The CHESS spectral survey of star forming regions: Peering into the protostellar shock L1157-B1. I. Shock chemical complexity


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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 $\text{H}_2$ ro-vibrational lines at $\approx 250$ 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 ($4–11 \, L_{\odot}$) 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 $H_2$ images (Davis & Eisloffel 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).

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 ($4–11 \, L_{\odot}$) 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 $H_2$ images (Davis & Eisloffel 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
The driving protostar. The labels indicate the main B1 clumps detected in the coordinates used for the present HIFI observations (contours), from BVC07. The maps are centred on the δ J2000 = +25°6 and Δα = −63°5 from the driving protostar. The labels indicate the main B1 clumps detected in different tracers. Circles are for the HPBW of the HIFI data presented here (39″) and of Band 7 (11″), i.e., at the highest frequencies of the CHESS surveys.

L1157-B1 is well traced by molecules thought to be released by dust mantles such as H2CO, CH3OH, and NH3 as well as typical tracers of high-speed shocks such as SiO (e.g., Gusdorf et al. 2008). Temperatures ∼60–200 K (from NH3, CH3CN, and SiO) as well as around 1000 K (from H2) 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 CHESS1 (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 H2O(10–10) lines are analysed in Leufloch 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 −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} (α_vSR = +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 H2O (Leufloch et al. 2010). We note that the HV emission is mostly confined to the eastern B1a clump (Fig. 1), within an emitting region of size ∼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-CHESS 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 H2O.

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}, implying a factor 5 moving towards higher velocities (Fig. 3), implying...
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 ($+2.6$ 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 NH$_3$(1–0), multiplied by a factor 7.4, H$_2$CO(8–7), multiplied by a factor 22.5, HCN(7–6), multiplied by a factor 9.0, and H$_2$O(110–101), the latter from Lefloch et al. (2010). The vertical solid line indicates the ambient LSR velocity ($+2.6$ km s$^{-1}$). The velocity ranges arbitrarily defined as HV ($-20$,$-6$ km s$^{-1}$; traced by H$_2$O), MV ($-6$,$-1.5$ km s$^{-1}$; outlined by the HCN and H$_2$CO secondary peak), and LV ($-1.5$,$+2.6$ km s$^{-1}$; the rest of the blue wing) are drawn (see text). Bottom panel: Intensity NH$_3$/H$_2$O line ratio as a function of velocity.

Fig. 4. Rotation diagrams for the CH$_3$OH 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 $E_u = 32$–$211$ K excitation range and (ii) 12 K (as Bachiller et al. 1995), for the PdBI lines, at lower excitation.

4. Physical properties along the B1 bow shock

We detected several lines from CH$_3$OH (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 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 $\sim 20$ K), which represents a lower limit to the kinetic temperature ($T_{kin}$). In the same figure, we report the methanol lines (2K–1K) 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 $E_u \leq 50$ K; BVC07) is definitely lower, $\sim 12$ 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 $f_f = 0.13$, derived by the CH$_3$OH maps obtained at the PdBI, the low temperature component column density is $8 \times 10^{14}$ 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 CH$_3$OH emission separately do not allow us to infer any clear difference.

It is possible to more tightly constrain the emitting gas temperature and $n_{\text{H}_2}$ 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$^5$ cm$^{-3}$, the gas temperature exceeds 200 K. A similar result is obtained by considering H$_2$CO 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 CH$_3$OH, 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 $n_{\text{H}_2}$ of around 4 × 10$^4$ cm$^{-3}$. Interestingly, when we check for a possible dependence of $n_{\text{H}_2}$ on velocity, the LV range is found to be indicative of a denser medium (∼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., H$_2$O, NH$_3$, H$_2$CO, CH$_3$OH). This has allowed us to trace with these species the existence of a high excitation component with $T_{\text{kin}}$ ≥200–300 K. Temperature components from ≃300 K to ~1400 K have been inferred from the analysis of the H$_2$ 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 H$_2$ 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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References


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30 Page 5 is available in the electronic edition of the journal at http://www.aanda.org
from the Cologne Database for Molecular Spectroscopy (Müller et al. 2005). Upper level energies refer to the ground state of each symmetry.

Notes. CO and H$_2$O emission is discussed in Lefloch et al. (2010). Peak velocity and intensity (in Table 1.) Gaussian fit.

