Water cooling of shocks in protostellar outflows:

Herschel-PACS map of L1157*


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ABSTRACT

Context: The far-IR/sub-mm spectral mapping facility provided by the Herschel-PACS and HIFI instruments has made it possible to obtain, for the first time, images of H2O emission with a spatial resolution comparable to ground based mm/sub-mm observations.

Aims: In the framework of the Water in Star-forming regions with Herschel (WISH) key program, maps in water lines of several outflows from young stars are being obtained, to study the water production in shocks and its role in the outflow cooling. This paper reports the first results of this program, presenting a PACS map of the o-H2O 179 μm transition obtained toward the young outflow L1157.

Methods: The 179 μm map is compared with those of other important shock tracers, and with previous single-pointing ISO, SWAS, and Odin water observations of the same source that allow us to constrain the H2O abundance and total cooling.

Results: Strong H2O peaks are localized on both shocked emission knots and the central source position. The H2O 179 μm emission is spatially correlated with emission from H2 rotational lines, excited in shocks leading to a significant enhancement of the water abundance. Water emission peaks along the outflow also correlate with peaks of other shock-produced molecular species, such as SiO and NH3. A strong H2O peak is also observed at the location of the proto-star, where none of the other molecules have significant emission. The absolute 179 μm intensity and its intensity ratio to the H2O 557 GHz line previously observed with Odin/SWAS indicate that the water emission originates in warm compact clumps, spatially unresolved by PACS, having a H2O abundance of the order of $10^{-4}$. This testifies that the clumps have been heated for a time long enough to allow the conversion of almost all the available gas-phase oxygen into water. The total H2O cooling is $\sim 10^{-1} L_\odot$, about 40% of the cooling due to H2 and 23% of the total energy released in shocks along the L1157 outflow.

Key words. Stars: formation,ISM: jets and outflows, Individual objects: L1157

1. Introduction

Among the main coolants in molecular shocks, water is the tracer most sensitive to physical variations and the temporal evolution of protostellar outflows, thus representing a very powerful probe of their shock conditions and thermal history (e.g., Bergin et al. 1998). Water emission and excitation in shocks were studied extensively for the first time with the Infrared Space Observatory (ISO), the first space facility with spectroscopic capabilities in the mid- and far-IR. ISO surveyed the water emission in a large sample of outflows from young stellar objects (YSOs), providing a global statistical picture of the importance of water in the outflow cooling and of variations in its abundance with shock properties and ages (see e.g., Nisini 2003, van Dishoeck 2004). Following ISO, the SWAS and Odin facilities made it possible to observe the ortho-H2O fundamental line at 557 GHz, providing important constraints on the water abundance and kinematics in the cold outflow gas components (e.g., Franklin et al. 2008, Bjerkeli et al. 2009). All these facilities, however, had poor spatial resolution (i.e. greater than 80″), which did not allow one to locate the origin of the water emission nor study variations in abundances and excitation within individual flows.

In this framework, a sample of YSO outflows will be surveyed in different water lines by the PACS and HIFI instruments onboard the Herschel satellite, as part of the key program WISH (Water In Star-forming-regions with Herschel). This paper presents the first results obtained from this survey, consisting of a PACS map of the H2O 212–201 179 μm line covering the outflow of the protostar L1157-mm, obtained during the Herschel Science Demonstration Phase. The 179 μm line is the transition connecting the lower two back-bone levels of ortho-H2O. It is therefore one of the brightest water lines expected in collisionally excited conditions, thus representing an ideal tracer of the water distribution in shocked regions. L1157 is a well...
known outflow driven by a low mass class 0 object (L1157-mm, $L_{bol} \sim 8.3 \ L_\odot$, D=440 pc, Froebrich 2005). It is considered to be the prototype of chemically active flows, given the large number of different species detected in its shocked regions (e.g., Bachiller & Perez-Gutierrez 1997). This paper is presenting the first of several observations planned for this source by the WISH team.

