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LETTER TO THE EDITOR

The CHESSE spectral survey of star forming regions: Peering into the protostellar shock L1157-B1

I. Shock chemical complexity^{★,★★}

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ABSTRACT

We present the first results of the unbiased survey of the L1157-B1 bow shock, obtained with HIFI in the framework of the key program Chemical *Herschel* Survey of Star forming regions (CHESSE). The L1157 outflow is driven by a low-mass Class 0 protostar and is considered the prototype of the so-called chemically active outflows. The bright blue-shifted bow shock B1 is the ideal laboratory for studying the link between the hot (~1000–2000 K) component traced by H₂ IR-emission and the cold (~10–20 K) swept-up material. The main aim is to trace the warm gas chemically enriched by the passage of a shock and to infer the excitation conditions in L1157-B1. A total of 27 lines are identified in the 555–636 GHz region, down to an average 3 σ level of 30 mK. The emission is dominated by CO(5–4) and H₂O(1₁₀–1₀₁) transitions, as discussed by Lefloch et al. in this volume. Here we report on the identification of lines from NH₃, H₂CO, CH₃OH, CS, HCN, and HCO⁺. The comparison between the profiles produced by molecules released from dust mantles (NH₃, H₂CO, CH₃OH) and that of H₂O is consistent with a scenario in which water is also formed in the gas-phase in high-temperature regions where sputtering or grain-grain collisions are not efficient. The high excitation range of the observed tracers allows us to infer, for the first time for these species, the existence of a warm (≥ 200 K) gas component coexisting in the B1 bow structure with the cold and hot gas detected from ground.

Key words. ISM: individual objects: L1157 – ISM: molecules – stars: formation

1. Introduction

A newborn protostar generates a fast and well collimated jet, possibly surrounded by a wider angle wind. In turn, the ejected material drives (bow-)shocks travelling through the surrounding high-density medium and traced by H₂ ro-vibrational lines at excitation temperatures of around 2000 K. As a consequence, slower and cold (10–20 K) molecular outflows are formed by swept-up material, usually traced by CO. Shocks heat the gas and trigger several processes such as endothermic chemical reactions and ice grain mantle sublimation or sputtering. Several molecular species undergo significant enhancements in their abundances (see e.g., van Dishoeck & Blake 1998), as observed by observations at millimeter wavelengths towards a number of outflows (Garay et al. 1998; Bachiller & Pérez Gutiérrez 1997, BP97 hereafter; Jørgensen et al. 2007). The link between the gas

components at ~10 K and the hot 2000 K shocked component is crucial to understanding how the protostellar wind transfers momentum and energy back to the ambient medium. In this context, the understanding of the chemical composition of a typical molecular bow-shock is essential because it represents a very powerful diagnostic tool for probing its physical conditions.

The L1157 outflow, located at a distance estimated to be between 250 pc (Looney et al. 2007) and 440 pc (Viotti 1969) may be regarded as the ideal laboratory for observing the effects of shocks on the gas chemistry, being the archetype of the so-called chemically rich outflows (Bachiller et al. 2001). The low-luminosity (4–11 L_⊙) Class 0 protostar IRAS20386+6751 drives a precessing powerful molecular outflow associated with several bow shocks seen in CO (Gueth et al. 1996) and in IR H₂ images (Davis & Eislöffel 1995; Neufeld et al. 2009). In particular, the brightest blue-shifted bow-shock, called B1 (Fig. 1), has been extensively mapped with the PdB and VLA interferometers at mm- and cm-observations revealing a rich and clumpy structure, the clumps being located at the wall of the cavity with an arch-shape (Tafalla & Bachiller 1995; Gueth et al. 1998; Benedettini et al. 2007, hereafter BVC07; Codella et al. 2009).

* *Herschel* is an ESA space observatory with science instruments provided by European-led principal Investigator consortia and with important participation from NASA.

