**Herschel–PACS observations of shocked gas associated with the jets of L1448 and L1157**

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1. **Introduction**

During the earliest stages of star formation, young stars produce fast collimated jets that collide with the dense parent cloud generating strong interstellar shocks. These processes strongly modify the chemical composition of the surrounding gas and are identified by intense line emission. Among the diatomic molecules, water is a key molecule and a unique diagnostic tool of local conditions and energetic processes occurring in star-forming regions (e.g. van Dishoeck et al. 2011), since its abundance varies by many orders of magnitude during the shock lifetime (e.g. Bergin et al. 1998). In particular, water abundance with respect to H$_2$ is expected to increase from $<10^{-7}$ in cold regions to about $10^{-4}$ in the warm gas, due to the combined effects of evaporation of icy mantles and high-temperature chemical reactions which drive all the atomic oxygen into H$_2$O.

Space instruments, such as SWAS, Odin, and ISO, have allowed the study of water in outflows. It was possible to resolve the water line profiles (e.g. Benedettini et al. 2002; Bjerkeli et al. 2000), and to measure the water abundance in shocks through comparison with CO emission. In particular, values within the range $10^{-7}$—$10^{-6}$ have been derived for the H$_2$O abundance showing that it depends on the gas temperature and velocity.
processes. In this context, the low-luminosity Class 0 protostellar systems L1448 (7.5 L☉) and L1157 (4 L☉) are excellent targets. At the distance of 232 pc (Hirot a et al. 2011), L1448 is the prototype of a source driving a molecular jet (Eisloffel 2000). It has a powerful and highly collimated outflow, which has been extensively studied (e.g. Guilloteau et al. 1992; Bachiller et al. 1995; Hirano et al. 2010). Gas excited in shocks has been detected along the outflow through near- and mid-IR emission of molecular hydrogen (e.g. Neufeld et al. 2009; Giannini et al. 2011). At a distance of 250 pc, L1157 is perhaps the most active outflow from a chemical point of view (Bachiller & Perez Gutierrez 1997; Bachiller et al. 2001), often quoted as being the prototype of the so-called chemically rich outflows. Detailed Herschel observations of the L1157 outflow by the Chemical Herschel Surveys of Star forming regions (CHESS) program have been presented by Codella et al. (2010); Lefloch et al. (2010); Codella et al. (2012a,b); Benedettini et al. (2012); Lefloch et al. (2012).

The Herschel key program Water In Star-forming regions with Herschel (WISH, van Dishoeck et al. 2011) employed more than 400 hours of telescope time to observe H2O and related molecules toward about 80 protostars at different evolutionary stages and masses to study the physical and chemical conditions of the gas in nearby star-forming regions. Within the WISH framework, several results concerning outflows have been presented (e.g. Bjerkeli et al. 2011; Kristensen et al. 2011, 2012; Bjerkeli et al. 2012; Herczeg et al. 2012; Tafalla et al. 2013). Both the L1448 and L1157 outflows have been mapped to study the spatial distribution of water and the results have been presented by Nisini et al. (2010a) for the L1157 outflow and Nisini et al. (2013) for the L1448 outflow. They show a clumpy water distribution, with emission peaks corresponding to shock positions along the outflow. Multi-transition observations (with excitation energies ranging from 53 to 249 K, and to PACS maps of the H2O 2 12 − 1 11 line at 179.5 μm along the two outflows (Nisini et al. 2010a, 2013, see also Fig. 1).

The data were processed with the ESA-supported package Herschel interactive processing environment (HIPE, Ott 2010) version 4.2 (except for the data relative to the L1157-R position that were processed with HIPE version 5)2. The observed fluxes were normalized to the telescope background and then converted into absolute fluxes using Neptune as a calibrator. The flux calibration uncertainty of the PACS observations is 30%, based on the flux repeatability for multiple observations of the same target in different programs and on cross-calibration with HIPI and ISO. Further data reduction, to obtain continuum subtracted line maps, and the analysis of the data were performed using IDL and the GILDAS3 software.

The Herschel diffraction limit at 179 μm is 12′′ and for wavelengths below 133 μm it is smaller than the PACS spaxel size of 9′′.4. To correct for the different beam sizes in the excitation analysis presented in Sect. 4, we convolved all maps to the resolution of the transition with the longest wavelength, that

1 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.
2 We have checked the data processed with the latest version of HIPE (version 10) and we find an agreement in the flux densities within 15–20%, which is definitely within the PACS calibration uncertainty (30%).
3 http://www.iram.fr/IRAMFR/GILDAS/
Fig. 1. PACS H$_2$O 179 $\mu$m images of L1448 and L1157 (Nisini et al. 2010a, 2013). The PACS line survey positions are indicated for L1448-B2 and R4 with crosses, for L1157-B2 and R with triangles. The field of view of the PACS observations is displayed as a box at the selected positions.

Table 1. Fluxes of the lines observed with PACS and relative 1σ errors in parentheses.

| Transition          | Frequency (GHz) | Wavelength ($\mu$m) | $E_u/k_B$ (K) | Flux $(10^{-15}$ erg s$^{-1}$ cm$^{-2}$) |
|---------------------|-----------------|---------------------|--------------|----------------------------------------|
| [O$\text{I}$] $^3P_1 - ^3P_2$ | 4744.78         | 63.2                | 227.7        | 167 (8) 27 (6) 26 (4) 32 (4)           |
| $\alpha$-H$_2$O $2_{21}-1_{10}$ | 2773.98         | 108.1               | 194.1        | 22 (2) 20 (4) <16 9 (2)                |
| CO 24−23            | 2756.39         | 108.8               | 1656.5       | 14 (4) <19 <17 <19                     |
| CO 22−21            | 2528.17         | 118.6               | 1397.4       | 13 (2) 7 (2) <11 <11                   |
| OH $^3H_2^1J = 5/2^-3/2^-$ | 2514.31         | 119.2               | 120.7        | 17 (2) <1 <11 <11                     |
| OH $^3H_2^1J = 5/2^-3/2^+$ | 2509.95         | 119.4               | 120.5        | $-$ $-$ $-$ $-$                        |
| $p$-H$_2$O $^3_{01}-^3_{13}$ | 2391.57         | 125.4               | 319.5        | 6 (2) 6 (1) <11 5 (1)                 |
| $p$-H$_2$O $3_{13}-2_{02}$ | 2164.13         | 138.5               | 204.7        | 16 (2) 20 (2) 5 (1) 15 (1)            |
| CO 18−17            | 2070.62         | 144.8               | 945.0        | 32 (2) 11 (2) <9 <8                    |
| [O$\text{I}$] $^3P_0 - ^3P_1$ | 2060.07         | 145.5               | 326.6        | 8 (1) $<$8 $<$9 6 (3)                 |
| CO 16−15            | 1841.35         | 162.8               | 751.7        | 39 (2) 17 (2) 5 (2) 10 (2)            |
| $\alpha$-H$_2$O $3_{03}-2_{12}$ | 1716.77         | 174.6               | 196.8        | 51 (2) 77 (1) 22 (1) 45 (1)          |
| $\alpha$-H$_2$O $2_{12}-1_{01}$' | 1669.90         | 179.5               | 114.4        | 90 (9) 139 (35) 85 (8) 53 (13)        |

Notes. Fluxes are measured at the central spaxel of the maps after convolving to 12″, i.e. the PACS resolution of the transition with the longest wavelength (179 $\mu$m). The relative rms error is measured at the same spaxel and does not include 30% calibration accuracy. ($^a$) The fluxes and relative rms errors are given at the peak of the H$_2$O emission, which is at a position offset of (2", −9") from the central spaxel (see Fig. 3). ($^b$) The value represents the sum of the fluxes of the two listed OH lines (at 119.2 and 119.4 $\mu$m). The OH 119.4/119.2 line ratio measured at the central spaxel of the map is 1.3. ($^c$) The values are measured from the PACS maps of the two outflows at 179 $\mu$m (Nisini et al. 2013).

