The CHESS Spectral Survey of Star Forming Regions: Peering into the protostellar shock L1157-B1. II. Shock Dynamics

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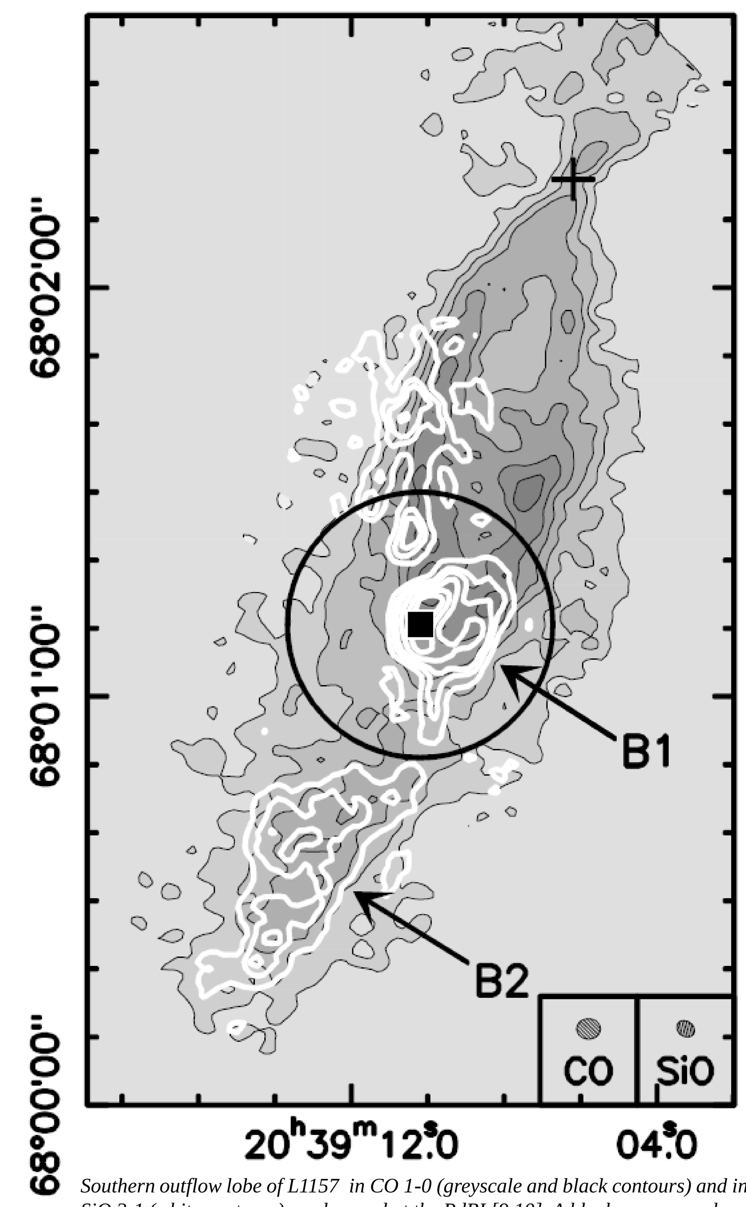
Abstract :
The outflow driven by the low-mass class 0 protostar L1157 is the prototype of the so-called chemically active outflows. The bright bowshock B1 in the Southern outflow lobe is a privileged testbed of Magneto-Hydrodynamical (MHD) shocks .We present the first results of the unbiased spectral survey of the L1157-B1 bowshock, obtained in the framework of the Key Program "Chemical Herschel Surveys of Star Forming Regions" (CHESS). The main aim is to trace the warm and chemically enriched gas and to infer the excitation conditions in the shock region.
The CO 5-4 and o-H_2O 1_{10}-1_{01} lines have been detected at high-spectral resolution in the unbiased spectral survey of the HIFI-Band 1b spectral window (555-636 GHz). Complementary ground-based observations help establish the origin of the emission detected and the physical conditions in the shock. Both lines exhibit broad wings which extend to velocities much higher than reported up to now. We find that the molecular emission arises from two regions with distinct physical conditions: an extended, warm (100 K), dense (3x10^5 cm^{-3}) component at low-velocity, which dominates the water line flux in Band 1b; a secondary component in a small region of B1 (a few arcsec) associated with high-velocity, hot (> 400 K) gas of moderate density ((1.0-3.0)x10^4 cm^{-3}), which appears to dominate the flux of the water line at 179μm observed with PACS. The water abundance is enhanced by two orders of magnitude between the low- and the high-velocity component, from 8x 10^{-7} up to 8x 10^{-5}. The properties of the high-velocity component are in good agreement with the predictions of steady-state C-shock models.

