCOOH abundance in these studies is about
$10^{-10}$, two orders of magnitude smaller than our abundance estimates in L1157. Hence, only a negligible fraction of the
complex species observed in L1157 could be due to processes unrelated to the outflow shock.

Recent surveys of abundances of complex species in hot cores, hot corinos (the presumed low-mass counterparts of hot
cores), and molecular clouds in the Galactic center (GC) region favor the grain surface formation scenario (e.g., Bottinelli et

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### Table 2: Estimates of Temperature, Column Density, and Abundance

| Molecule      | $T_{\text{rot}}$ (K) | $N$ ($10^{14}$ cm$^{-2}$) | $X = N/N_{\text{H}_2}$ |
|----------------|----------------------|----------------------------|-------------------------|
| HCOOCH$_3$-'A' | 27 ± 4              | 15 ± 4                     | 11 ± 3                  |
| HCOOCH$_3$-'E' | 18 ± 13             | 12 ± 11                    | 8 ± 7                   |
| CH$_3$CN       | 110 ± 50            | 0.1 ± 0.05                 | 0.07 ± 0.04             |
| HCOOH          | 8.0                 | 8                          | 5                       |
| C$_2$H$_5$OH   | 25$^a$              | 10                         | 7                       |

$^a$ Error estimates come from linear fit to rotational diagram.
$^b$ No error estimate included as column density was not obtained.
$^c$ No error estimate included as only two points were used for linear fit to rotational diagram.
$^d$ $T_{\text{rot}}$ assumed to be similar to the one derived for HCOOCH$_3$.
The abundance ratio of the complex molecules with respect to CH$_3$OH (another, more abundant, grain mantle constituent) can be used to investigate the origin and evolution of these complex species (e.g., Bottinelli et al. 2007). Using the abundance of CH$_3$OH in B1 reported by BP97 (about 10$^{-3}$), we derive the abundance ratios HCOOCH$_3$/CH$_3$OH, HCOOH/CH$_3$OH, C$_2$H$_5$OH/CH$_3$OH, and CH$_3$CN/CH$_3$OH to be on the order of $10^{-3}$, $10^{-3}$, $10^{-3}$, and $10^{-2}$, respectively. The first three are in agreement (within an order of magnitude) with the average abundance ratios found in hot cores and molecular clouds in the GC region (Requena-Torres et al. 2006; Bisschop et al. 2007), and are also consistent with the upper limits obtained toward the L1448 outflow by Requena-Torres et al. (2007). Taken together these results suggest the dust in hot cores, GC molecular clouds, and the L1157 molecular cloud have similar mantle composition (as similarly argued by Requena-Torres et al. 2006, 2007). In hot cores, unlike the other sources, the abundance of HCOOCH$_3$ and HCOOH with respect to methanol is 2 orders of magnitude higher that in the B1 position of L1157. Such high relative abundance in hot cores could be due to a longer warm-up phase of the gas surrounding low-mass protostars, when complex species are produced relatively more efficiently (Garrod & Herbst 2006). The CH$_3$CN-to-CH$_3$OH ratio is significantly lower by about 3 orders of magnitude for B1 than for hot cores and hot corinos (it has not been measured for GC clouds). One possible explanation for the low CH$_3$CN/CH$_3$OH in B1 could be that processes in the shocked region (but not present in hot cores or hot corinos) rapidly destroy CH$_3$CN once it is in the gas phase. It is also possible that CH$_3$CN is truly a daughter species and it shows very low abundance because there has not been enough time ($< 2 \times 10^3$ yr) for large abundances of this molecule to form in the warm gas associated with B1. With our current data we cannot confidently state which scenario is more likely and further observations are needed.

Similar abundance ratios of a number of molecules in the L1157 outflow (and in hot cores) compared to the abundance ratio of molecules in the comet Hale-Bopp led Bockelée-Morvan et al. (2000) to argue that there is a direct link between cometary and interstellar ices. The estimates of HCOOCH$_3$/CH$_3$OH and HCOOH/CH$_3$OH we obtain for L1157 are roughly similar to those of Hale-Bopp. Our results are consistent with the conclusions reached by Bockelée-Morvan et al. (2000) that molecules in cometary ices could have formed by processes very similar to those that produce the chemically rich icy mantles on interstellar grains.

In summary, our results clearly indicate that in molecular clouds with only low-mass star formation complex organic molecules can form through grain surface reactions. Outflow shocks can heat the surrounding medium and evaporate the icy grain mantles where the complex species reside, thereby releasing them into the gas phase and chemically enriching the circumstellar environment. Our results show that a protostar’s radiation is not the sole mechanism that can generate complex molecules near forming stars and that the impact of outflows needs to be considered when studying complex species around protostars. If no subsequent chemical reactions alter the abundance of complex molecules once they are released into the gas phase by the shock, then the abundance estimates from millimeter observations can be used to study the mantle composition of the dust in the cloud. Comparing the results from our observations of the B1 clump in the L1157 outflow with those of other regions observed by others suggest that the grain mantle composition in the L1157 dark cloud is comparable to that of the grains in hot cores and molecular clouds in the Galactic center region. Observations of more complex molecules and estimates of their relative abundance toward other chemically active outflows will allow us to determine the reliability of millimeter observations of shocked molecular gas for estimating the abundance of complex molecules in grains and whether similar grain mantle compositions are found in different regions of low-mass star formation.

REFERENCES