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Letter to the Editor

Methanol enhancemant in young bipolar outflows

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Abstract. We report observations of the 2_k–1_k, 3_k–2_k, and 5_k–4_k thermal lines of CH_3OH toward young bipolar outflows. Strong emission ($\gtrsim$ 6 K, in the case of L 1157) is observed toward the shocked molecular regions associated with the lobes of some outflows, whereas the emission from the cold quiescent material in the surrounding molecular core is rather weak ($\lesssim$ 1 K). We have derived the methanol abundance by combining the CH_3OH data with new $C^{18}O$ observations. It results that methanol is enhanced by large factors toward the shocked regions ($\sim$ 400 toward the blue-shifted lobe of L 1157). Although the shocked gas is known to be heated to about 100 K, the CH_3OH rotation temperatures have moderate values: in L 1157 $T_{\rm rot}$ increases from 8 K in the ambient gas to 12 K in the shocked region. Radiative transfer calculations, carried out to simulate the CH_3OH excitation in different physical circumstances, confirm that in the range of physical conditions discussed here the methanol molecules are very subthermally excited, and $T_{\rm rot}$ is not a good measure of the kinetic temperature ($T_{\rm rot} << T_{\rm K}$). The observed methanol abundance enhancements are likely caused by processes of desorption of grain mantles in shocks.

Key words: Stars: formation — ISM: jets and outflows — ISM: individual objects: L 1157 — ISM: molecules — ISM: abundances — Radio lines: ISM

1. Introduction

Bipolar outflows are the most spectacular phenomenon observed around newly formed stars. In recent years, the study of highly collimated outflows (Bachiller & Gómez-González 1992) has revealed that there is a class of bipolar outflows which are driven by jets that accelerate the ambient gas via the propagation of large bow shocks (e.g. Raga & Cabrit 1993). The shocked molecular material is well observed in lines of H_2 (e.g. Hodapp 1994), SiO (Martín-Pintado et al. 1992), and NH_3 (Bachiller et al. 1993). The shocked gas is highly excited, and in particular, one concludes that shock processing of the dust grains has caused an enhancement of the abundance of some Si or S–containing molecules (e.g. Bachiller et al. 1991; Chernin et al. 1994). It is of importance to ascertain which other species show enhanced abundances.

Methanol, CH_3OH, is known to be present in interstellar ice mantles and is thus expected to be desorbed from grains (e.g. Millar et al. 1991; Charnley et al. 1992). We present in this *Letter* the first results of a survey for CH_3OH emission in highly collimated bipolar outflows. The CH_3OH abundance is observed to be spectacularly enhanced in the bow shocks of some outflows, confirming the importance of grain desorption in shocks as a formation process for interstellar methanol.

2. Observations

The observations were carried out with the IRAM 30-m radio telescope at Pico Veleta (near Granada, Spain) in March and September 1994. We used three SIS receivers operating in the bands around $\lambda\lambda$ 3, 2, and 1 mm to simultaneously observe some of the J_k=2_k→1_k (96.7 GHz), 3_k→2_k (145.1 GHz), and 5_k→4_k (241.8 GHz) lines of CH_3OH. The SSB noise temperature of the receivers was 85 K at 96.7 GHz, and close to 150– 180 K at the other frequencies. The antenna half-power beamwidths and main beam efficiencies were 25″ and 0.63 at 96.7 GHz, 17″ and 0.56 at 145.1 GHz, and 11″ and 0.42 at 241.8 GHz. Pointing was checked every hour by observing nearby planets or continuum sources, and was found to be accurate to within 3″. The spectrometers were autocorrelators providing a spectral resolution of 0.12 km s^{-1} at 96.7 GHz, 0.16 km s^{-1} at 145.1 GHz, and 0.39 km s^{-1} at 241.8 GHz. All observations were made in position switching mode (the ON and OFF positions were separated by typically 10– 15′), and linear baselines were subtracted from the spectra. The calibration of the data was achieved by the chopper wheel method. Intensities are given in units of main beam brightness temperature.

The J=1→0 and 2→1 lines of $C^{18}O$ at 109.8, and 219.6 GHz were also observed at some particular positions with the aim of studying the CH_3OH abundance. The telescope HPBW and and main beam efficiencies were 22″ and 0.61 at 109.8 GHz, and 12″ and 0.46 at 219.6 GHz. Receiver temperatures were similar to those during the CH_3OH observations.

3. Results

We observed selected positions in the bipolar outflows listed in Table 1. These are highly collimated bipolar outflows in which the shocked molecular regions are known to be prominent from previous H_2, SiO, or NH_3 observations. As an illustration of our results, we discuss the L 1157 outflow with some more detail.