I. Introduction

Shocks in protostellar outflows play a crucial role in the molecular cloud evolution and star formation by transferring momentum and energy back to the ambient medium. They often involve a magnetic precursor, where ionic and neutral species are kinematically decoupled. Magneto-Hydrodynamical (MHD) shocks are important not only for the cloud dynamics but also for the chemical evolution through temperature and density changes, which favors the activation of endothermic reactions, ionization, and dust destruction through sputtering and shattering in the ion-neutral drift zone. These various processes lead to abundance enhancements up to several orders of magnitude, as reported for various molecular species in "chemically active" outflows [1].

Along with H_2, H_2O and CO are two key-molecules predicted to dominate the cooling of MHD shocks [13]. The abundance of H_2O in protostellar regions can be greatly enhanced in shocks, even of moderate velocity. This occurs both from the sputtering of frozen water from grain mantles and through high-temperature sensitive reactions in the gas phase [4,5,6]. Multi-transition observations of these two molecules therefore serve as good probes of shock regions with various excitation conditions, and can be used to set stringent constraints on MHD shock models [8].



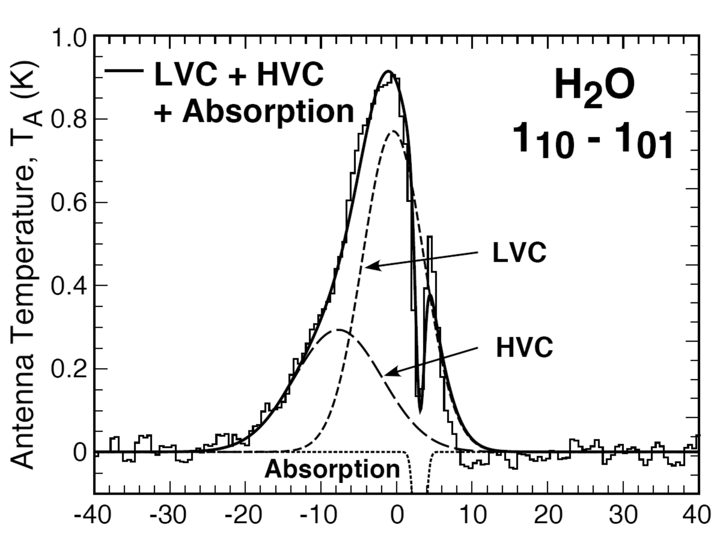
Southern outflow lobe of L1157 in CO 1-0 (greyscale and black contours) and in SiO 2-1 (white contours) as observed at the PdBI [9,10]. A black square marks the nominal position bowshock L1157-B1 observed with HIFI. The HIFI main-beam is represented with a black circle.

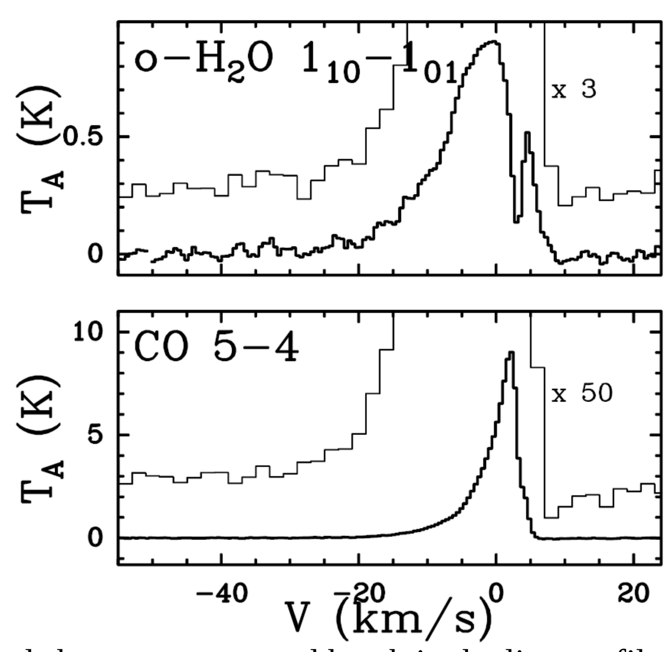
L1157-mm is a low-mass Class 0 protostar located at a distance estimated between 250 pc [14] and 440 pc [17]. It drives a spectacular bipolar outflow, which has been studied in detail at millimeter and far-infrared wavelengths. Mapping of the southern lobe of L1157 with the Plateau de Bure Interferometer (PdBI) reveals two limb-brightened cavities [9,10], each one terminated by a strong bow shock, dubbed "B1" and "B2" respectively, which are likely the result of episodic ejection events in a precessing, highly collimated jet.