3. Results

The PACS spectra of all the lines detected in the four examined shocked positions are presented in Appendix A, whereas a summary of the main line parameters is given in Table 1, along with the fluxes of the detected lines. The source L1448-B2 represents the position in which we detected the largest number of lines and it is the only position where we detected the OH fundamental line at 119 $\mu$m.

The original PACS maps of selected lines, not convolved to a common angular resolution, are shown in Figs. 2 and 3.
Fig. 2. Overlay between PACS H$_2$O $3_{03}-2_{12}$ (174 $\mu$m), H$_2$O $2_{11}-1_{10}$ (108.1 $\mu$m), [OI] $^{1}P_{1}$-$^{1}P_{2}$ (63.2 $\mu$m), CO(16 − 15), OH (119 $\mu$m), and other tracers in the B2 (upper panel) and R4 (lower panel) shocked spots along the L1448 outflow. In particular, JCMT CO(3−2) emission (Half Power Beam Width, HPBW $\sim$ 14$''$) from Nisini et al. (2013), Spitzer [FeII] emission at 26 $\mu$m from Neufeld et al. (2009), IRAC 8 $\mu$m emission from Tobin et al. (2007), and H$_2$ emission at 2.12 $\mu$m from Davis & Smith (1995) are shown. In the bottom-right panel relative to L1448-B2 the EHV CO(3−2) emission ($v \gtrsim -50$ km s$^{-1}$) and the HV CO(3−2) emission ($v \lesssim -40$ km s$^{-1}$) are shown in dashed and solid lines, respectively. The contours in each map are traced every 3$\sigma$, starting from 5$\sigma$, except for the CO(3−2) in L1448-B2, where the contours are traced in steps of 5$\sigma$, starting from 5$\sigma$. The crosses represent the pointing of the 25 spaxels.
Fig. 3. Same as in Fig. 2, but for the L1157 outflow. Contours are displayed for IRAM-30 m CO(2−1) and SiO(3−2) emission (HPBW equal to 11′′ and 18′′, respectively) from Bachiller et al. (2001) and are traced in steps of 5σ, starting from 5σ. Spitzer-IRAC 8 μm emission and Spitzer-IRS H₂ S(1) emission at 17 μm from Neufeld et al. (2009) are shown.
respectively, for L1448 and L1157. The figures present the overlay between the H$_2$O $3_0^2$–$2_1$ (174 $\mu$m), H$_2$O $2_{11}^1$–$1_{10}^1$ (108.1 $\mu$m), CO(16–15), [OI] $P_{1_1}$–$P_{2_2}$ (63.2 $\mu$m), OH (119 $\mu$m) emission, and other tracers from complementary observations. Along the L1448 outflow several interesting features can be noticed. In particular, the peak of the H$_2$O emission at L1448-B2 is at the apex of the bow-shock, as traced by the H$_2$ emission at 2.12 $\mu$m, and at L1448-R4 it corresponds to the peak of the IRAC 8 $\mu$m emission. We found no shift at this angular resolution between the H$_2$O emission at 174 $\mu$m and CO(16–15) emission, both in L1448-B2 and L1448-R4, which indicates that at this angular resolution high-J CO and H$_2$O are spatially coincident and trace shocked gas.

The bottom-right panel relative to L1448-B2 shows the comparison between H$_2$O and CO(3–2). For CO, the EHV gas (i.e. $v \gtrsim -50$ km s$^{-1}$, Bachiller et al. 1990) has been separated from the standard outflow high-velocity (HV, $v \lesssim -40$ km s$^{-1}$) gas emission. We see that the HV gas is totally uncorrelated with the water emission, a result already found in other studies (Santangelo et al. 2012; Nisini et al. 2013; Tafalla et al. 2013).

The EHV gas, on the other hand, has a peak shifted north-west with respect to the H$_2$O peak. Thus, the low-J CO emission traces entrained ambient gas and not the shocked gas, independent of the velocity components.

Finally, we do not see any significant spatial shift at this angular resolution between the peaks of H$_2$O, [OI], and [FeII] emission, although the H$_2$O emission appears to be more extended than [OI] and [FeII]. Nevertheless, at the L1448-B2 position, and possibly at the adjacent spaxels along the outflow direction, a hint of a velocity shift in the [OI] line at 63 $\mu$m was detected: the line is blue-shifted by $\sim 80$ km s$^{-1}$ (see Fig. A.1), which is comparable with the resolution element of PACS at this wavelength ($\sim 90$ km s$^{-1}$). Similar [OI] velocity shifts have been found in HH46 by van Kempen et al. (2010a) and in Serpens SMM1 by Goicoechea et al. (2012), who suggested the presence of fast dissociative shocks close to the protostar, related with an embedded atomic jet. Moreover, Karska et al. (2013) analysed PACS spectra of a large sample of Class 0/I protostars and they found such profile shifts toward at least 1/3 of their targets. We point out that Fe has an ionization potential of 7.9 eV and thus we expected to find [FeII] co-spatial with [OI] (ionization potential of 13.6 eV).

A much smaller number of lines was detected along the L1157 outflow. In particular, only four lines were detected at L1157-B2. Here the emission is elongated in the outflow direction, according to all tracers. Similarly to L1448, the H$_2$O emission at 174 $\mu$m is spatially associated with the [OI] $P_{1_1}$–$P_{2_2}$ emission at 63.2 $\mu$m and the CO(16–15) emission. Two emission peaks can be identified in the PACS maps: the brightness one is found at the central spaxel and is spatially associated with the H$_2$ emission, as seen from the overlay with the Spitzer-IRAC image at 8 $\mu$m; the other emission peak is at a position offset of (12″,−18″) from the central spaxel, close to the edge of the PACS map. The SiO(3–2) emission (Bachiller et al. 2001) also appears to be elongated along the outflow direction with a peak roughly corresponding to the central spaxel of the PACS maps. On the other hand, the CO(2–1) emission is not spatially associated with any other molecular species. At L1157-R a bright emission peak is seen in H$_2$O and in all species observed with PACS. This H$_2$O peak is shifted with respect to the central spaxel of (2″,−9″) and is spatially associated with the H$_2$ emission. A second peak is found in the [OI] $P_{1_1}$–$P_{2_2}$ emission (63.2 $\mu$m), at a position offset of (−12″,8″) from the central spaxel, and is also visible in H$_2$O. On the other hand, the SiO(3–2) emission peaks at the central spaxel position, thus offset from the H$_2$O emission. Finally, the CO(2–1) emission is more diffuse than the other tracers and has an emission peak at the central spaxel position, thus shifted with respect to the H$_2$O and high-J CO emission.

In conclusion, the inspection of the PACS maps highlights the following results: in both outflows the H$_2$O emission is spatially associated with mid-IR H$_2$ and high-J CO emission, whereas the low-J CO emission seems to be associated with a different gas component. Our findings are consistent with the results obtained by Nisini et al. (2010a, 2013) from mapping the H$_2$O $2_{12}^1$–$1_{01}^1$ emission along the L1448 and L1157 outflows and by Tafalla et al. (2013) from the analysis of H$_2$O $1_{10}^1$–$1_{01}^1$ and $2_{11}^1$–$1_{01}^1$ emission in a large sample of shocked positions. Moreover, Karska et al. (2013) found a tight correlation between H$_2$O $2_{12}^1$–$1_{01}^1$ at 179 $\mu$m and high-J CO line fluxes, concluding that they likely arise in the same gas component. The SiO emission appears to be slightly shifted with respect to H$_2$O, consistent with the two gas components tracing shock regions with different excitation conditions, as discussed in Santangelo et al. (2012) and Vasta et al. (2012). Finally, no shift is observed at the PACS angular resolution between the [OI] and [FeII] lines and the H$_2$O emission.