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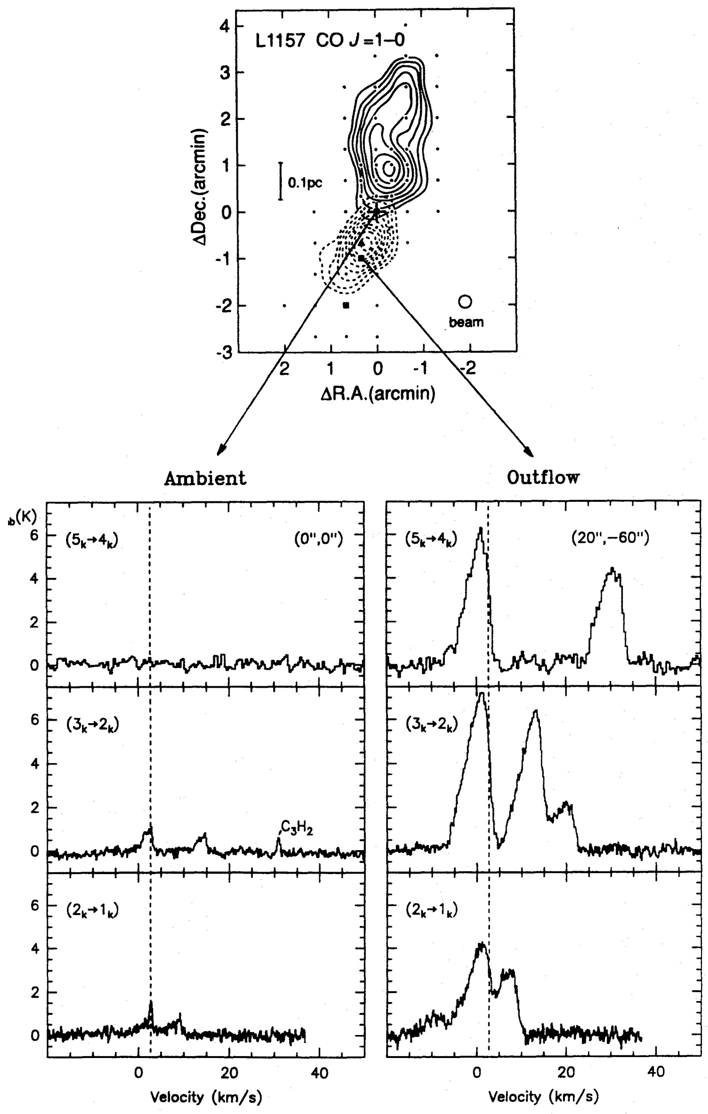

Fig. 1. Below are shown CH_3OH spectra obtained toward two selected positions in the L 1157 outflow. Above is the CO (1–0) map from Umemoto et al.(1992) with the observed positions marked. Offsets on this map and elsewhere are relative to the position given in the caption to Table 1. Dashed contours on the CO map show the distribution of blue shifted emission (-5 to 1 km s^{-1}) and solid contours red shifted (4.5 to 10.5 km s^{-1}). Toward the position of the IRAS source 20386+6751 (offset 0,0), weak and narrow emission lines of 2_0-1_0 A^+, $2_{-1}-1_{-1}$E, 3_0-2_0 A^+, and $3_{-1}-2_{-1}$E are detected. However, toward position (20″,–60″), in the blueshifted lobe, the lines are broader and brighter and we detect the more highly excited J=5 and 3_0-2_0E lines. The velocity scales of the spectra are calculated with respect to the frequency of the 2_0–1_0 A^+ line (96.74142 GHz), 3_0–2_0 A^+ (145.10323 GHz), and 5_0–4_0 A^+ (241.79143 GHz), for the low, middle, and upper panels, respectively. The 3_{12}–2_{21} line of C_3H_2 is detected towards the (0,0) position. The dashed line at 2.7 km s^{-1} indicates the velocity of the ambient quiescent emission. Note the blue-shift of the emission at position (20″,–60″).

3.1. L 1157

At a distance of 440 pc, and with a very favorable orientation, the outflow in L 1157 is one of the best targets for the study of shocked molecular gas. In particular, the blue-shifted lobe of the outflow presents clear signs of shock-excitation in line emission from CO (Umemoto et al. 1992), SiO (Mikami et al. 1992), H_2 (Hodapp 1994), and NH_3 (Bachiller et al. 1993). The outflow is excited by IRAS 20386+6751, a cold source of 11 $L_\odot$ embedded within a dense core at 12 K. In contrast, the molecular material associated with the shocked region, traced by NH_3 lines, is heated to about 100 K (Bachiller et al. 1993).