2. Observations

Observations were performed on 26 October 2009 with the PACS instrument (Poglitsch et al. 2010) onboard the Herschel Space Observatory (Pilbratt et al. 2010) in line spectroscopic mode, with the grating centered on the H$_2$O 2$_{12}$-1$_{10}$ line at 179.527 $\mu$m. The L1157 outflow region (of about 6' $\times$ 2') was covered by 3 individual PACS raster maps, arranged along the outflow axis. Each map consists of 3x3 PACS frames acquired in steps of 10". The instrument is a 5 x 5 pixel array providing a spatial sampling of 9.4"/pixel, while the spectral resolution at 179 $\mu$m is $R \sim$1500 (i.e., $\sim$210 km s$^{-1}$). The data were reduced with HIPE 2.0. Additional IDL routines were developed to construct a final integrated and continuum-subtracted line map. Flux calibrations used calibration files obtained by ground tests that remain very uncertain at the time of paper writing, essentially for extended sources. To evaluate the flux uncertainty, we compared with the three measurements performed by the ISO satellite along the outflow (Giannini et al. 2001). To do that, we performed aperture photometry of the line emission in the PACS map within the 80" ISO circular beam. The ratio of PACS to ISO fluxes ranges between 1.1 and 1.8 at the three positions: we adopt this as the uncertainty in our quantitative analysis. The typical rms noise across the map is of the order of 2 $10^{-5}$ ergs$^{-1}$ cm$^{-2}$ sr$^{-1}$.

3. Results and comparison with other tracers

Figure 1 presents the PACS map of the 179 $\mu$m line emission. In the same figure, the H$_2$O map is overlaid with contours of the emission from the H$_2$ 0-0 S(1) (Neufeld et al. 2009), CO 2-1 and SiO 3-2 (Bachiller et al. 2001) transitions. The water map exhibits several emission peaks corresponding to the positions of previously-known shocked knots, labelled as B0-B1-B2 for the south east blue-shifted lobe, and R0-R-R2 for the north west red-shifted lobe, following the nomenclature of Bachiller et al. (2001). These emission knots represent the actual working surfaces of a precessing and pulsed jet and are thus associated with the present location of the active shock regions. With respect to CO, H$_2$O emission appears more localized, having a less prominent diffuse component. About 60% of the total 179 $\mu$m flux is found within 30" apertures centered on the knots. This could be partly related to the line excitation: the 179 $\mu$m line excitation temperature is ~80 K above the o-H$_2$O ground state (compared to the 17 K for CO 2-1), and the critical density of its upper level is above 10$^5$ cm$^{-3}$ for $T \leq 500$ K. It may however also be a consequence of the specific conditions needed to ensure a significant production of water. The H$_2$O abundance is indeed significantly higher in shocks strong enough to release the water ice located on grain mantles by sputtering and grain-grain collisions or to activate the gas-phase reactions that convert the gas-phase oxygen into water. Both these processes become efficient at shock velocities $v_s \sim 15$ km s$^{-1}$ (Caselli et al. 1997, Jiménez-Serra et al. 2008, Kaufman & Neufeld 1996). In this respect, we note that the H$_2$O emission peaks correspond rather closely to both the position and the relative intensity of the H$_2$ rotational emission (with the H$_2$O 179 $\mu$m/H$_2$ 17 $\mu$m ratio in the range (2-3)$\times$10$^{-2}$ for all the H$_2$ peaks). Peaks of low-J/H$_2$ pure rotational lines are associated with warm gas (with $T \sim 300$-500 K) excited in low velocity non-dissociative shocks that are tracers of regions in which a high H$_2$O abundance is expected. Other molecules are known to have strongly enhanced abundances in shocks. One of the most well studied of these molecules is SiO, for which Fig. 1 shows that, like water, its emission is very localized around the shocked knots. A similar behavior is found for other molecules, such as NH$_3$ and CH$_3$OH (Bachiller et al. 2001, Tafalla & Bachiller 1995).