II. Observations

A full coverage of the band 1b towards the bowshock L1157-B1 was carried out with the HIFI heterodyne instrument on board of the Herschel Space Observatory during the Performance Verification phase on 2009, August 1st (OBS_1342181160). The HIFI band 1b (555.4 - 636.2 GHz) was covered in double beam switching. Both polarizations (H and V) were observed simultaneously. The receiver was tuned in double sideband (DSB) with a total integration time of 140 minutes. In order to obtain the best possible data reconstruction, the survey has been acquired with a degree of redundancy of 4. The final rms noise is 13 mK.

III. Water and CO in L1157-B1

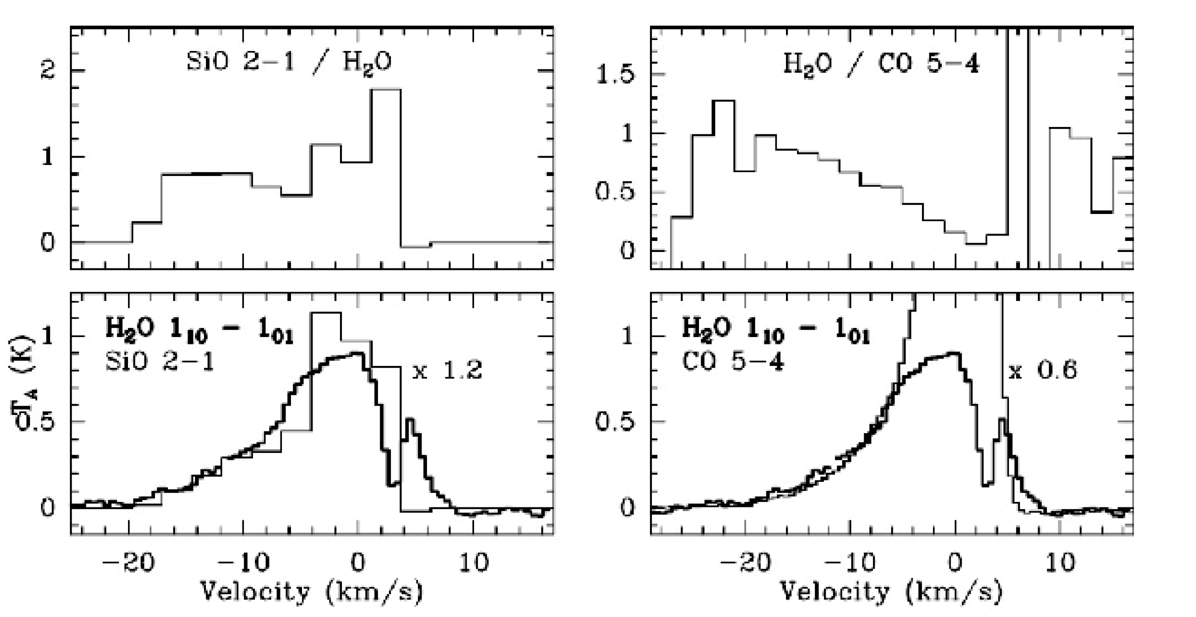




All the other molecular tracers detected in the HIFI band show a pronounced break in the line profile at v ≈ -7.2 km/s (see poster by Codella et al.). We define the regions with :

v < -7.25 km/s as the high-velocity component (HVC)