4. Analysis

In this section we discuss the excitation conditions of the observed lines, complemented with Spitzer H$_2$ data, when available. In particular, we will concentrate our analysis on the L1448-B2 shock, where we detected the largest number of lines with high signal-to-noise ratio (S/N). Given the observed strict correlation between H$_2$O and H$_2$ mid-IR emission, we will first use the Spitzer H$_2$ lines to constrain the H$_2$O temperature. The H$_2$O line ratios and absolute intensities will then be used to derive the density and column density of the gas and the size of the emitting region. The physical parameters derived for H$_2$O are then used for the CO emission and both H$_2$O and CO abundances with respect to H$_2$ are estimated. Finally, the emission at the other shock spots with respect to the excitation conditions in L1448-B2 will be discussed.

4.1. The L1448-B2 shock

4.1.1. H$_2$ rotational diagram

We used Spitzer H$_2$ observations by Giannini et al. (2011) and converted the H$_2$ intensities, averaged in a 13″ beam, into column densities ($N_H$) to construct the H$_2$ rotational diagram, which is presented in the upper panel of Fig. 4. The fluxes have not been corrected for visual extinction, since it is only a marginal effect ($A_V = 6$ mag for L1448 Giannini et al. 2011; Nisini et al. 2000). As explained in Giannini et al. (2011), the ortho-to-para ratio is temperature dependent: in particular, an ortho-to-para ratio close to 1 is found for the low-J transitions that trace gas at $T \lesssim 400$ K, while the high temperature equilibrium value of 3 is reached by the lines with $J$ larger than 3.

The fact that the observed transitions do not align on a single straight line on the rotational diagram indicates that gas components at different temperatures are present within the spatial resolution element or along the line of sight. In particular, two temperature components can be identified in the diagram, in the assumption of LTE conditions: a warm component at $T$ in the range $\sim 350$–$450$ K, where the uncertainty depends on the lines considered for the fit, i.e. the S(0)–S(2) or the S(0)–S(3) lines,
4.1.2. The H$_2$O emission

Previous HIFI observations in L1448-B2 of H$_2$O lines with excitation energies $E_u$ ranging from 53 to 137 K \citep{Santangelo2012} are consistent with very dense gas with $n$(H$_2$) $\sim$ 10$^9$ cm$^{-3}$ and $T$ = 450 K and with moderate H$_2$O column densities of $\sim$ 3 $\times$ 10$^{14}$ cm$^{-2}$. The bulk of the HIFI H$_2$O emission can be thus associated with the warm component identified from the H$_2$ rotational diagram.

To analyse the excitation conditions of the H$_2$O emission observed with PACS, we used the radiative transfer code RADEX \citep{vanDerTak2007} in the plane-parallel geometry, with the collisional rate coefficients from \cite{Dubernet2006, Dubernet2009} and \cite{Daniel2010, Daniel2011}, to build a grid of models with density ranging between 10$^5$ and 10$^8$ cm$^{-3}$ and H$_2$O column density between 10$^{15}$ and 10$^{18}$ cm$^{-2}$. We adopted a typical line width $\Delta v$ of 50 km s$^{-1}$ (full-width at zero intensity, FWZI), from the spectrally resolved HIFI observations of H$_2$O \citep{Santangelo2012}. An uncertainty on the assumed line width value translates into an uncertainty on the H$_2$O column density determination, since the H$_2$O line ratios depend on the ratio $N$(H$_2$O)/$\Delta v$. An ortho-to-para ratio equal to 3 was assumed, as implied by the HIFI observations of the warm component.

Figure 5 shows the ratios between H$_2$O lines observed with PACS (having higher excitation than those observed with HIFI) as a function of temperature, for two values of H$_2$ density and H$_2$O column density. The warm component at $T$ $\sim$ 450 K does not reproduce the PACS H$_2$O line ratios. In particular, the top panel shows the 179 $\mu$m/174 $\mu$m line ratio. The arrows in the plot indicate that the observed ratio (shaded band) is an upper limit, since the H$_2$O 2$_{12}$--1$_{01}$ line ($E_u$ $\sim$ 114 K) is more contaminated than the H$_2$O 3$_{03}$--2$_{11}$ line ($E_u$ $\sim$ 197 K) by the warm gas component traced by the lower excitation H$_2$O lines observed with HIFI. The low H$_2$O column density $N$(H$_2$O) $\sim$ 3 $\times$ 10$^{14}$ cm$^{-2}$, derived for the warm component from the HIFI H$_2$O observations, does not reproduce the 179 $\mu$m/174 $\mu$m line ratio. This indicates the presence of an additional gas component with respect to the warm one traced by the bulk of the HIFI observations. In particular, a hot component with temperature higher than 600 K and H$_2$O column density larger than a few 10$^{15}$ cm$^{-2}$ is required to reproduce the higher excitation H$_2$O emission observed with PACS.

This evidence suggests that the bulk of the H$_2$O emission observed with PACS is associated with the hot component which is seen in the H$_2$ rotational diagram. Assuming a temperature $T$ = 1100 K for this component from the H$_2$ rotational diagram (see Fig. 4) and H$_2$ density $n$(H$_2$) $\geq$ 10$^9$ cm$^{-3}$, as obtained by \cite{Giannini2011}, the density and column density of this component are derived by fitting the intensity of all the PACS lines with excitation energy level $E_u$ $\geq$ 190 K and varying $n$(H$_2$), $N$(H$_2$O) and the size of the emitting region $\theta$. Table 2 summarizes the results of the fit: unlike the warm component, the emission region of the hot component should be compact (a few arcsec). In particular, assuming an emitting size of 1 arcsec, the hot component requires a density $n$(H$_2$) $\sim$ 5 $\times$ 10$^5$--5 $\times$ 10$^6$ cm$^{-3}$ and column density $N$(H$_2$O) $\sim$ 4 $\times$ 10$^{15}$--2 $\times$ 10$^{16}$ cm$^{-2}$. The obtained column densities correspond to moderately optically thick lines (the optical depths of the H$_2$O lines are lower than $\sim$23, corresponding to the maximum optical depth of the 179 $\mu$m line).

Fig. 4. Upper: rotational diagram at L1448-B2 for the H$_2$ emission lines detected with Spitzer by Giannini et al. (2011). The values have been derived from the H$_2$ fluxes integrated over a 13$''$ area for comparison with the PACS data. The black dots are the observed values, whereas the empty dot represents the H$_2$ S(1) line corrected for an ortho-to-para ratio equal to 1 (see Giannini et al. 2011). The green solid line represents the linear fit to the S(0)--S(3) H$_2$ lines, while the green dotted line is the fit obtained using the S(0)--S(2) H$_2$ lines. Finally, the blue line is the linear fit to the S(3)--S(7) lines. The resulting parameters ($T$, $N$) or range of parameters of the linear fits are reported in the diagram. Lower: H$_2$ rotational diagram at L1157-R. The symbols are the same as in the upper panel.

and a hot component at $T$ $\sim$ 1100 K, by fitting the S(3) (or S(2)) to S(7) lines. The H$_2$ column density is $N$(H$_2$) $\sim$ 0.8--1.2 $\times$ 10$^{20}$ cm$^{-2}$ for the warm component and $N$(H$_2$) $\sim$ 1.1 $\times$ 10$^{19}$ cm$^{-2}$ for the hot component. In conclusion, the properties of the hot component are well defined from the H$_2$ rotational diagram, while a slightly larger range of parameters can be associated with the warm component.

$^4$ The ortho-H$_2$O 3$_{03}$--2$_{11}$ line with $E_u$ = 249 K was not detected in B2 (see Santangelo et al. 2012), therefore the H$_2$O line with the highest energy used for the fit was the para-H$_2$O 2$_{11}$--2$_{03}$ line with $E_u$ = 137 K.
A visualization of the obtained results is presented in Fig. 6, which shows the two separate models for the H$_2$O emission, i.e. the warm and hot components, and the sum of the two models in red. The fluxes predicted by the models have been corrected for the filling factors (using $g_{\text{source}}/(g_{\text{source}} + g_{\text{emissive}})$) obtained by assuming the emitting size derived from the excitation analysis. Except for the H$_2$O $2_{11}-1_{01}$ line at 108.1 μm, which is over-estimated by a factor of 2.5, and the $2_{11}-2_{02}$ line at 752 GHz, which is under-estimated by a factor of 2, all H$_2$O lines are well reproduced by the two-component model.

