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 bow shock B1 in the Southern outflow lobe is a privileged target of Methane-Hydrodynamic (MH) shocks. It is important not only for the cloud dynamics but also for the chemical evolution through temperature and density changes, which favours the activation of endothermic reactions, ionization, and dust destruction through sputtering and impacting in the ion-neutral drift zone. These processes lead to abundances enhancements up to several orders of magnitude, as reported for various molecular species in "chemically active" outflows [1]. Along with CO, H2O and CO2 are two key-molecules predicted to dominate the cooling of MHD shocks [13]. The abundance of H2O in protostellar regions can be greatly enhanced in shocks, even of moderate velocity. The occurrence of luminous sources from warm mantles and through high-temperature sensitive reactions in the gas phase [4,5]. 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].

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, whose ionic and neutral species are kinematically decoupled. Methane-Hydrodynamic (MH) shocks are important not only for the cloud dynamics but also for the chemical evolution through temperature and density changes, which favours the activation of endothermic reactions, ionization, and dust destruction through sputtering and impacting in the ion-neutral drift zone. These processes lead to abundances enhancements up to several orders of magnitude, as reported for various molecular species in "chemically active" outflows [1]....

II. Observations
A full coverage of the band 1b towards the bow shock 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 1" (OBS1_1432411660). The HIFIB band 1b (554 - 636 GHz) was covered in double beam switching. Both polarizations (HI and H0) were observed simultaneously. The receiver was tuned in double sideband (DSB) with a total integration time of 1400 s elements. 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:

\[ v = 7.25 \text{ km/s as the high-velocity component (HVC)} \]
\[ v = 22.3 \text{ km/s as the low-velocity component (LVC)} \]

Line profiles differ noticeably and the ratio of the H2O / 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 (\( \Delta \nu = 1160 \text{ cm}^{-1} \)) the CO 6-5 (\( 170 \text{ km/s} \)) transition is a good probe of the warm regions where H2O can evaporate from warm mantles and reside in the gas phase. L1157-B1, "the bright bow shock" observed at the PdBI, as well as the HVC at 23.5 km/s is a particularly good tracer of shocks strong enough to ionize the cold, quiescent molecular gas

The LVC emission arises from an extended region of \( \sim 25 \text{"} \)
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 H2 179 mm 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 H2O spatial distribution is expected to be asymmetric, to that observed in many other tracers such as CS or HC3N [3], as shown by the PACS map of the H2 179 mm line (Nisini et al., 2010, this conf.).

The HVC emission arises from a small region of \( \sim 9" \)
The H/O SiO 2-1 line ratio profiles is approximately constant \( \sim 0.8 \) in the range of the HVC. Due to its small size, the low intensities measured in the high-velocity component (a few tenths of K) point to a small size. This is direct evidence that the H2O emission detected falls only partly in the HII region. Indeed, the bulk of the SiO HVC originates from a small region of \( 4" \times 12" \) at B1, corresponding to a filling factor f = 0.03. - If silicon comes from grain erosion, the SiO profile is predicted to be much narrower than H2O because it takes a long time for SiO to oxidize into SiO and only the cold postshock [10,11]. The similarity of the SiO and H2O 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.

Results
1) The HVC emission arises from hot gas (\( T = 400 \text{ K} \)), of moderate density (3 x 10^3 cm^-3), whereas the LVC emission arises from gas at a lower temperature (100 K) and higher density (3 x 10^5 cm^-3)
2) For the temperature range derived from our CO analysis, we estimate ortho-H2O column densities of (4.5-10^17) cm^-2 and 2.5 x 10^16 cm^-2 for the HVC and the LVC, respectively. We obtain an abundance ratio \( \text{H}_2\text{O/O}_2 \approx 0.8 \) in the HVC, which is consistent with previous results from ODIN [2] and in reasonable agreement with the predictions of steady-state shock models for this set of physical parameters (\( v_{\text{peak}} = 20 \text{ km/s} \), pre-shock density \( n_0 \approx 10^4 \text{ cm}^{-3} \)).
3) The HVC emission is also observed from this line in the LVC emission. The higher temperature of this component drives the neutral-neutral reactions that efficiently form H2O, and the higher shock velocity can more efficiently remove water from grain mantles [14], resulting in the much greater ortho-H2O column density than in the LVC. Comparison with H2O also suggests that the water production in the HVC is strongly dominated by high-T reactions. The higher ortho-H2O column density is what produces the higher 179 mm line flux from this component.

Follow-up observations of the higher-excitation lines of CO and H2 with HIFI will help us constrain more accurately the physical conditions of each velocity component (density, temperature) and more generally in the shock.