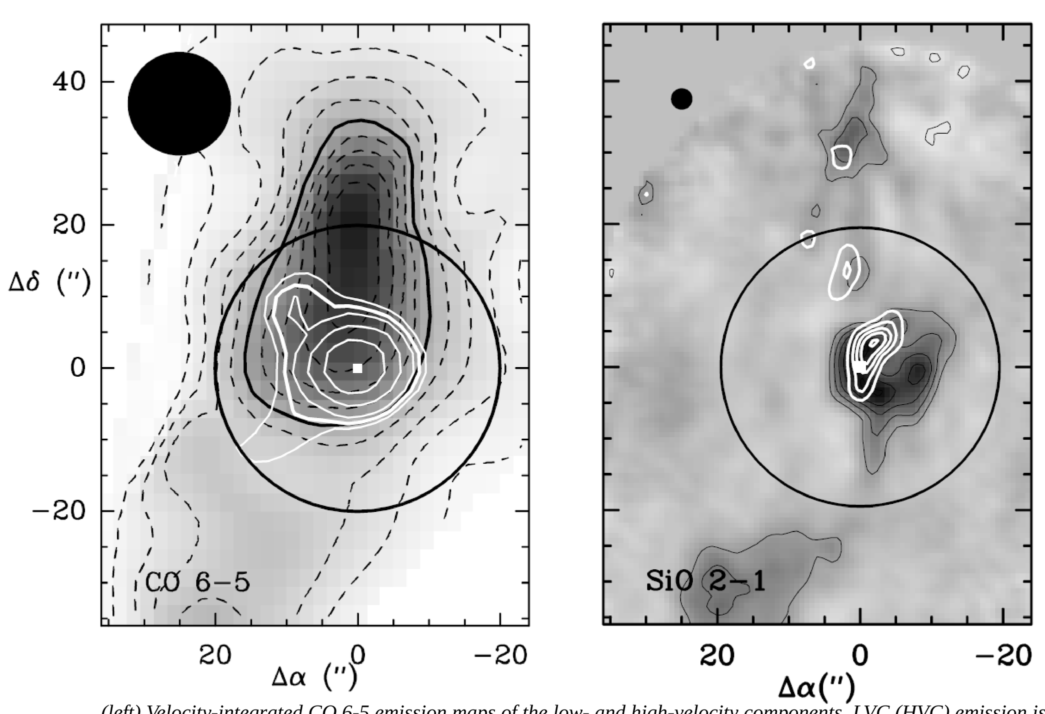
v > -7.25 km/s as the low-velocity component (LVC).



Line profiles differ noticeably and the ratio of the H_2O / CO 5-4 line intensities increases with increasing velocities from about 0.2 in the ambient gas up to 0.9 at v= -25 km/s .

IV. Origin of the emission

Due to its relatively high energy above the ground state (E_{up}= 116K) the CO 6-5 transition is a good probe of the warm regions where H_2O can evaporate from grain mantles and be released in the gas phase. SiO 2-1, observed at the PdBI at 2.5'' resolution is a particularly good tracer of shocks strong enough to release refractory elements in the gas phase, as it is usually undetected in the cold, quiescent molecular gas.



(left) Velocity-integrated CO 6-5 emission maps of the low- and high-velocity components. LVC (HVC) emission is represented in greyscale and thin dashed contours (white contours); first contour and contour interval are 3σ and 1σ (10% of the peak flux), respectively, Contours at half-power are drawn in thick. (right) Same for SiO 2-1 observed at the PdbI. The HIFI main-beam is represented with a black circle.

The LVC emission arises from an extended region of ≈ 25''

The overall SiO emission is strongly peaked at the position of B1. PdBI maps reveal extended emission along the eastern wall of the cavity and downstream of B1, at velocities close to systemic, both blue and red. Interestingly, the PACS map of the H_2O 179 μm line reveals large-scale emission, spatially coinciding with SiO 2-1 emission in the outflow (Nisini et al. 2010). This is consistent with the CO 6-5 data. The LVC emission is located in the wake of B1, reaching 40'' North from the apex. The H_2O spatial distribution is expected to be asymmetric, similar to that observed in many other tracers such as CS or HCN [3], as shown by the PACS map of the H_2O 179 μm line (Nisini et al. 2010, this conf.).

The HVC emission arises from a small region of ≈ 7''

The H_2O / SiO 2-1 line ratio profiles is approximately constant = 0.8 in the range of the HVC:

- Both emissions most likely arise from the same region and are optically thick. In that case, the low intensities measured in the high-velocity component (a few tenths of K) point to a small size extent. This is direct evidence that the H_2O emission detected fills only partly the HIFI beam. Indeed, the bulk of the SiO HVC originates from a small region of 4'' x 12'' in B1, corresponding to a filling factor ff ~ 0.03.