We note that this model predicts that the hot component seen in L1448-B2 should contribute very little to the emission of the low-excitation H$_2$O lines observed with HIFI (Santangelo et al. 2012) and indeed these lines show very similar profiles with no clear evidence of variations in shape with excitation. However, the HIFI observations of L1448-R4 and L1157-R show a different trend, with high velocity gas preferentially associated with the low-excitation lines (see Santangelo et al. 2012; Vasta et al. 2012). Nevertheless, in these cases geometrical effects related to the presence of bow shocks and self-absorption by cold H$_2$O gas in the lines at lower excitation may contribute to modifying the line profiles.

Finally, Fig. 7 presents the H$_2$O rotational diagram, with the flux predictions from the two separate models for H$_2$O and from their sum. The models identify two gas components in the rotational diagram, with the blue one (associated with the hot component) showing more scatter than the green one (associated with the warm component), because of the larger associated optical depths. However, when the sum of the two separate models is considered, the two temperature components are no longer discernible. The total rotational ladder shows a single-temperature aspect, although the large scatter suggests that sub-thermal excitation and optical depth effects are significant. The rotational temperature obtained from a single-temperature fit is ~50 K, which is within the range of rotational temperatures obtained for low-mass Class 0 protostars (e.g. Herczeg et al. 2012; Goicoechea et al. 2012; Karska et al. 2013).

4.1.3. The CO emission

Figure 8 shows the CO rotational diagram obtained by converting the fluxes of the high-$J$ CO lines observed with PACS and the CO($3\rightarrow2$) line observed with the JCMT telescope (beam size equal to 14″) into column densities ($N_c$). A global fit to the PACS CO lines reveals a gas with rotational temperature $T \sim 290$ K and CO column density, averaged in the 12″ beam, of $N$(CO) $\sim 10^{15}$ cm$^{-2}$. This is consistent with the warm gas component identified from the H$_2$ rotational diagram and associated with the bulk of the H$_2$O emission observed with HIFI. Although only four CO lines have been detected with PACS, a hint of a possible curvature occurs at excitation energies $E_u \geq 1000$ K, since the CO(24–23) transition lies above the straight line followed by the other PACS lines. If we assume that this line comes from a different gas component, a slightly lower temperature $T \sim 240$ K is found from the lower excitation PACS lines and correspondingly $N$(CO) $\sim 2 \times 10^{15}$ cm$^{-2}$. The same diagram shows that the CO(3–2) line lies well above the other CO lines, which is consistent with its origin in a colder gas.

The presence of multiple excitation temperature components in the CO emission has been found by other studies of CO ladders in low-mass Class 0 protostars and their outflows (see e.g. van Kempen et al. 2010b; Benedettini et al. 2012; Goicoechea et al. 2012; Herczeg et al. 2012; Yıldız et al. 2012, 2013; Karska et al. 2013; Manoj et al. 2013). In particular,
Table 2. Summary of the best-fit models derived for the two gas components at the L1448-B2 position.

| Comp. | $T$ (K) | $n$(H$_2$) (cm$^{-3}$) | $N$(H$_2$O) (cm$^{-2}$) | $\Theta$ (arcsec) | $N$(CO) (cm$^{-2}$) | [H$_2$O]/[H$_2$]$^a$ | [CO]/[H$_2$]$^a$ |
|-------|---------|----------------------|-----------------------|-------------------|-------------------|------------------|------------------|
| Warm$^b$ | 450 | $10^6$ | $3 \times 10^{14}$ | 17 | $3 \times 10^{15}$ | $3 \times 4 \times 10^{-6}$ | $3 - 4 \times 10^{-5}$ |
| Hot | 1100 (0.5–5) $\times 10^6$ | (0.4–2) $\times 10^{16}$ | $\sim 1$ | (1.5–3) $\times 10^{16}$ | (0.3–1.3) $\times 10^{-5}$ | (1–2) $\times 10^{-5}$ |

Notes. $^a$ The H$_2$O and CO abundances of each gas component are obtained from the H$_2$O and CO column densities after correcting for the relative beam filling factor. $^b$ See the B2-2 model from Santangelo et al. (2012), shown in their Table 2. The H$_2$O column density is, however, slightly different because it has been derived using the collisional rate coefficients from Dubernet et al. (2006, 2009) and Daniel et al. (2010, 2011).

Karska et al. (2013) present CO rotational diagrams for a large sample of protostars, showing two distinct components, a warm component with $T_{\text{rot}} \sim 300$ K and a hot component with $T_{\text{rot}} \sim 700$ K, in addition to a cold component with $T_{\text{rot}} \sim 100$ K, observed in the $J \lesssim 14$ lines (Goicoechea et al. 2012; Yıldız et al. 2012, 2013). They found the break between warm and hot gas in the CO diagrams around $E_u \sim 1500$ K. Thus, the presence of different components in our PACS CO data, a warm and a hot component, is probably valid and may reflect true differences in the excitation conditions of the gas traced by the different ranges of CO transitions in Class 0 sources.

We can then use the physical conditions derived for the warm and hot H$_2$O components to verify whether they are able to reproduce our PACS CO observations. The comparison is presented in Fig. 9. In particular, we used the temperature and density derived from the H$_2$O analysis to fit the CO line ratios, normalizing the warm component to the CO($16 - 15$) line and deriving the CO column density of the hot component so that the sum of the two components (warm plus hot) reproduced the observed CO fluxes and upper limits. The CO column densities derived in this fashion are reported in the last column of Table 2. The two blue models in Fig. 9 for the hot gas component represent the extremes of the density range obtained from the H$_2$O excitation analysis (see Table 2). We obtained $N$(CO) = $(1.5-3) \times 10^{16}$ cm$^{-2}$ for the hot gas component and $N$(CO) = $3 \times 10^{15}$ cm$^{-2}$ for the warm component, both averaged over the relative emitting size.

To summarize, the CO and H$_2$O line ratios trace two gas components, a warm gas component at $T \sim 450$ K (with $n$(H$_2$) = $10^6$ cm$^{-3}$), which is visible in the H$_2$O emission with...
Fig. 7. H$_2$O rotational diagram at L1448-B2. Calibration uncertainties of 20% for the HIFI data and 30% for the PACS data have been assumed. The predictions of the two best-fit models for L1448-B2, corrected for the relative predicted filling factors, are shown (see Table 2 and Fig. 6). Symbols are as in Fig. 6.

On the other hand, we derive a [CO]/[H$_2$] abundance of $(3-4) \times 10^{-5}$ for the warm component and $(1-2) \times 10^{-5}$ for the hot component. The derived [CO]/[H$_2$] abundances do not depend on the emitting size, because both CO and H$_2$ lines are optically thin; therefore, their absolute intensity depends on the beam diluted column density.

Our data suggest that the CO abundance is lower by a factor from 3 to 10 with respect to the canonical value of $2.7 \times 10^{-4}$ measured for dense interstellar clouds (e.g. Lacy et al. 1994). Shocks that are non-dissociative, like those implied by our molecular observations (see Sect. 5), are not expected to alter the original CO/H$_2$ abundance ratio in the cloud. We point out however that a CO abundance less than the canonical value has been recently measured in different environments, including the inner envelopes of low- and intermediate-mass protostars (e.g. Yildiz et al. 2010, 2012; Fuente et al. 2012) and toward the Orion region (Wilson et al. 2011), which indicates that such low values are indeed not peculiar to the considered shock regions.

By comparing the H$_2$O and CO column densities, we find a [H$_2$O]/[CO] abundance ratio of 0.1 for the warm and 0.1–1.3 for the hot component. Thus, an estimate of the H$_2$O abundance, based on the assumption that the CO abundance with respect to H$_2$ is equal to $10^{-4}$, would lead to higher values for the hot component (about $1-13 \times 10^{-5}$). For this reason our obtained H$_2$O abundance values are different from those obtained previously from ISO observations (e.g. Nisini et al. 1999, 2000; Giannini et al. 2001): our analysis points to a CO abundance with respect to H$_2$ lower than the standard value of $10^{-4}$ for the hot component and correspondingly to a lower H$_2$O abundance.