** Table 1 is only available in electronic form at <http://www.aanda.org>

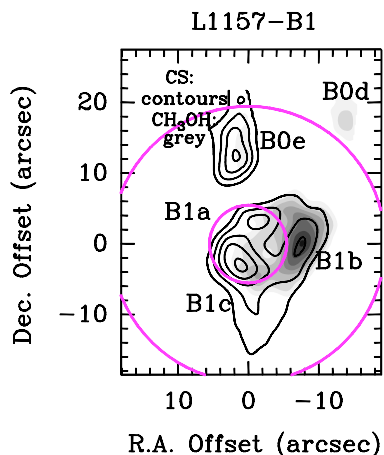


Fig. 1. The B1 clump. PdBI emission of $\text{CH}_3\text{OH}(2_{1-1})\text{A}^-$ (grey) on the CS(2–1) one (contours), from BVC07. The maps are centred on the coordinates used for the present HIFI observations $\alpha_{J2000} = 20^{\text{h}}39^{\text{m}}10^{\text{s}}.2$, $\delta_{J2000} = +68^{\circ}01'10''.5$, i.e. at $\Delta\alpha = +25''.6$ and $\Delta\delta = -63''.5$ from the driving protostar. The labels indicate the main B1 clumps detected in different tracers. Circles are for the HPBWs of the HIFI data presented here (39'') and of Band 7 (11''), i.e., at the highest frequencies of the CHES surveys.

L1157-B1 is well traced by molecules thought to be released by dust mantles such as H_2CO , CH_3OH , and NH_3 as well as typical tracers of high-speed shocks such as SiO (e.g., Gusdorf et al. 2008). Temperatures ≈ 60 –200 K (from NH_3 , CH_3CN , and SiO) as well as around 1000 K (from H_2) have been derived (Tafalla & Bachiller 1995; Codella et al. 2009; Nisini et al. 2007, in prep.). However, a detailed study of the excitation conditions of the B1 structure has yet to be completed because of the limited range of excitation covered by the observations performed so far at cm- and mm-wavelengths. Observations of sub-mm lines with high excitation (≥ 50 –100 K above the ground state) are thus required.

As part of the *Herschel* key program CHES¹ (Chemical *HERschel* Surveys of Star forming regions), L1157-B1 is currently being investigated with an unbiased spectral survey using the HIFI instrument (de Graauw et al. 2010). In this Letter, we report the first results based on HIFI observations in the 555–636 GHz spectral window, confirming the chemical richness and revealing different molecular components at different excitation conditions coexisting in the B1 bow structure.

2. Observations

The observations were performed on 2009, August 1, during the Performance Verification phase of the HIFI heterodyne instrument (de Graauw et al. 2010) on board of the *Herschel* Space Observatory (Pilbratt et al. 2010). The band called 1b (555.4–636.2 GHz) was covered in double-sideband (DSB) with a total integration time of 140 min. The wide band spectrometer was used with a frequency resolution of 1 MHz. The typical HPBW is 39''. The data were processed with the ESA-supported package HIPE² (*Herschel* interactive processing environment) for baseline subtraction and sideband deconvolution and then analysed with the GILDAS³ software. All the spectra (here in units of antenna T_a) were smoothed to a velocity resolution of

1 km s^{-1} , except those showing the weakest emission, which were smoothed to lower spectral resolutions (up to 4 km s^{-1}). At a velocity resolution of 1 km s^{-1} , the rms noise is 6–13 mK (T_a scale), depending on the line frequency. The main-beam efficiency (η_{mb}) has not yet been reliably determined. When needed, we adopted an average η_{mb} of 0.72.