The strongest water peak is located at the position of the B1 knot, which is known to be the most chemically active of the L1157 spots (e.g. Bachiller & Perez-Gutierrez 1997, Benedettini et al. 2007, Codella et al. 2010). This knot at near-IR wavelengths appears as a bow shock with intense H$_2$ 2.12$m$ emission (Davis & Eisloffel 1995) and has a significant H$_2$ column density enhancement (Nisini et al. 2010). Although the spatial resolution of the present observations prevents us from completely resolving the bow shock structure, the observed morphology at the B1/B0 positions suggests that water emission is mainly localized at the bow apex and eastern wing. A similar morphology has been observed for molecules such as SiO, NH$_3$, and CS (Benedettini et al. 2007, Tafalla & Bachiller 1997), while other shock produced molecules, such as CH$_3$OH, noticeably have emission localized on the bow western wing (e.g. Codella et al. 2009). This behavior probably relates to an asymmetry in the excitation conditions along the bow structure, most likely induced by the jet precession or the propagation of shocks in an inhomogeneous medium.

Strong, spatially unresolved, water emission is also detected on-source. This localized emission can originate in different components, including shocks impacting on a dense medium at the jet base, the infalling protostellar envelope, or emission from a UV-heated outflow cavity, as discussed in van Kempen et al. (2010) for the HH46-IRS case. The precise origin of this emission will be investigated by dedicated Herschel observations, but we note here the interesting evidence that no other molecule exhibits significant emission at the central position. In particular, the non-detection of strong emission from molecules such as CH$_3$OH indicates that grain ice mantle evaporation in the protostellar envelope is unlikely to be the origin of the on-source H$_2$O emission, since the two molecules should desorb at similar temperatures. The non-detection of the H$_2$ 0-0 S(1) line at the central position is also remarkable. This may be caused by the heavy extinction close to the central source. Assuming an intrinsic H$_2$O 179 $\mu$m/H$_2$ 17 $\mu$m ratio in the range of that observed along the outflow, we estimate that $A_V$ on-source should be $\geq 150$ mag to be able to explain the H$_2$ line non-detection. Alternatively, C-type shocks with very high pre-shock densities ($\geq 10^5$cm$^{-3}$) and velocities between 20 and 40 km s$^{-1}$ are expected to have a large H$_2$O/H$_2$ cooling ratio (Kaufman & Neufeld 1996).

4. Water abundance and total cooling

To constrain the range of water column densities that could produce the observed 179 $\mu$m emission, we consider the SWAS and Odin observations of the H$_2$O 1$_{01}$-0$_{00}$ 557 GHz (538$\mu$m) line observed in this outflow (Franklin et al. 2008, Bjerkeli et al. 2009). Given the large size of the apertures of these two instruments relative to the PACS spatial resolution, we evaluate here only properties averaged over large outflow regions. In particular, we consider the Odin observations acquired towards the
blue (B) and red (R) outflow lobes at offsets (+29”, -52”) and (-21”, +121”) (Bjerkeli et al. 2009). The 179 μm/557 GHz intensity ratios are obtained by diluting the PACS observations to the 126” Odin resolution. The same procedure was adopted for the SWAS observation that encompasses almost the entire L1157 PACS mapped region with its 3.5’ × 5.0’ elliptical aperture. Figure 2 presents large velocity gradient (LVG) predictions, assuming a slab geometry, of the 179 μm line brightness versus the 179 μm/557 GHz line ratio, compared to the observations combined above. The absolute brightnesses are those averaged within an area enclosing 90% of the total PACS emission inside each considered Odin/SWAS aperture. These emitting areas are 5.9 × 10⁻⁸, 8.0 × 10⁻⁸, and 2.7 × 10⁻⁷ sr for the R, B, and the SWAS apertures, respectively. The line intensity derived in this way was considered to be a lower limit to the true 179 μm brightness if the PACS emission originates in a clumpy medium, of which the clump size is smaller than the Herschel diffraction limit at 179 μm.