We searched the outflow area for methanol emission and present some profiles in Fig. 1. Weak narrow lines ($\sim$ 1 K) are observed toward the IRAS position. Both the central velocity and the linewidth are characteristic of the dense core. In contrast, the lines observed toward the outflow lobes are much brighter and broader. The profiles toward (20″,–60″) are clearly blueshifted with respect to the ambient velocity and typical linewidths are $\sim$ 6 km s^{-1}, indicating that the profiles are dominated by emission associated with the outflow. The CH_3OH profiles are similar to those of other lines tracing the shocked molecular material (e.g.: SiO, NH_3 (3,3)). Methanol emission is clearly enhanced in the shocked molecular gas.

Up to 17 lines of CH_3OH were detected toward position (20, –60) (we only display a few of them in Fig. 1 for clarity). In order to estimate rotational temperatures and column densities, we have used the standard "rotation diagram" method. This method has been extensively used by many authors in the interpretation of multiline molecular observations (e.g.: Cummins et al. 1986). We present in Fig. 2 the rotation diagrams corresponding to the IRAS position and the outflow. Least-square fits to all detected lines yield rotational temperatures of $T_{\rm rot}$ = 8 K (ambient) and 12 K (outflow). The column densities averaged over the beam are $N(CH_3OH) = 1.4\ 10^{14}$ cm^{-2} (ambient), and 3.0 10^{15} cm^{-2} (outflow).

We have estimated the H_2 column densities toward the quiescent gas using our observations of $C^{18}O$, and applying the conversion of $C^{18}O$ intensity to H_2 column density given by Cernicharo and Guélin (1987). Toward the high-velocity gas, the H_2 column density is estimated from previously published CO observations (Umemoto et al. 1992). We find (see Table 1) that the CH_3OH abundance is enhanced by a factor 400 toward the shocked molecular gas associated with the outflow.

3.2. Other sources

Methanol emission enhancements similar to that seen in L 1157 are observed toward the outflow around IRAS 03282+3035, and NGC 2071. We show in Fig. 3 some of the observed profiles. Toward IRAS 03282+3035, the methanol emission is relatively weak: in fact, the quiescent gas emission is hardly seen toward the (0,0) position. However, broad emission lines have been detected toward position (150″, -110″) in the blue-shifted lobe. In NGC 2071, the profiles obtained toward the (0,0) position are very complex; they exhibit very deep self-absorption dips together with the outflow wings, and it is very difficult to separate the quiescent and the outflow emission components. In contrast, the profiles obtained toward position (30″, 60″) have narrow lines centered at the velocity of the ambient cloud, and are more representative of the dense core (see Fig. 3). On the other hand, the emission toward (-80″, -80″) is brighter, broader, and red-shifted with respect to the ambient cloud.

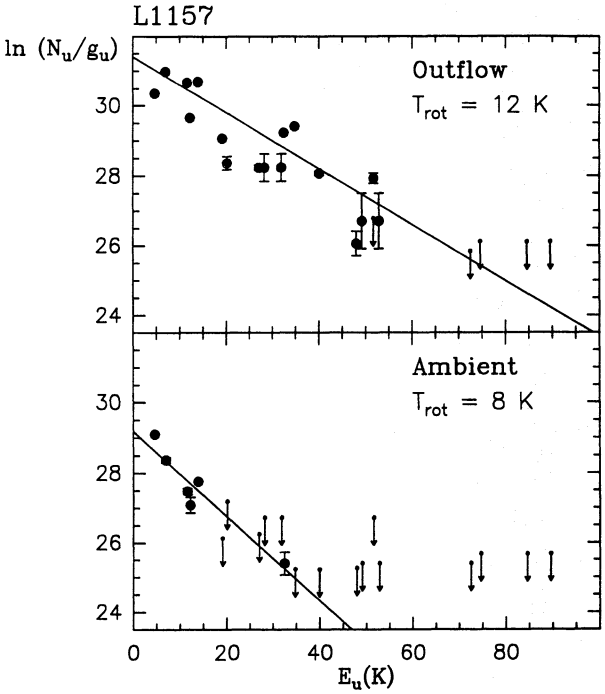

Fig. 2. Rotation diagrams for the methanol transitions measured toward positions (0″,0″) and (20″,–60″) in L 1157. N_u, g_u, and E_u, are the column density, the degeneracy, and the energy for the upper levels of the considered transitions. Errorbars are given at 1σ level, and arrows represent upper-limits. The straight lines are linear least-square fits to the detection points. The derived values of the rotation temperatures are also given.