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

<table>
<thead>
<tr>
<th>Transition</th>
<th>$v_0$ (MHz)</th>
<th>$E_u$ (K)</th>
<th>$T_{\text{peak}}$ (mK)</th>
<th>rms (mK)</th>
<th>$V_{\text{peak}}$ (km s$^{-1}$)</th>
<th>$V_{\text{min}}$ (km s$^{-1}$)</th>
<th>$V_{\text{max}}$ (km s$^{-1}$)</th>
<th>$F_{\text{int}}$ (K km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>o-H$<em>2$O(10$</em>{10}$–9$_{09}$)</td>
<td>556 396.002</td>
<td>27</td>
<td>910(17)</td>
<td>17</td>
<td>-0.37(1.00)</td>
<td>-25.4</td>
<td>+7.6</td>
<td>11.68(0.10)</td>
</tr>
<tr>
<td>CH$<em>3$OH E (11$</em>{1,9}$ – 10$_{1,8}$)</td>
<td>558 344.500</td>
<td>168</td>
<td>47(10)</td>
<td>10</td>
<td>+0.60(1.00)</td>
<td>-2.9</td>
<td>+2.7</td>
<td>0.16(0.02)</td>
</tr>
<tr>
<td>o-H$<em>2$CO(8$</em>{18}$–7$_{17}$)</td>
<td>561 899.318</td>
<td>118</td>
<td>92(4)$^b$</td>
<td>8</td>
<td>+0.38(0.14)$^b$</td>
<td>-4.5</td>
<td>+3.6</td>
<td>0.49(0.03)$^b$</td>
</tr>
<tr>
<td>CH$<em>3$OH E (3$</em>{1,5}$ – 2$_{1,4}$)</td>
<td>568 566.054</td>
<td>32</td>
<td>42(8)</td>
<td>8</td>
<td>+0.60(1.00)</td>
<td>-2.6</td>
<td>+2.7</td>
<td>0.31(0.02)</td>
</tr>
<tr>
<td>o-NH$<em>3$(1$</em>{0}$–0$_{0}$)</td>
<td>572 498.068</td>
<td>28</td>
<td>122(7)</td>
<td>7</td>
<td>+1.03(0.80)</td>
<td>-6.9</td>
<td>+5.0</td>
<td>0.89(0.03)</td>
</tr>
<tr>
<td>CO(5–4)</td>
<td>576 267.931</td>
<td>83</td>
<td>883(10)</td>
<td>10</td>
<td>+1.60(1.00)</td>
<td>-36.5</td>
<td>+6.0</td>
<td>49.30(0.07)</td>
</tr>
<tr>
<td>p-H$<em>2$CO(8$</em>{08}$–7$_{07}$)</td>
<td>576 708.315</td>
<td>125</td>
<td>41(7)</td>
<td>7</td>
<td>+1.80(1.00)</td>
<td>-5.4</td>
<td>+2.7</td>
<td>0.22(0.02)</td>
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<tr>
<td>CH$<em>3$OH A$^+$ (2$</em>{2,1}$ – 1$_{2,0}$)</td>
<td>579 084.700</td>
<td>45</td>
<td>53(8)</td>
<td>8</td>
<td>+0.60(1.00)</td>
<td>-6.0</td>
<td>+3.7</td>
<td>0.29(0.03)</td>
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<tr>
<td>CH$<em>3$OH E (12$</em>{2,12}$ – 11$_{1,11}$)</td>
<td>579 151.003</td>
<td>178</td>
<td>44(8)</td>
<td>8</td>
<td>-0.30(1.00)</td>
<td>-4.0</td>
<td>+4.0</td>
<td>0.25(0.02)</td>
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<tr>
<td>CH$<em>3$OH A$^+$ (12$</em>{1,12}$ – 11$_{0,11}$)</td>
<td>579 459.639</td>
<td>181</td>
<td>48(7)</td>
<td>7</td>
<td>+0.90(1.00)</td>
<td>-3.9</td>
<td>+4.9</td>
<td>0.27(0.02)</td>
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<td>CH$<em>3$OH A$^+$ (2$</em>{2,1}$ – 1$_{1,1}$)</td>
<td>579 921.342</td>
<td>45</td>
<td>42(7)</td>
<td>7</td>
<td>-0.60(1.00)</td>
<td>-3.3</td>
<td>+2.6</td>
<td>0.21(0.02)</td>
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<td>CH$<em>3$OH E (12$</em>{2,10}$ – 11$_{2,9}$)</td>
<td>580 902.721</td>
<td>195</td>
<td>11(4)</td>
<td>4</td>
<td>-3.00(3.00)</td>
<td>-3.9</td>
<td>+2.5</td>
<td>0.09(0.02)</td>
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<tr>
<td>CH$<em>3$OH A$^+$ (6$</em>{1,8}$ – 5$_{0,5}$)</td>
<td>584 449.896</td>
<td>63</td>
<td>88(9)</td>
<td>9</td>
<td>-0.30(1.00)</td>
<td>-6.0</td>
<td>+2.9</td>
<td>0.58(0.03)</td>
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<tr>
<td>CS(12–11)</td>
<td>587 616.240</td>
<td>183</td>
<td>23(2)$^b$</td>
<td>5</td>
<td>-0.61(0.57)$^b$</td>
<td>-7.3</td>
<td>+6.5</td>
<td>0.19(0.03)$^b$</td>
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<tr>