- If silicon comes from grain erosion, the SiO profile is predicted to be much narrower than H_2O because it takes a long time for Si to oxidize into SiO, so SiO comes only from the cold postshock [10,11]. The similarity of the SiO and H_2O line profiles suggests that SiO forms more extensively in the shock than predicted by oxidation of sputtered Si atoms. As it can be released in the gas phase even at low velocities in the shock, SiO is present in the gas phase over the full width of the shock wave.

V. Physical conditions in the bowshock

The physical conditions in the CO gas were first estimated from the 5-4 and the 3-2 and 6-5 lines, as observed at the CSO, both in the HVC and LVC. We modeled each velocity component as a simple uniform slab, adopting the size estimated above (IV). Calculations were done in the Large-Velocity Gradient approach, using the CO collisional coefficients determined by [6] for ortho-H_2 collisions in the range 5K-400K. For temperatures beyond 400 K, the collisional coefficients are extrapolated adopting a temperature dependence of $(T/400\ K)^{1/2}$. Using the physical conditions derived from the CO analysis, we have modeled the integrated intensity and the line profile of the ground state o-H_2O transition as well as the reported PACS-measured 179μm H_2O line intensity to compute the total ortho water abundance in each velocity component. We used a radiative transfer code in the Large-Velocity Gradient approach (and slab geometry) detailed in [14], taking into account an ortho to para ratio (OPR) of 1.2 for H_2, as derived from Spitzer [15]. We assumed that the absorption component at +2.9 km/s is due to foreground gas unrelated to L1157-B1.

	H_2O 557GHz	CO 5-4	CO 6-5[1]	CO 3-2[1]	Size	N(CO)[2]	n(H_2)[2]	T[2]	X(H_2O)[3]	F(179 μm)
	(K km s^{-1})	(K km s^{-1})	(K km s^{-1})	K km s^{-1}	('')	(cm^{-2})	(cm^{-3})	(K)	(cm^{-2})	(W cm^{-2})
LVC	7.83	45.4	29.2	40.4	25	8.0(16)	(1.0-3.0)(5)	100	0.8(-6)	4.2(-20)
HVC	4.28	3.98	1.34	3.11	7	5.0(16)	(1.0-3.0)(4)	400	0.8(-4)	7.1(-20)

[1] From CSO observations smoothed down to the resolution of the HIFI observations.

[2] Determined from LVG analysis of the CO emission.

[3] From comparison of LVG-derived N(o − H_2O) with N(CO), assuming a water OPR of 3 and an abundance $[CO]/[H_2] = 10^{-4}$.

Results

1) The HVC emission arises from hot gas (T > 400 K) of moderate density (3.0 x10 ^{4} cm^{-3}), whereas the LVC emission arises from gas at a lower temperature (100 K) and higher density (3.0 x 10 ^{5} cm^{-3}).

2) For the temperature range derived from our CO analysis, we estimate ortho-H_2O column densities of (4.0-5.0)x10^{14} cm^{-2} and (2.5-3.0)x10^{16} cm^{-2} for the LVC and the HVC, respectively. We obtain an abundance ratio $H_2O/CO \simeq 0.8$ in the high-velocity gas, which is consistent with previous results from ODIN [2] and in reasonable agreement with the predictions of steady-state C-shock models for this set of physical parameters ($V_{shock} \simeq 20$ km/s, pre-shock density n(H_2)= 5x10^3 cm^{-3}) [10,11].

3) The HVC contribution to the 179μm flux is predicted to dominate over the LVC contribution. The higher temperature of this component drives the neutral-neutral reactions that efficiently form H_2O, and the higher shock velocity can more efficiently remove water from grain mantles [14], resulting in the much greater ortho-H_2O column density than in the LVC. Comparison with NH_3 also suggests that the water production in the HVC is strongly dominated by high-T reactions. The higher ortho-H_2O column density is what produces the higher 179μm line flux from this component.

Follow-up observations of the higher-excitation lines of CO and H_2O with HIFI will help us constrain more accurately the physical conditions of each velocity component (density, temperature) and more generally in the shock.

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