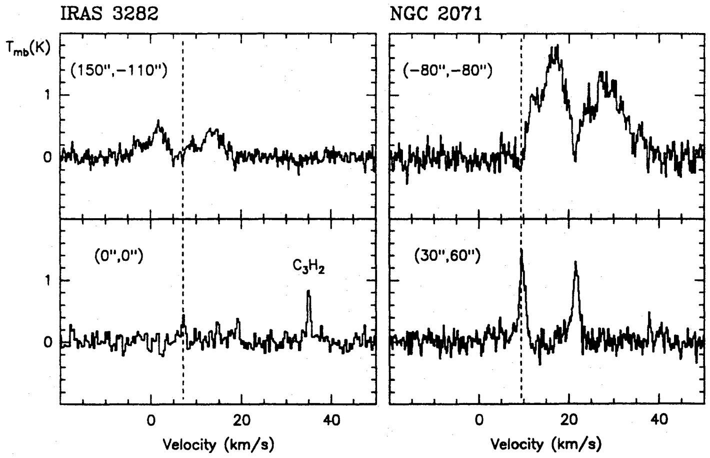

Fig. 3. CH_3OH spectra obtained toward two selected positions around IRAS 03282+3035, and NGC 2071. The velocity scales of the spectra are calculated as in Fig. 1. The dashed line indicates the velocity of the ambient quiescent emission. The 3_{12}–2_{21} line of C_3H_2 is detected towards the (0,0) offset in IRAS 03282.

We observed other outflows in which the interpretation is unclear. Toward some positions of L 1448 and L 1551, methanol is detected but no prominent wing emission is observed. Toward Cep-A, the profiles present broad wings, but the presence of self-absorption dips complicates the data analysis.

In Table 1 we give the rotation temperatures and column densities derived for selected positions. Methanol abundances have been estimated, as in the case of L 1157, by comparing with $C^{18}O$ observations for the quiescent gas, and with CO for the high-velocity gas. For orientation, we also give a new determination of the methanol abundance toward the cyanopolyyne emission peak in TMC 1 ($\sim 1.5\times10^{-9}$), which is in good agreement with previous estimates (Friberg et al. 1988). Toward the shocked gas associated with IRAS 03282 and NGC 2071, the methanol abundance is observed to be enhanced by factors of 40 and 170, respectively.

4. Methanol excitation

One of the more intriguing results from our study is that the measured rotation temperature (see Fig. 2) increases by only a factor of 1.5 when one compares the ambient core gas (8 K in the case of L 1157) and the shocked gas (12 K). By contrast, the kinetic temperature derived from ammonia changes from 12 to 100 K between these two positions (Bachiller et al. 1993). In order to clarify this, we used the statistical equilibrium code described by Walmsley et al. (1988) to calculate level populations for methanol at these two temperatures. For this purpose, we considered levels up to J=15 and K up to 3 in both A and E-type methanol. The calculations were carried out assuming that a) the A-type to E-type methanol abundance ratio is unity and b) the methanol column density to line width ratio $N(CH_3OH)/\Delta v$ is $2\,10^{14}$ cm^{-2}(km s^{-1})$^{-1}$. This latter assumption in particular is somewhat arbitrary but the column density is in the range needed to account for the observations. However, our objective is not to fit the data but to show that for all likely densities, the methanol populations are likely to be extremely sub–thermal and that, as a consequence, the rotation temperatures derived in the manner described above are likely to be considerably smaller than the kinetic temperature.

With this in mind, we have varied the H_2 density between 10^5 and 10^8 cm^{-3} and analysed the results of the statistical equilibrium calculation in the same manner as the observational data. That is to say we have assumed low optical depth in order to compute the level column densities in the upper levels of the appropriate transitions and fit the results to a Boltzmann distribution. In this way, we determine a theoretical T_{rot} for T_K =100 K which varies from 9.6 K at n(H_2) = 10^5 cm^{-3} to 59 K at n(H_2)= 10^8 cm^{-3}. At a density of $2\,10^6$ cm^{-3}, T_{rot} is equal to 12.5 K and is thus equal within the errors to the observed value in the shocked gas toward L 1157. By contrast at a temperature of 12 K, the fitted T_{rot} varies from 5 K at 10^5 cm^{-3} to 10.5 K at 10^8 cm^{-3}. We conclude from this that at densities below about 10^7 cm^{-3}, the temperatures derived from methanol "rotation diagrams" should be extremely sub-thermal. Our data suggests that the H_2 number density in both the ambient core and towards the shocked region in L 1157 is of order 10^6 cm^{-3}. However, we note that our conclusions are based upon somewhat uncertain assumptions concerning the methanol collisional rates. In particular, it is relevant here that collisions changing the k quantum number appear to be relatively forbidden (Lees & Haque 1974) leading to lower excitation temperatures between k–ladders than along k–ladders. Clearly, theoretical and experimental studies of methanol collisional rates are needed to verify this point.