4.1.4. H$_2$O and CO abundance ratios

A direct estimate of the H$_2$O and CO abundances with respect to H$_2$ for both gas components can be obtained by comparing the column density of these species, averaged over a 13$''$ beam. We find an [H$_2$O]/[H$_2$] abundance ratio of $(3-4) \times 10^{-6}$ for the warm component and $(0.3-1.3) \times 10^{-5}$ for the hot component. The inferred H$_2$O abundances are much higher than the typical value of $\sim 10^{-9} - 10^{-8}$, which is found in cold interstellar clouds (e.g. Caselli et al. 2010). However, even for the hot component, this is lower than $\sim 10^{-6}$, which is the value expected in hot shocked gas (e.g. Kaufman & Neufeld 1996; Flower & Pineau Des Forêts 2010). The derived H$_2$O abundances for the warm component are consistent with the values obtained by Santangelo et al. (2012); Vasta et al. (2012); Nisini et al. (2013) from HIFI velocity-resolved observations. In particular, Nisini et al. (2013), from the analysis of H$_2$O 2$_{12}$--1$_{01}$ and 1$_{10}$--1$_{01}$ maps of L1448, derived a relatively constant water abundance along the outflow of about $(0.5-1) \times 10^{-6}$, with an increase by roughly one order of magnitude at the protostar position. Similarly, low H$_2$O abundances in the warm gas have been derived in other outflows by several authors (e.g. Bjerkeli et al. 2012; Tafalla et al. 2013).

On the other hand, we derive a [CO]/[H$_2$] abundance of $(3-4) \times 10^{-5}$ for the warm component and $(1-2) \times 10^{-5}$ for the hot component. The derived [CO]/[H$_2$] abundances do not depend on the emitting size, because both CO and H$_2$ lines are optically thin; therefore, their absolute intensity depends on the beam diluted column density.

Our data suggest that the CO abundance is lower by a factor from 3 to 10 with respect to the canonical value of $2.7 \times 10^{-4}$ measured for dense interstellar clouds (e.g. Lacy et al. 1994). Shocks that are non-dissociative, like those implied by our molecular observations (see Sect. 5), are not expected to alter the original CO/H$_2$ abundance ratio in the cloud. We point out however that a CO abundance less than the canonical value has been recently measured in different environments, including the inner envelopes of low- and intermediate-mass protostars (e.g. Yildiz et al. 2010, 2012; Fuente et al. 2012) and toward the Orion region (Wilson et al. 2011), which indicates that such low values are indeed not peculiar to the considered shock regions.

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Fig. 8. Rotational diagram at L1448-B2 for the CO emission lines (both the detections and the non-detections) observed with PACS (in a 12\textprime 6 beam) and the JCMT CO(3–2) line (empty symbol; beam size equal to 14\textprime). Calibration uncertainties of 30% have been assumed. The solid line represents the linear fit to the four detected CO lines, the dotted line the linear fit only to the three lower excitation CO lines. As in Fig. 7, the predictions of the two best-fit models for L1448-B2 corrected for the relative predicted filling factors are shown.

4.1.5. The spatial extent of the warm and hot components

According to the excitation analysis, different sizes are associated with the two H$_2$O gas components: the warm gas is found to be rather extended (17\textprime), while the hot gas should be compact (<5\textprime). Based on our model, from Fig. 6 we expect the contribution of the warm component to the total H$_2$O flux at 179 $\mu$m to be similar or stronger than that of the hot component, whereas at 174 $\mu$m the hot component dominates the H$_2$O emission with little contribution from the warm component. One way of studying the spatial extent of the two components and verifying the results obtained from our analysis is to use the maps of these two H$_2$O lines (179 and 174 $\mu$m), which are also the strongest H$_2$O lines we detected with PACS, and analyse the relative contribution of the two predicted components from their line ratio. In particular, we expect the ratio between the 179 $\mu$m and the 174 $\mu$m H$_2$O lines to increase going from the central position outwards, thanks to the dominant contribution of the compact central component to the H$_2$O 174 $\mu$m flux.

Figure 10 presents the ratio between the PACS maps of the two H$_2$O lines (at 179 $\mu$m and 174 $\mu$m). As predicted by our excitation analysis, the H$_2$O line ratio increases going from the centre of the map toward the edges in both directions along the outflow. This result supports the scenario in which two gas components coexist: a compact component which dominates the H$_2$O emission above $E_u \sim 190$ K and an extended component that dominates the H$_2$O emission at lower excitation energies.

4.2. Excitation conditions and water abundance at the other shocked positions

At the other selected shock spots a detailed analysis like the one we performed for L1448-B2 is precluded because of the smaller number of lines, the lower S/N of the detections, and the lack of H$_2$ data that would allow us to get a direct measure of the water abundance. The only other position, among the selected ones, where Spitzer spectroscopic data are available is L1157-R (Nisini et al. 2010b). Therefore, at this position an estimate of the water abundance can be obtained in a similar fashion.

The rotational diagram, constructed in L1157-R from the Spitzer mid-IR data (see lower panel of Fig. 4), shows once more the presence of two gas components: a warm component at a temperature of about $T \sim 420$ K and a hot component with $T \sim 800$–850 K. The break is found at approximately 2000 K. The corresponding H$_2$ column densities are $N$(H$_2$) $\sim 1.2 \times 10^{20}$ cm$^{-2}$ for the warm component and $N$(H$_2$) $\sim (0.7$–$1.3) \times 10^{19}$ cm$^{-2}$ for the hot component, both averaged over 13\textprime.

As we did for L1448-B2, we assume that the bulk of the H$_2$O emission observed with PACS is associated with the hot component identified from the H$_2$ rotational diagram, and we adopt a RADEX analysis to derive the excitation conditions of this hot component. In particular, we derived the H$_2$ density, the H$_2$O column density, and the emitting size by fitting the PACS H$_2$O lines with excitation energy level $E_u \gtrsim 190$ K, under the assumption of a temperature $T \sim 800$–850 K from the H$_2$ data and a line width of 25 km s$^{-1}$ from the HIFI observations by Vasta et al. (2012).
Fig. 9. Same comparison presented in Fig. 6, but for the CO fluxes measured with PACS toward L1448-B2 (both the detections and the non-detections). The two blue models represent the extremes of the density range derived from the H2O excitation analysis.

Fig. 10. Ratio between the H2O 212−101 map at 179 μm and the 303−212 map at 174 μm for L1448-B2. The ratio is shown only above a 5σ detection level in both maps. The crosses represent the pointing of the 25 spaxels.

A compact gas component is found to be associated with the bulk of the PACS emission, with n(H2) ∼ (0.1−5) × 10^6 cm^{-3} and N(H2O) ∼ (0.2−6) × 10^{16} cm^{-2}. The obtained excitation conditions appear to be similar to those derived for the hot component at L1448-B2, but a larger uncertainty on the H2O column densities is associated with L1157-R. The corresponding abundance, obtained by comparing the H2O column densities (corrected for the relative filling factor) with the H2 column density, is in the range (0.1−5) × 10^{-5} (see Sect. 4.1.4 for comparison).