3. Different tracers at different velocities

A total of 27 emission lines were detected, with a wide range of upper level energies, from a few tens to a few hundreds of Kelvin. Table 1 lists the spectroscopic and observational parameters of all the transitions. For the first time, high excitation (up to ≈ 200 K) emission lines related to species whose abundance is largely enhanced in shocked regions were detected. The CO(5–4) and $\text{H}_2\text{O}(1_{10-1_{01}})$ lines are analysed in Lefloch et al. (2010). Figure 2 presents representative examples of line profiles observed towards L1157-B1. All the spectra contain lines with blue-shifted wings peaking near 0 km s^{-1} , which have a terminal velocity equal to $\sim -8, -6$ km s^{-1} . Previous PdBI observations showed that L1157-B1 is associated with very high velocities (HVs) of as low as ≈ -20 km s^{-1} ($v_{\text{LSR}} = +2.6$ km s^{-1} , BP97). We cannot exclude the lack of detected emission in the HV regime in the present HIFI spectra being caused by their relatively low signal-to-noise (S/N) ratio. The PdBI images indicate that the brightness of the emission lines in the HV regime is indeed weaker than the emission at low velocities by a factor of 5–10. The spectra in Fig. 2 clearly show that this weak emission would lie below the noise. On the other hand, the HV gas is detected in the very bright lines of CO and H_2O (Lefloch et al. 2010). We note that the HV emission is mostly confined to within the eastern B1a clump (Fig. 1), within an emitting region of size $\leq 10''$ (Gueth et al. 1998; BVC07), whereas low velocity lines originate in both the bow-structure and the walls of the outflow cavity (e.g., the B0e and B0d in Fig. 1), of typical size 15''–18''. Therefore, the forthcoming HIFI-CHES observations at higher frequencies and higher spatial resolution (see the dashed circle in Fig. 1) should allow us to study the HV wings in species other than CO and H_2O .

The uniqueness of HIFI lies in its high spectral profile resolution for many high excitation transitions of a large number of molecular species. The analysis of the present HIFI spectra reveals a secondary peak occurring between -3.0 and -4.0 km s^{-1} (here defined medium velocity, MV) and well outlined by e.g., HCN(7–6). The MV peak is also visible in $\text{NH}_3(1_{0-0_0})$ and in some lines of CH_3OH and H_2CO (see Fig. 3), but its occurrence does not show any clear trend with the choice of tracer of line excitation. No single-dish spectra had previously detected this spectral feature (BP97; Bachiller et al. 2001). An inspection of the spectra observed at PdBI shows that the MV secondary peak is observed in a couple of lines of the $\text{CH}_3\text{OH}(2_{\text{K}}-1_{\text{K}})$ series (see Fig. 3 of BVC07) and only towards the western B1b clump (size $\sim 5''$). This finding implies that there is a velocity component originating mainly in the western side of B1, while the HV gas is emitted from the eastern one (see above).

Figure 3 compares the profiles of the $\text{NH}_3(1_{0-0_0})$ and $\text{H}_2\text{CO}(8_{17-7_{16}})$ lines with the $\text{H}_2\text{O}(1_{10-1_{01}})$ profile, where the S/N allows such an analysis (MV and LV ranges). By assuming that the emission in the MV range is optically thin (including the H_2O line) and originates in the same region, we obtained from the comparison of their profiles a straightforward estimate of the relative abundance ratios of the gas at different velocities. As a notable example, the $\text{NH}_3/\text{H}_2\text{O}$ intensity ratio decreases by a factor ~ 5 moving towards higher velocities (Fig. 3), implying

¹ <http://www-laog.obs.ujf-grenoble.fr/heberges/ches/>

² HIPE is a joint development by the *Herschel* Science Ground Segment Consortium, consisting of ESA, the NASA *Herschel* Science Center, and the HIFI, PACS and SPIRE consortia.