Table 1. Physical parameters deduced from observations. The integrated intensity, velocity and linewidth are given for the $3_0 \rightarrow 2_0 A^+$ transition.

Source	Offset [a] ($''$, $''$)	$\int T_{mb} dv$ [b] (K km s^{-1})	v_{LSR} [b] (km s^{-1})	Δv [b] (km s^{-1})	T_{rot} [b] (K)	N_{CH_3OH} (cm^{-2})	X_{CH_3OH}
Quiescent cloud positions							
L 1157	(0, 0)	2.4(0.2)	2.0(0.1)	2.3(0.2)	8(2)	1.4 10^{14}	1.8 10^{-8}
NGC 2071	(30, 60)	2.2(0.1)	9.7(0.1)	1.6(0.1)	8(4)	1.2 10^{14}	6 10^{-9}
IRAS 03282	(0, 0)	0.5(0.2)	6.7(0.1)	1.8(0.4)	9(3)	4.0 10^{13}	4.9 10^{-9}
TMC 1	(0, 0)	0.3(0.1)	5.8(0.1)	0.4(0.1)	5(2)	2.5 10^{13}	1.4 10^{-9}
Shock positions							
L 1157	(20, −60)	44.5(0.3)	0.2(0.1)	5.9(0.1)	12(2)	3.0 10^{15}	7.0 10^{-6}
NGC 2071	(−80, −80)	12.1(0.3)	16.2(0.1)	7.3(0.2)	11(3)	7.3 10^{14}	~10^{-6}
IRAS 03282	(150, −110)	2.5(0.2)	1.2(0.1)	5.8(0.5)	14(2)	1.8 10^{14}	2 10^{-7}

[a] Offsets given with respect to the following center positions (1950.0): L 1157: $20^h38^m39^s.6$, 67°51′33″, NGC 2071: $05^h44^m23^s.0$, 00°20′40″, IRAS 03282: $03^h28^m15^s.2$, 30°35′14″, TMC 1: $04^h38^m38^s.0$, 25°35′45″. [b] Numbers in parentheses are 1 rms errors.

5. Discussion and conclusions

The main result emerging from our observations is that the methanol abundance can be very enhanced within the shocked regions associated with bipolar outflows. Such methanol enhancements generated by shocks have been thought to be important for a long time, and some recent observations confirm this. From low angular resolution data, Slysh et al. (1994) observed that the 1_0–0_0 A^+ line at 48.4 GHz was brighter in clouds with high velocity outflows. Sandell et al. (1994) reported an enhancement of the 5_k–4_k line emission in the shocked region associated with the outflow in NGC 1333/IRAS 2. Additionally, the prototypical Orion molecular cloud has been extensively observed with the aim of studying the behavior of the methanol abundance. In the Orion Compact Ridge, there is a unusually high abundance of CH_3OH (Blake et al. 1987; Menten et al. 1988) which was explained by Millar et al. (1991) and Charnley et al. (1992) as a result of desorption from grains due to shocks. In fact, the two prominent emission peaks observed near Orion KL and S 6 (see for instance the maps by Menten et al. 1988) are associated with FIR sources which drive energetic outflows. In dense cores similar to those in the Compact Ridge or in L 1157, the complex molecules are probably accreted or formed on the grain surfaces during the collapse of the cold cloud core. Such molecules could be released again to the gas phase by the shock-processing of the dust grains caused by the bipolar outflows from newly formed stars. But surprisingly, the Orion Hot Core, which is a region denser and hotter than the Compact Ridge, does not show any strong methanol enhancement. Caselli et al. (1993) have recently suggested that the higher temperature of the Hot Core prevents volatile CO molecules from remaining on dust particles thus impeding the formation of CH_3OH.

Our data suggests that CH_3OH is enhanced in certain shocked regions where the physical conditions are not so extreme as in the Orion Hot Core. The shocked molecular layers associated with bipolar outflows from young stars of low to moderate luminosity appear to be suitable locations for such enhancements. This might occur for example in C-type shocks as a consequence of the relative velocity of ionized grains and neutral molecules. It is unclear whether the CH_3OH molecules are released directly from the dust grains, or if methanol forms in gas phase from simpler molecules released from the grain mantles (see e.g. Charnley et al. 1992). More observations of CH_3OH and of other chemically related species are needed before drawing detailed conclusions concerning the origin of the CH_3OH enhancements reported here.

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