For the remaining two shock spots, namely L1448-R4 and L1157-B2, the lack of mid-IR H2 data in both cases does not allow us to get constraints on the temperature and to estimate the H2O abundance. To investigate the physical and excitation conditions of the hot gas component at these positions, we used the L1448-B2 shock position as a template and compared the ratios of the detected lines with the relative line ratios observed in L1448-B2. The comparison is presented for all the selected shock spots in Fig. 11, where all the line ratios are normalized with respect to the H2O 303−212 line at 174 μm. The observed H2O line ratios are roughly comparable within the relative errors with those observed in L1448-B2, within a factor of 2. We can thus conclude that the excitation conditions of the hot gas component are comparable in all selected shock positions, as already deduced for L1157-R. We note that the bright H2O 179/174 μm line ratio at the L1157-B2 shock position may provide evidence for an older shock with respect to the other selected positions. Because this line ratio is indicative of the relative contribution between the warm and the hot component, the high value observed at L1157-B2 may suggest a smaller contribution of the hot component relative to the warm component compared to the other shock positions. This is consistent with this position being the signpost of an older shock, as already suggested by previous studies (e.g. Bachiller & Perez Gutierrez 1997; Rodríguez-Fernández et al. 2010; Vasta et al. 2012). Assuming a constant shock propagation velocity,
Gueth et al. (1998) derived a dynamical age for the L1157-B2 shock spot of ~3000 yr, which is larger than or similar to the typical cooling time of J-type and C-type shocks (≤ 102–103 yr, respectively, Flower & Pineau Des Forêts 2010). Therefore, in L1157-B2 the hot component has already had the time to cool down to a few hundred Kelvin.

Figure 11 shows that CO/H2O line ratios lower by a factor of ~4 with respect to L1448-B2 are found at all other positions. Under the assumption of similar H2O excitation conditions, this would suggest a higher H2O abundance with respect to L1448-B2, which is in line with the range estimated for L1157-R using Spitzer mid-IR H2 data.

The L1448-R4 and L1157-B2 shock positions thus appear to be more similar to L1157-R than to L1448-B2 in terms of H2O abundance. This conclusion is supported by the PACS detection at L1448-B2 of OH and brighter [O i] emission (see Fig. 11), which suggests that not all oxygen has been converted into H2O or that water is partially dissociated. Indeed, the L1448-B2 shock position is intrinsically peculiar with respect to all the other selected positions, since it is close to the driving outflow source. Thus, this position may be affected by the strong UV radiation field coming from the central protostar or from dissociative internal jet shocks (e.g. Hollenbach & McKee 1989; van Kempen et al. 2009), which can photodissociate the freshly formed H2O.

### 4.3. The [O i] ratio

It is useful to compare the observed ratio between the [O i] 3P1 − 3P0 line at 63.2 μm and the [O i] 3P0 − 3P1 line at 145.5 μm to infer additional information on the gas excitation conditions (see Liseau et al. 2006). We detected both [O i] lines only at the L1448-B2 and L1157-R positions (at the latter position the [O i] line at 145 μm was detected only at ~2σ level) and the measured [O i]63/145 μm ratios are ~20 and ~6, respectively. The observed line ratios are displayed in Fig. 12, along with the line ratios predicted from the RADEX code assuming optically thin lines, for collisions with atomic hydrogen or with molecular hydrogen; the predicted line ratio for optically thick lines is also shown. We have neglected O excitation due to collisions with electrons, since it becomes relevant (i.e. it contributes more than 10%) only for n(e)/n(H) fractions larger than 0.6, clearly in contrast with the mostly molecular/atomic gas observed in the considered shocks. Thus, assuming optically thin lines excited by collisions with H2, the ratio observed at L1448-B2 is consistent with a H2 volume density between 105 and a few 105 cm−3 and a temperature T ≥ 100 K, which is within the range of parameters derived from our excitation analysis (see Sects. 4.1.2 and 4.1.3). On the other hand, assuming collisions with H, it corresponds to n(H) ~ 103−104 cm−3 and T ≥ 100 K. We can thus distinguish two possibilities for the origin of the [O i] emission at L1448-B2: either H2O, CO, and [O i] emission arise from the same molecular gas with density n(H2) ~ 5 × 103 cm−3, or the [O i] emission originates in a low-density component of atomic gas. This will be discussed further in Sect. 5. Instead, the lower line ratio measured at L1157-R is consistent either with n(H2) ~ 103−104 cm−3 and T ≥ 200 K for optically thin lines excited by collisions with H2, or with optically thick lines and temperatures lower than 200 K.

Finally, in both positions the [O i] column density averaged over the PACS beam is of the order of 2−5×1015 cm−2 at L1448-B2 and 5−10×1015 cm−2 at L1157-R, which is consistent with optically thin lines.

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**Fig. 11.** Line ratios between the H2O, CO, [O i], and OH lines and the H2O 300−212 line at 174 μm at all selected shock positions. 1σ errors are indicated with errorbars.

**Fig. 12.** Optically thin [O i]63 μm/[O i]145 μm flux ratios as a function of temperature are shown in dotted lines for collisions with atomic hydrogen H and in solid lines for collisions with molecular hydrogen H2 (as in Liseau et al. 2006). The logarithms of the density (in cm−3) are indicated for each curve. The broken line outlines the ratio of optically thick lines. Observed line ratios are depicted by the shaded areas for the L1448-B2 position and the L1157-R position. The data have been smoothed to a common angular resolution of 12″6.
5. Comparison with shock models

The observed fluxes are compared with the grid provided by Flower & Pineau Des Forêts (2010) for stationary C- and J-type shock models. The grid explores a range of shock velocities from 10 to 40 km s\(^{-1}\) and two pre-shock densities, 2 \(\times\) 10\(^{3}\) and 2 \(\times\) 10\(^{5}\) cm\(^{-3}\). In the upper panel of Fig. 13 we present the observed flux of the [O\(i\)] \(^3\)P\(_1\)\(^{-}\)P\(_2\) line at 63.2 \(\mu\)m with the shock model predictions. Unsmoothed peak line fluxes have been used to minimize beam dilution effects. At the L1448-B2 position only a J-type shock, with velocity \(v_s > 20\) km s\(^{-1}\) for pre-shock density \(n = 2 \times 10^5\) cm\(^{-3}\) and \(v_s > 10\) km s\(^{-1}\) for \(n = 2 \times 10^3\) cm\(^{-3}\), can reproduce the observed flux; C-type shocks under-estimate this line by at least one order of magnitude. A pre-shock density \(n = 2 \times 10^5\) cm\(^{-3}\), and a corresponding shock velocity \(v_s > 10\) km s\(^{-1}\), are not consistent with the results of the H\(_2\)O and CO excitation analysis (Table 2). From the comparison between this pre-shock density and the maximum post-shock density that can be evinced from the [O\(i\)] line ratio (see Sect. 4.3 and Fig. 12), a very small compression factor would be derived. In addition, a comparison with shock models by Hollenbach & McKee (1989) shows that even a lower pre-shock density of 10\(^3\) cm\(^{-3}\) and shock velocity \(v_s \geq 30\) km s\(^{-1}\) can reproduce our [O\(i\)] data. This suggests that at L1448-B2 the [O\(i\)] emission originates in a fast dissociative shock with pre-shock density \(n \leq 2 \times 10^3\) cm\(^{-3}\) and \(v_s > 20\) km s\(^{-1}\). The presence of a dissociative shock giving rise to ionizing photons is also supported by the detection at the [O\(i\)] peak of OH at 119 \(\mu\)m and [Fe\(ii\)] at 26 \(\mu\)m (see Fig. 2).

On the other hand, at the other shock positions we are not able to discriminate between C- and J-type shocks. The observations are consistent either with a low-velocity (\(v_s < 20\) km s\(^{-1}\)) C-type shock or with a J-type shock with velocity \(v_s > 20\) km s\(^{-1}\) for \(n = 2 \times 10^4\) cm\(^{-3}\) and \(v_s > 10\) km s\(^{-1}\) for \(n = 2 \times 10^3\) cm\(^{-3}\).