³ <http://www.iram.fr/IRAMFR/GILDAS>

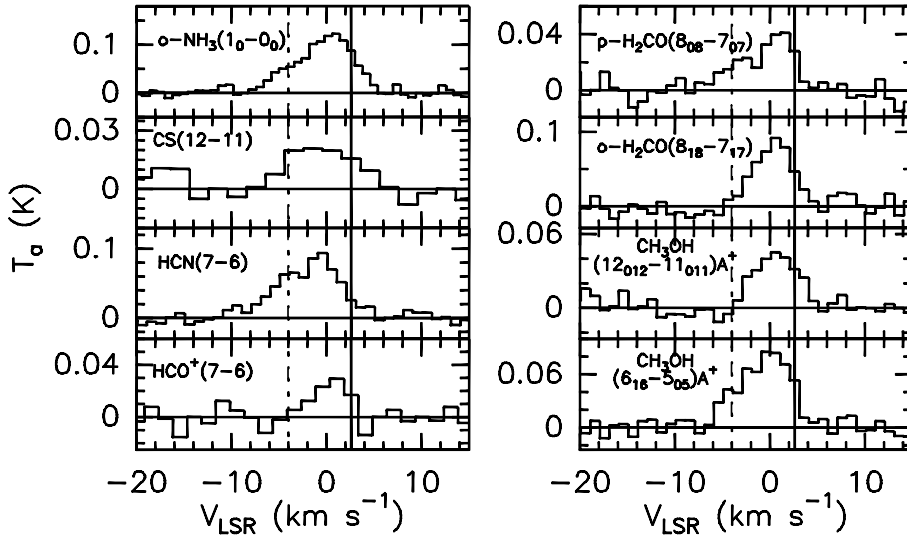


Fig. 2. Molecular line profiles observed towards L1157-B1: species and transitions are reported in the panels. The vertical solid line indicates the ambient LSR velocity ($+2.6 \text{ km s}^{-1}$ from C^{18}O emission; BP97), while the dashed one is for the secondary peak at -4.0 km s^{-1} .

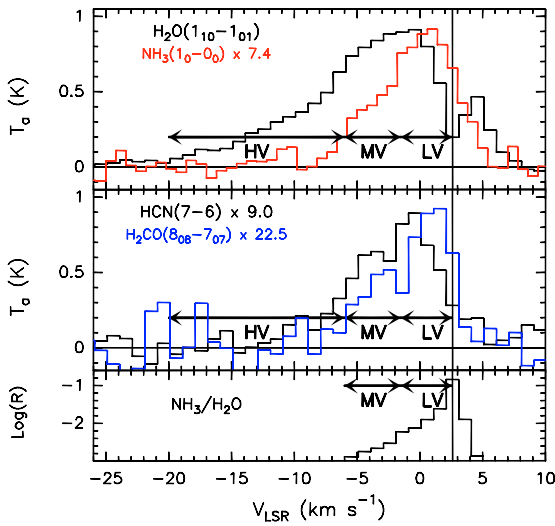


Fig. 3. *Top and middle panels:* Comparison between the profiles of $\text{NH}_3(1_0-0_0)$, multiplied by a factor 7.4, $\text{H}_2\text{CO}(8_{17}-7_{16})$, multiplied by a factor 22.5, $\text{HCN}(7-6)$, multiplied by a factor 9.0, and $\text{H}_2\text{O}(1_{10}-1_{01})$, the latter from Lefloch et al. (2010). The vertical solid line indicates the ambient LSR velocity ($+2.6 \text{ km s}^{-1}$). The velocity ranges arbitrarily defined as HV ($-20, -6 \text{ km s}^{-1}$; traced by H_2O), MV ($-6, -1.5 \text{ km s}^{-1}$; outlined by the HCN and H_2CO secondary peak), and LV ($-1.5, +2.6 \text{ km s}^{-1}$; the rest of the blue wing) are drawn (see text). *Bottom panel:* Intensity $\text{NH}_3/\text{H}_2\text{O}$ line ratio as a function of velocity.

that a similar decrease in the abundance ratios occurs. This may reflect different pre-shock ice compositions in the gas emitting the MV emission. Alternatively, this behavior is consistent with NH_3 being released by grain mantles, but water both being released by grain mantles and, in addition, copiously forming in the warm shocked gas from endothermic reactions, which convert all gaseous atomic oxygen into water (Kaufman & Neufeld 1997; Jiménez-Serra et al. 2008, and references therein). The water abundance may be enhanced with respect to ammonia in the fast and warm ($\geq 220 \text{ K}$) gas, which might explain why the H_2O wings are larger than those of NH_3 , CH_3OH , and H_2CO , all species being directly evaporated from dust grain mantles.