<td>CH$<em>3$OH A$^+$ (7$</em>{3,5}$ – 6$_{2,4}$)</td>
<td>590 277.688</td>
<td>115</td>
<td>42(9)</td>
<td>9</td>
<td>+0.60(1.00)</td>
<td>-1.0</td>
<td>+3.0</td>
<td>0.16(0.02)</td>
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<tr>
<td>CH$<em>3$OH A$^+$ (7$</em>{3,4}$ – 6$_{2,5}$)</td>
<td>590 440.291</td>
<td>115</td>
<td>40(9)</td>
<td>9</td>
<td>-0.60(1.00)</td>
<td>-2.6</td>
<td>+0.8</td>
<td>0.10(0.02)</td>
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<tr>
<td>CH$<em>3$OH E (9$</em>{0,9}$ – 8$_{1,8}$)</td>
<td>590 790.957</td>
<td>110</td>
<td>40(10)</td>
<td>10</td>
<td>+0.60(1.00)</td>
<td>-4.7</td>
<td>+4.3</td>
<td>0.28(0.03)</td>
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<td>o-H$<em>2$CO(8$</em>{17}$–7$_{16}$)</td>
<td>600 374.604</td>
<td>126</td>
<td>29(7)$^b$</td>
<td>9</td>
<td>-0.14(0.57)$^b$</td>
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<td>+1.8</td>
<td>0.19(0.04)$^b$</td>
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<tr>
<td>CH$<em>3$OH E (4$</em>{2,3}$ – 3$_{1,2}$)</td>
<td>616 979.984</td>
<td>41</td>
<td>47(6)</td>
<td>6</td>
<td>+0.90(1.00)</td>
<td>-4.5</td>
<td>+2.6</td>
<td>0.26(0.02)</td>
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<td>HCN(7–6)</td>
<td>620 304.095</td>
<td>119</td>
<td>94(7)</td>
<td>7</td>
<td>-0.60(1.00)</td>
<td>-7.6</td>
<td>+3.2</td>
<td>0.68(0.03)</td>
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<td>HCO$^+$(7–6)</td>
<td>624 208.180</td>
<td>119</td>
<td>30(3)$^b$</td>
<td>8</td>
<td>+0.53(0.47)$^b$</td>
<td>-3.6</td>
<td>+4.5</td>
<td>0.11(0.03)$^b$</td>
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<td>CH$<em>3$OH A$^+$ (3$</em>{2,2}$ – 2$_{1,1}$)</td>
<td>626 626.302</td>
<td>52</td>
<td>18(5)</td>
<td>5</td>
<td>-1.20(4.00)</td>
<td>-2.5</td>
<td>+6.3</td>
<td>0.18(0.07)</td>
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<td>CH$<em>3$OH E (13$</em>{13}$ – 12$_{12}$)</td>
<td>627 170.503</td>
<td>209</td>
<td>33(7)</td>
<td>7</td>
<td>-0.30(1.00)</td>
<td>-3.2</td>
<td>+2.5</td>
<td>0.15(0.02)</td>
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<td>CH$<em>3$OH A$^+$ (13$</em>{0,11}$ – 12$_{0,12}$)</td>
<td>627 558.440</td>
<td>211</td>
<td>41(9)</td>
<td>9</td>
<td>+0.60(1.00)</td>
<td>-3.6</td>
<td>+2.5</td>
<td>0.19(0.02)</td>
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<td>CH$<em>3$OH A$^+$ (3$</em>{1,2}$ – 2$_{1,2}$)</td>
<td>629 140.493</td>
<td>52</td>
<td>52(9)</td>
<td>9</td>
<td>+0.60(1.00)</td>
<td>-3.5</td>
<td>+3.7</td>
<td>0.24(0.03)</td>
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<td>CH$<em>3$OH A$^+$ (7$</em>{1,7}$ – 6$_{0,6}$)</td>
<td>629 921.337</td>
<td>79</td>
<td>70(13)</td>
<td>13</td>
<td>+1.50(1.00)</td>
<td>-3.9</td>
<td>+3.7</td>
<td>0.37(0.04)</td>
</tr>
<tr>
<td>o-H$<em>2$CO(9$</em>{10}$–8$_{18}$)</td>
<td>631 702.813</td>
<td>149</td>
<td>66(4)$^b$</td>
<td>9</td>
<td>+0.45(0.17)$^b$</td>
<td>-1.5</td>
<td>+2.6</td>
<td>0.22(0.02)$^b$</td>
</tr>
</tbody>
</table>

Notes. CO and H$_2$O emission is discussed in Lefloch et al. (2010). Peak velocity and intensity (in $T_s$ scale), integrated intensity ($F_{\text{int}}$), as well as the terminal velocities of the line emission ($V_{\text{min}}$ and $V_{\text{max}}$) 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 CH$_3$OH, 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.