A comparison of the observed CO and H\(_2\)O emission with shock models is presented in the lower panel of Fig. 13 for the L1448-B2 and L1448-R4 shock positions. At the L1448-B2 position the CO and H\(_2\)O emissions are also consistent with a J-type shock having a pre-shock density \(n = 2 \times 10^5\) cm\(^{-3}\) but at a lower shock velocity \((\leq 20\) km s\(^{-1}\)) with respect to the [O\(i\)] emission. According to Flower & Pineau Des Forêts (2010), a high compression factor of about 100 is predicted for a low-velocity (\(v_s \leq 20\) km s\(^{-1}\)) J-type shock, as observed at this shock position. This corresponds to a post-shock density of about \(2 \times 10^6\) cm\(^{-3}\), which is within the range of post-shock density derived from the H\(_2\)O and CO excitation analysis (Table 2) for the hot gas component. On one hand, the plot highlights that the physical conditions at this shock position are different with respect to the other selected shock spots. In particular, at the L1448-R4 position the observations are consistent with a C-type shock with pre-shock density \(n = 2 \times 10^5\) cm\(^{-3}\) and velocity larger than 20 km s\(^{-1}\), in contrast with the predictions from C-type shock models for the [O\(i\)] emission at the same shock position. A lower compression factor with respect to L1448-B2, in the range 2.5--25, is suggested at L1448-R4 from the comparison between the derived pre-shock densities and the post-shock densities obtained from the excitation analysis. This is consistent with the proposed scenario in which CO and H\(_2\)O emissions are produced in a C-type shock.

In conclusion (see Table 3 for a summary), our analysis suggests that at the L1448-B2 shock position the H\(_2\)O and CO emissions are produced in a low-velocity non-dissociative J-type shock along the outflow cavity walls, whereas the [O\(i\)] and maybe the OH emission originate in a fast dissociative shock. The bright and velocity-shifted [O\(i\)] emission at 63 \(\mu\)m, along with the detection of the [Fe\(ii\)] line and the high [O\(i\)]/H\(_2\)O line ratio (\(\sim 20\)), supports the presence of fast dissociative shocks related to the presence of an embedded atomic jet near the protostar (e.g. Hollenbach & McKee 1989; Flower & Pineau Des Forêts 2010).

At the other shock positions, we can conclude that the excited H\(_2\)O and high-J CO emissions are produced in a C-type shock with velocity greater than 20 km s\(^{-1}\), whereas a partially dissociative J-type shock is needed to explain the [O\(i\)] emission. As discussed in Sect. 4.2, the H\(_2\)O abundance of the hot gas at
these positions appears to be higher than at L1448-B2 by a factor of ~4. This is consistent with L1448-B2 being the signpost of a J-type shock, in which the predicted H$_2$O abundance is of the order of $2 \times 10^{-9}$ (see Flower & Pineau Des Forêts 2010).

Finally, our results are also consistent with previous HIFI observations by Santangelo et al. (2012), showing that the H$_2$O line ratios at L1448-B2 are consistent with a non-dissociative J-type shock, with pre-shock density $n = 2 \times 10^4$ cm$^{-3}$. On the other hand, the authors found that in L1448-R4 the shock conditions of the low-velocity component, which dominates the emission in the relatively higher excitation lines, are more degenerate and a C-type shock origin could not be ruled out. The same degeneracy has been inferred for the two positions along the L1157 outflow by Vasta et al. (2012), thus consistent with a possible C-type shock origin for the H$_2$O emission.

With this in mind, a test comparison with available shock models can only be roughly indicative of the real physical situation occurring in the investigated shock events. In particular, geometrical complexity as well as chemical effects induced by diffuse UV fields (both from the star and from associated fast shocks) would need to be properly included in a more realistic model.

6. Conclusions

Herschel--PACS observations of H$_2$O, high-J CO, [OI], and OH toward two selected positions along the bright outflows L1448 and L1157 have been presented, as part of the WISH key program. The main conclusions of this work are the following:

1. Consistent with other studies, at all selected shock positions we find a close spatial association, at the angular resolution of our PACS observations, between H$_2$O emission and high-J CO emission, whereas the low-J CO emission seems to trace a different gas component, not directly associated with shocked gas. A spatial association is also found between H$_2$O emission and mid-IR H$_2$ emission at all selected positions. Moreover, no shift is found at this angular resolution between H$_2$O, [OI], and [FeII] emission, although the H$_2$O emission appears to be more extended than [OI] and [FeII].

2. The excitation conditions at the L1448-B2 shock position close to the driving outflow source indicate a two-component model to reproduce the H$_2$O and CO emission. In particular, an extended warm component with temperature $T \sim 450$ K and density $n(H_2)=10^4$ cm$^{-3}$ is traced by the bulk of the HIFI H$_2$O emission ($E_a = 53-137$ K) and by the PACS CO emission up to $J = 22-21$; furthermore, a compact hot component with $T = 1100$ K and density $n(H_2) = (0.5-5) \times 10^7$ cm$^{-3}$ is traced by the bulk of the PACS higher-excitation H$_2$O emission ($E_a > 190$ K) and by the PACS higher-J CO emission. A similar stratification of gas components at different temperatures has been found for the Spitzer H$_2$ gas.

3. Among the selected positions L1448-B2 is found to be peculiar, possibly because of its proximity to the central driving source of the L1448 outflow. In particular, a non-dissociative J-type shock at the point of impact of the jet on the cloud seems to be responsible for the H$_2$O and CO hot gas component at this position, whereas a C-type shock is needed to explain the origin of the hot component at the other selected positions. On the other hand, the observations suggest a dissociative J-type shock at L1448-B2, related to the presence of an embedded atomic jet, to explain the observed OH and [FeII] emission and the bright and velocity-shifted [OI] emission. A J-type shock that is at least partially dissociative is needed to explain the [OI] emission at the other selected positions as well.

4. From the comparison between H$_2$O and H$_2$, at L1448-B2 we obtain a H$_2$O abundance of $3 \times 10^{-5}$ for the warm component and of $(0.3-1.3) \times 10^{-4}$ for the hot component. At the other examined shock positions the H$_2$O abundance of the hot component appears to be higher by a factor of ~4, reflecting evolutionary effects on the timescales of the outflow propagation. The indication that the H$_2$O abundance may be higher in the hotter gas in some shock positions is in line with ISO data by other authors (e.g. Giannini et al. 2001). This result is also consistent with L1448-B2 being closer to the driving outflow source than the other selected positions. This makes it more affected by the strong FUV radiation field coming from the nearby protostar that may photodissociate H$_2$O in the post-shock gas and thus decrease the H$_2$O abundance. An estimate of the CO abundance was also derived at L1448-B2 and is of the order of $(3-4) \times 10^{-5}$ for the warm component, whereas it is $(1-2) \times 10^{-4}$ for the hot component.

5. These results, along with the spatial extent inferred for the different gas components, lead us to the conclusion that the two gas components represent a gas stratification in the post-shock region. In particular, the extended and low-abundance warm component traces the post-shocked gas that has already cooled down to a few hundred Kelvin, whereas the compact and possibly more abundant hot component is associated with the gas that is currently undergoing a shock episode, being compressed and heated to a thousand Kelvin. This hot gas component is thus possibly affected by evolutionary effects on the timescales of the outflow propagation, which explains the variations of H$_2$O abundance we observed at the different positions along the outflows.