4. Physical properties along the B1 bow shock

We detected several lines from CH_3OH (17 lines with upper level energies up to 211 K). We can derive a first estimate of the emitting gas temperature by means of the standard analysis

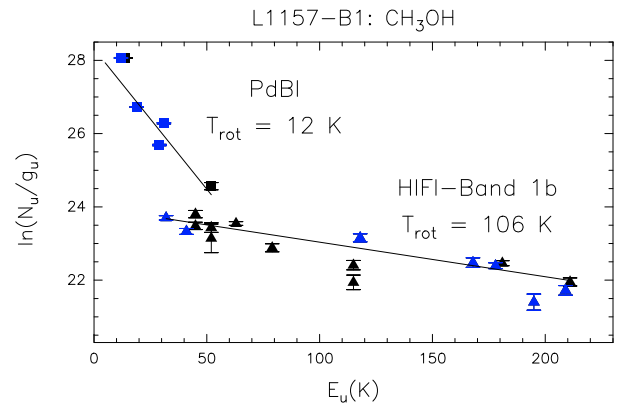


Fig. 4. Rotation diagrams for the CH_3OH transitions measured with HIFI (triangles) and from ground (PdBI; squares). Black and blue points are for A- and E-form, respectively. The parameters N_u , g_u , and E_u are, respectively, the column density, the degeneracy and the energy (with respect to the ground state of each symmetry) of the upper level. The derived values of the rotational temperature are reported: (i) 106 K, for the HIFI lines covering the $E_u = 32\text{--}211 \text{ K}$ excitation range and (ii) 12 K (as Bachiller et al. 1995), for the PdBI lines, at lower excitation.

of the rotational diagram. We show the case of methanol (A- and E-forms) in Fig. 4. The derived rotational temperature (T_{rot}) is 106 K (with an uncertainty of $\sim 20 \text{ K}$), which represents a lower limit to the kinetic temperature (T_{kin}). In the same figure, we report the methanol lines (2_K-1_K) observed with PdBI and whose intensity is integrated in the HIFI 39'' beam. The T_{rot} derived from the ground-based data (based only on lines with $E_u \leq 50 \text{ K}$; BVC07) is definitely lower, $\sim 12 \text{ K}$, in perfect agreement with that found with the 30-m spectra in the same excitation range by Bachiller et al. (1995). As discussed by Goldsmith & Langer (1999), this behavior may be caused by either two components at different temperatures or both non-LTE effects and line opacity. These two possibilities cannot be distinguished based only on the rotational diagram. However, given that a range of T_{kin} and n_{H_2} is naturally expected in a shock, if we were to assume that two gas components provide an explanation, they would not only have different temperatures but also a different column densities. Taking the filling factor $f = 0.13$, derived by the CH_3OH maps obtained at the PdBI, the low temperature component column density is $8 \times 10^{14} \text{ cm}^{-2}$ (in agreement with Bachiller et al. 1995), whereas the high temperature component has a column density of around 10^{14} cm^{-2} . We note that the rotation diagrams

obtained for the MV and LV CH₃OH emission separately do not allow us to infer any clear difference.

It is possible to more tightly constrain the emitting gas temperature and n_{H_2} density for the species where the collisional rate coefficients are known, by performing a non-LTE analysis. To this end, we used the non-LTE excitation code RADEX with an escape probability formalism for the radiative transfer (Van der Tak et al. 2007) coupled with the LAMDA database (Schöier et al. 2005). Methanol is the species detected in the largest number of lines. The full non-LTE study will be reported in a forthcoming paper. Here we analysed only the E-form, for which the collisional rate coefficients are available (Pottage et al. 2004). The major result of this analysis is that for a range of densities of 10^3 – 10^7 cm⁻³, the gas temperature exceeds 200 K. A similar result is obtained by considering H₂CO emission.

Finally, by combining the HIFI CS(12–11) line with CS(2–1) and (3–2) lines observed with ground-based telescopes, we also derive a kinetic temperature that is definitely above 300 K for the outflowing gas. In this case, caution should be taken since we are able to trace different gas components, as suggested by CH₃OH, the gas at higher excitation being traced by CS(12–11). If we analyse only the (2–1)/(3–2) intensity ratio, the non-LTE approach does not allow us to constrain the temperature in this way, but we are able to infer n_{H_2} of around 4×10^4 cm⁻³. Interestingly, when we check for a possible dependence of n_{H_2} on velocity, the LV range is found to be indicative of a denser medium ($\sim 10^5$ cm⁻³) by an order of magnitude with respect to the MV gas.