In the figure, observations are indicated as boxes that take into consideration the uncertainty of a factor of about 1.5 in the 179 μm flux, estimated by comparing with the ISO observations (Sect. 2). Theoretical curves were derived as a function of the O-H₂O column density, using the RADEX code (Van der Tak et al. 2007) assuming temperature and density conditions measured from the H₂ Spitzer observations or ground-based millimeter observations (Nisini et al. 2010, Nisini et al. 2007, Mikami et al. 1992). The temperature is between 300 and 500 K and the density is in the range 1–5 × 10⁵ cm⁻³, the blue lobe being on average colder and denser than the red lobe. Part of the 557 GHz emission can arise from a gas colder than these assumed values, given the lower excitation temperature of this line with respect to the 179 μm line. To evaluate the effect of different temperature components along the line of sight on the ratio of the two considered transitions, Fig. 2 also plots the theoretical predictions assuming a temperature stratification where the column density

![Fig. 1. Continuum subtracted PACS map of the integrated H₂O 179 μm emission along the L1157 outflow. Offsets are with respect to the L1157-mm source, at coordinates α(2000) = 20:39:06.2, δ(2000) = +68:02:16. The different emission peaks are labelled following the nomenclature adopted by Bachiller et al. (2001) for individual CO peaks. The same map is shown in the other panels with overlays of other tracers, namely H₂ 0–0 S(1) at 17μm (Neufeld et al. 2009), CO 2–1, and SiO 3–2 (Bachiller et al. 2001). The spatial resolution of these images are ~11”, for H₂ and CO, and 18” for SiO. Note that the H₂ observed region does not cover the B2 and R2 shocked peaks.](image1)

![Fig. 2. LVG theoretical predictions of the 179 μm line brightness versus the 179 μm/557 GHz line ratio, compared with observed values. See text for the details.](image2)
in each layer at a given $T$ varies as $T^{-6}$ (Neufeld & Yuan 2008). A minimum and maximum temperature of 100 K and 4000 K, respectively are assumed, and $b$ values between 2 and 4, i.e., the range of values that consistently fit the $H_2$ rotational lines (Neufeld et al. 2009). These curves give the same range of predicted values as the single $T$ curves, indicating that contributions from high-temperature gas do not significantly affect the considered transitions.

Several general conclusions can be drawn from the inspection of Fig. 2. Firstly, the data are consistent with model predictions only if we assume that the real emitting areas are smaller than those estimated from the PACS map. In particular, agreement with the theoretical curves is found for covering factors ($f_c$) ~ 0.1-0.2, which suggests that the emission is concentrated on some unresolved emission knots that together do not fill an area larger than a few arcsec. This is not unexpected, since interferometric mm observations illustrate the extreme clumpiness of the shocked gas, individual knots being of sizes of a few arcsec each (e.g., Benedettini et al. 2007, Lefloch et al. 2010).