Table 3. Origin of the emission observed with PACS.

| Position   | [OI] & OH | H$_2$O & high-J CO |
|------------|----------|------------------|
| L1448-B2   | J-type shock ($v_0 > 20$ km s$^{-1}$, $n \leq 2 \times 10^4$ cm$^{-3}$) | J-type shock ($v_0 < 20$ km s$^{-1}$, $n = 2 \times 10^4$ cm$^{-3}$) |
| L1448-R4   | J-type shock ($v_0 > 10$ km s$^{-1}$) | C-type shock ($v_0 > 20$ km s$^{-1}$, $n = 2 \times 10^4$ cm$^{-3}$) |

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References

Bachiller, R., & Perez Gutierrez, M. 1997, ApJ, 487, L93
Bachiller, R., Martin-Pintado, J., Tafalla, M., Cernicharo, J., & Lazareff, B. 1990, A&A, 231, 174
Bachiller, R., Guilloteau, S., Dutrey, A., Planesas, P., & Martin-Pintado, J. 1995, A&A, 299, 857
Bachiller, R., Perez Gutierrez, M., Kumar, M. S. N., & Tafalla, M. 2001, A&A, 372, 899
Benedettini, M., Viti, S., Gianinni, T., et al. 2002, A&A, 395, 657
Benedettini, M., Busquet, G., Lefloch, B., et al. 2012, A&A, 539, L3
Bergin, E. A., Neufeld, D. A., & Melnick, G. J. 1998, ApJ, 499, 777
Bjerke, P., Liseau, R., Olberg, M., et al. 2009, A&A, 507, 1455
Bjerke, P., Liseau, R., Nisini, B., et al. 2011, A&A, 533, A80
Bjerke, P., Liseau, R., Larson, B., et al. 2012, A&A, 546, A29
Caselli, P., Keta, E., Pagani, L., et al. 2010, A&A, 518, L112
Codella, C., Lefloch, B., Ceccarelli, C., et al. 2010, A&A, 518, L112
Coffey, C., Ceccarelli, C., Lefloch, B., et al. 2012a, ApJ, 757, L29
Codella, C., Ceccarelli, C., Lefloch, B., et al. 2012a, ApJ, 757, L9
Codella, C., Ceccarelli, C., Lefloch, B., et al. 2012b, ApJ, 757, L45
Daniel, F., Dubernet, M.-L., Paucaud, F., & Grosjean, A. 2010, A&A, 517, A13
Daniel, F., Dubernet, M.-L., & Grosjean, A. 2011, A&A, 536, A76
Davis, C. J., & Smith, M. D. 1995, ApJ, 443, L41
de Graauw, Th., Helmich, F. P., Phillips, T. G., et al. 2010, A&A, 518, L6
Dubernet, M.-L., Daniel, F., Grosjean, A., et al. 2006, A&A, 460, 323
Dubernet, M.-L., Daniel, F., Grosjean, A., & Lin, C. Y. 2009, A&A, 497, 911
Dutrey, A., Guilleto, S., & Bacheril, R. 1997, A&A, 325, 178
Eisloffel, J. 2000, A&A, 354, 236
Flower, D. R., & Pineau Des Forêts, G. 2010, MNRAS, 406, 1745
Franklin, J., Snell, R. L., Kaufman, M. J., et al. 2008, ApJ, 674, 1015
Fuentes, A., Caselli, P., McCoe, C., et al. 2012, A&A, 540, A75
Gianinni, T., Nisini, B., & Lorenzetti, D. 2001, ApJ, 555, 40
Gianinni, T., Nisini, B., Neufeld, F., et al. 2011, ApJ, 738, 80
Goicoechea, J. R., Cernicharo, J., Karsa, A., et al. 2012, A&A, 548, A77
Gueth, F., Guilleto, S., & Bacheril, R. 1998, A&A, 333, 287
Guilleto, S., Bacheril, R., Fuente, A., & Lucas, R. 1992, A&A, 265, L49
Herczeg, G. J., Karsa, A., Bruderer, S., et al. 2012, A&A, 540, A84
Hirano, N., Ho, P. P. T., Liu, S.-Y., et al. 2010, ApJ, 717, 58
Hirota, T., Honma, M., Imai, H., et al. 2011, PASJ, 63, 1
Hollenbach, D., & McKee, C. F. 1989, ApJ, 343, 306
Karsa, A., Herczeg, G. J., van Dishoeck, E. F., et al. 2013, A&A, 552, A141
Kaufman, M. J., & Neufeld, D. A. 1996, ApJ, 456, 611
Kristensen, L. E., van Dishoeck, E. F., Tafalla, M., et al. 2011, A&A, 531, L1
Kristensen, L. E., van Dishoeck, E. F., Bergin, E. A., et al. 2012, A&A, 542, A8
Lacy, J. H., Knacke, R., Gabele, T. R., & Tokunaga, A. T. 1994, ApJ, 428, L69
Lefloch, B., Cabrit, S., Codella, C., et al. 2010, A&A, 518, L113
Lefloch, B., Cabrit, S., Busquet, G., et al. 2012, ApJ, 757, L25
Liseau, R., Ceccarelli, C., Larson, B., et al. 1996, A&A, 315, L181
Liseau, R., Justtanont, K., & Tielens, A. G. G. M. 2006, A&A, 446, 561
Manoj, P., Watson, D. M., Neufeld, D. A., et al. 2013, ApJ, 763, 83
Neufeld, D. A., & Dalgarno, A. 1989, ApJ, 340, 869
Neufeld, D. A., Nisini, B., Giannini, T., et al. 2009, ApJ, 706, 170
Nisini, B., Benedettini, M., Giannini, T., et al. 1999, A&A, 350, 529
Nisini, B., Benedettini, M., Giannini, T., et al. 2000, A&A, 360, 297
Nisini, B., Benedettini, M., Codella, C., et al. 2010a, A&A, 518, L120
Nisini, B., Giannini, T., Neufeld, D. A., et al. 2010b, ApJ, 724, 69
Nisini, B., Santangelo, G., Antonucci, S., et al. 2013, A&A, 549, A16
Ott, S. 2010, Astronomical Data Analysis Software and Systems XIX, 434, 139
Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, A&A, 518, L1
Poglitsch, A., Waelkens, C., Geis, N., et al. 2010, A&A, 518, L2
Rodríguez-Fernández, N. J., Tafalla, M., Gueth, F., & Bachiller, R. 2010, A&A, 516, A98
Santangelo, G., Nisini, B., Giannini, T., et al. 2012, A&A, 538, A45
Tafalla, M., Liseau, R., Nisini, B., et al. 2013, A&A, 551, A116
Tobin, J. J., Looney, L. W., Mundy, L. G., Kwon, W., & Hamidouche, M. 2007, ApJ, 659, 1044
van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, A&A, 468, 627
van Dishoeck, E. F., Kristensen, L. E., Benz, A. O., et al. 2011, PASP, 123, 138
van den Kempen, T. A., van Dishoeck, E. F., Güsten, R., et al. 2009, A&A, 507, 1425
van den Kempen, T. A., Kristensen, L. E., Herczeg, G. J., et al. 2010a, A&A, 518, L121
van den Kempen, T. A., Green, J. D., Evans, N. J., et al. 2010b, A&A, 518, L128
Vasta, M., Codella, C., Lorenzani, A., et al. 2012, A&A, 537, A98
Visser, R., Kristensen, L. E., Bruderer, S., et al. 2012, A&A, 537, A55
Wilson, T. L., Muders, D., Dumke, M., Henkel, C., & Kawanuma, J. H. 2011, ApJ, 728, 61
Yıldız, U. A., van Dishoeck, E. F., Kristensen, L. E., et al. 2010, A&A, 521, L40
Yıldız, U. A., Kristensen, L. E., van Dishoeck, E. F., et al. 2012, A&A, 542, A86
Yıldız, U. A., Kristensen, L. E., van Dishoeck, E. F., et al. 2013, A&A, 556, A89

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Appendix A: PACS maps

The PACS maps of all the lines observed at the four selected shock positions (B2 and R4 along L1448 and B2 and R along L1157) are presented in this section (see also Table 1). In particular, Figs. A.1 and A.2 are relative to the L1448 outflow (B2 and L1157 positions, respectively), whereas Figs. A.3 and A.4 concern the L1157 outflow (B2 and R positions, respectively).

Fig. A.1. PACS spectra of the detected transitions at the L1448-B2 position. The centre of each spaxel box corresponds to its offset position with respect to the coordinates of the central shock position. The velocity (km s$^{-1}$) and intensity scale (Kelvin) are indicated for one spaxel box and refer to all spectra of the relative transition. The labels in the top-right corner of every box indicate the relative transition.
Fig. A.1. continued.
Fig. A.1. continued.
**Fig. A.2.** Same as Fig. A.1 for the L1448-R4 position.
Fig. A.2. continued.
**Fig. A.3.** Same as Fig. A.1 for the L1157-B2 position.
Fig. A.4. Same as Fig. A.1 for the L1157-R position.
Fig. A.4. continued.