5. Conclusions

We have presented the HIFI unbiased spectral survey in the 555–636 GHz band towards the bright bow-shock B1 of the L1157 protostellar outflow. For the first time, we have detected high-excitation (up to ≈ 200 K) emission lines of species whose abundance is largely enhanced in shocked regions (e.g., H₂O, NH₃, H₂CO, CH₃OH). This has allowed us to trace with these species the existence of a high excitation component with $T_{\text{kin}} \geq 200$ –300 K. Temperature components from ~ 300 K to ~ 1400 K have been inferred from the analysis of the H₂ pure rotational lines (Nisini et al., in prep.). Therefore the present observations provide a link between the gas at $T_{\text{kin}} 60$ –200 K previously observed from the ground and the warmer gas probed by the H₂ lines. We plan to perform additional HIFI observations in the THz region towards L1157-B1 to observe more species and transitions, thus to be able to derive reliable abundances and study of the different gas components associated with the bow structure.

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Table 1. List of molecular species and transitions observed with HIFI (Band 1b).

| Transition | ν_0^a (MHz) | E_u^a (K) | T_{peak} (mK) | rms (mK) | V_{peak} (km s ⁻¹) | V_{min} (km s ⁻¹) | V_{max} (km s ⁻¹) | F_{int} (K km s ⁻¹) |
|--|--------------------|----------------|---------------------------|-------------|--|---|---|---|
| o-H ₂ O(1 ₁₀ -1 ₀₁) | 556 936.002 | 27 | 910(17) | 17 | -0.37(1.00) | -25.4 | +7.6 | 11.68(0.10) |
| CH ₃ OH E (11 _{2,9} - 10 _{1,9}) | 558 344.500 | 168 | 47(10) | 10 | +0.60(1.00) | -2.9 | +2.7 | 0.16(0.02) |
| o-H ₂ CO(8 ₁₈ -7 ₁₇) | 561 899.318 | 118 | 92(4) ^b | 8 | +0.38(0.14) ^b | -4.5 | +3.6 | 0.49(0.03) ^b |
| CH ₃ OH E (3 _{2,2} - 2 _{1,2}) | 568 566.054 | 32 | 42(8) | 8 | +0.60(1.00) | -2.6 | +2.7 | 0.31(0.02) |
| o-NH ₃ (1 ₀ -0 ₀) | 572 498.068 | 28 | 122(7) | 7 | +1.03(0.80) | -6.9 | +5.0 | 0.89(0.03) |
| CO(5-4) | 576 267.931 | 83 | 883(10) | 10 | +1.60(1.00) | -36.5 | +6.0 | 49.30(0.07) |
| p-H ₂ CO(8 ₀₈ -7 ₀₇) | 576 708.315 | 125 | 41(7) | 7 | +1.80(1.00) | -5.4 | +2.7 | 0.22(0.02) |
| CH ₃ OH A ⁻ (2 _{2,1} - 1 _{1,0}) | 579 084.700 | 45 | 53(8) | 8 | +0.60(1.00) | -6.0 | +3.7 | 0.29(0.03) |
| CH ₃ OH E (12 _{1,12} - 11 _{1,11}) | 579 151.003 | 178 | 44(8) | 8 | -0.30(1.00) | -4.0 | +4.0 | 0.25(0.02) |
| CH ₃ OH A ⁺ (12 _{0,12} - 11 _{0,11}) | 579 459.639 | 181 | 48(7) | 7 | +0.90(1.00) | -3.9 | +4.9 | 0.27(0.02) |