We note that the typical length scale for planar C-type shocks at the considered densities is of the order of $10^{15}$ cm, i.e., about 1/10 of the PACS spatial resolution at D=440 pc. The observed $179 \mu m$ emission ratios, ranging between 10 and 20, are consistent with $N(H_2O) \sim 2-9 \times 10^{11} \text{ cm}^{-2}$ (assuming a $A_V = 15 \text{ km s}^{-1}$ from the 557 GHz line width). The $H_2$ column densities, averaged within the PACS emitting areas, were measured from the $H_2$ mid-IR rotational lines and results in $< 5 \times 10^{10} \text{ cm}^{-2}$ in both regions covered by the B and R observations. The water abundance in the unresolved clumps is therefore estimated to be $N(H_2O)/N(H_2) \times 10^{-3}$, where $N(H_2O)$ is $3 \times 10^{-4}$ (with a H$_2$O o/p ratio of 3). Table 1 reports in more detail the range of values derived in each considered aperture. The total mass of the shocked gas involved in the 179 $\mu m$ emission is of the order of $5 \times 10^{-5} \text{ M}_\odot$, which is only a small fraction (~ 1/100) of the total mass of the outflow estimated from CO observations (e.g., Bachiller et al. 2001, Lefloch et al. 2010) that show H$_2$O components with different velocities are discernible in the 557 GHz data acquired by HIFI in a 40'' beam centred on the L1157-B1 knot. They separately analyse the different velocity components, confirming that small filling factors are required to explain their observations and finding that the component of higher velocity is the one exhibiting the water abundance of the order of $10^{-4}$. Lower $H_2$O abundance values, between $10^{-7}$ and $10^{-5}$, were estimated using only the SWAS and Odin 557 GHz emission, assuming that the 557 GHz emission originates in the same cool gas traced by the low-$J$ CO emission, thus a gas with a larger covering factor and lower temperature than considered here (Neufeld et al. 2000, Franklin et al. 2008, Bjerkeli et al. 2009). Combining ISO-179 $\mu m$ emission and SWAS observations, Benedettini et al. (2002) derived a water abundance for the warm shocked gas of $\sim 5 \times 10^{-5}$, thus in the lower range of values estimated in the present analysis. However, the ISO observations did not cover the entire L1157 outflow 179 $\mu m$ emission, and the inferred ISO 179 $\mu m$/SWAS 557 GHz ratio was underestimated by about a factor of 2. Given the considered conditions, the 179 $\mu m$ line contributes to about 30-40% of the water emission in the outflow: the total estimated H$_2$O luminosity is $\sim 8 \times 10^{-2} \text{ L}_\odot$, which is about 40% of the total H$_2$ shock luminosity (0.2 L$_\odot$, Nisini et al. 2010) and about 23% of the total shock cooling in the L1157 outflow, if we also consider the contributions given by CO and [O i] derived from ISO observations by Giannini et al. (2001). The high water abundance estimated in the present analysis is consistent with predictions of non-dissociative shock models, in which water is mainly produced by endothermic reactions, activated at $T \gtrsim 300$ K, where

\begin{table}[h]
\centering
\caption{Estimated water abundances}
\begin{tabular}{ccccccc}
\hline
$R^a$ & $T^b$ & $n(H_2)^c$ & $N(\text{H}_2\text{O})^d$ & $X(\text{H}_2\text{O})^e$ & $A^f_{\text{sf}}$ \\
\hline
B & 14-20 & 300 & $3 \times 10^{10}$ & 3-9 & 0.6-3 & $\sim 5 \times 10^{-9}$ \\
R & 10-14 & 500 & $1 \times 10^{11}$ & 2-4 & 0.8-2 & $\sim 9 \times 10^{-9}$ \\
\hline
\end{tabular}
\end{table}

5. Conclusions

We have presented a PACS spectral map of the H$_2$O 179 $\mu m$ transition obtained toward the L1157 protostellar outflow. Strong water emission peaks have been found at the location of previously-known shocked spots and correlate well with $H_2$ mid-IR rotational lines, as well as other important shock tracers, such as SiO and NH$_3$. The absolute 179 $\mu m$ intensity and the intensity ratios with respect to the previously-observed 557 GHz line, indicate that the water emission originates in warm compact clumps, spatially unresolved by PACS, that have a H$_2$O abundance of the order of $10^{-4}$. The total H$_2$O cooling has been estimated to be of the order of $8-9 \times 10^{-2} \text{ L}_\odot$, representing about 40% of the cooling due to H$_2$ and 23% of the total energy released in shocks along the L1157 outflow.

Additional Herschel PACS/HIFI observations of the L1157 outflow are planned by the WISH program. These will enable us to investigate variations in the water abundance within the outflow and correlate these with kinematical information.

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