| CH ₃ OH A ⁺ (2 _{2,0} - 1 _{1,1}) | 579 921.342 | 45 | 42(7) | 7 | -0.60(1.00) | -3.3 | +2.6 | 0.21(0.02) |
| CH ₃ OH E (12 _{2,10} - 11 _{2,9}) | 580 902.721 | 195 | 11(4) | 4 | -3.00(3.00) | -3.9 | +2.5 | 0.09(0.02) |
| CH ₃ OH A ⁺ (6 _{1,6} - 5 _{0,5}) | 584 449.896 | 63 | 88(9) | 9 | -0.30(1.00) | -6.0 | +2.9 | 0.58(0.03) |
| CS(12-11) | 587 616.240 | 183 | 23(2) ^b | 5 | -0.61(0.57) ^b | -7.3 | +6.5 | 0.19(0.03) ^b |
| CH ₃ OH A ⁺ (7 _{3,5} - 6 _{2,4}) | 590 277.688 | 115 | 42(9) | 9 | +0.60(1.00) | -1.0 | +3.0 | 0.16(0.02) |
| CH ₃ OH A ⁻ (7 _{3,4} - 6 _{2,5}) | 590 440.291 | 115 | 40(9) | 9 | -0.60(1.00) | -2.6 | +0.8 | 0.10(0.02) |
| CH ₃ OH E (9 _{0,9} - 8 _{1,8}) | 590 790.957 | 110 | 40(10) | 10 | +0.60(1.00) | -4.7 | +4.3 | 0.28(0.03) |
| o-H ₂ CO(8 ₁₇ -7 ₁₆) | 600 374.604 | 126 | 29(7) ^b | 9 | -0.14(0.57) ^b | -3.0 | +1.8 | 0.19(0.04) ^b |
| CH ₃ OH E (4 _{2,3} - 3 _{1,3}) | 616 979.984 | 41 | 47(6) | 6 | +0.90(1.00) | -4.5 | +2.6 | 0.26(0.02) |
| HCN(7-6) | 620 304.095 | 119 | 94(7) | 7 | -0.60(1.00) | -7.6 | +3.2 | 0.68(0.03) |
| HCO ⁺ (7-6) | 624 208.180 | 119 | 30(3) ^b | 8 | +0.53(0.47) ^b | -3.6 | +4.5 | 0.11(0.03) ^b |
| CH ₃ OH A ⁻ (3 _{2,2} - 2 _{1,1}) | 626 626.302 | 52 | 18(5) | 5 | -1.20(4.00) | -2.5 | +6.3 | 0.18(0.07) |
| CH ₃ OH E (13 _{1,13} - 12 _{1,12}) | 627 170.503 | 209 | 33(7) | 7 | -0.30(1.00) | -3.2 | +2.5 | 0.15(0.02) |
| CH ₃ OH A ⁺ (13 _{0,13} - 12 _{0,12}) | 627 558.440 | 211 | 41(9) | 9 | +0.60(1.00) | -3.6 | +2.5 | 0.19(0.02) |
| CH ₃ OH A ⁺ (3 _{1,2} - 2 _{1,2}) | 629 140.493 | 52 | 52(9) | 9 | +0.60(1.00) | -3.5 | +3.7 | 0.24(0.03) |
| CH ₃ OH A ⁺ (7 _{1,7} - 6 _{0,6}) | 629 921.337 | 79 | 70(13) | 13 | +1.50(1.00) | -3.9 | +3.7 | 0.37(0.04) |
| o-H ₂ CO(9 ₁₉ -8 ₁₈) | 631 702.813 | 149 | 66(4) ^b | 9 | +0.45(0.17) ^b | -1.5 | +2.6 | 0.22(0.02) ^b |

Notes. CO and H₂O emission is discussed in Lefloch et al. (2010). Peak velocity and intensity (in T_a scale), integrated intensity (F_{int}), as well as the terminal velocities of the line emission (V_{min} and V_{max}) are reported. ^(a) Frequencies and spectroscopic parameters have been extracted from the Jet Propulsion Laboratory molecular database (Pickett et al. 1998) for all the transition except those of CH₃OH, which have been extracted from the Cologne Database for Molecular Spectroscopy (Müller et al. 2005). Upper level energies refer to the ground state of each symmetry. ^(b) Gaussian fit.