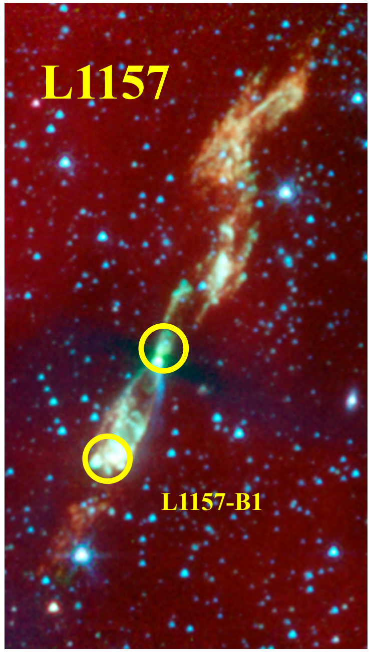
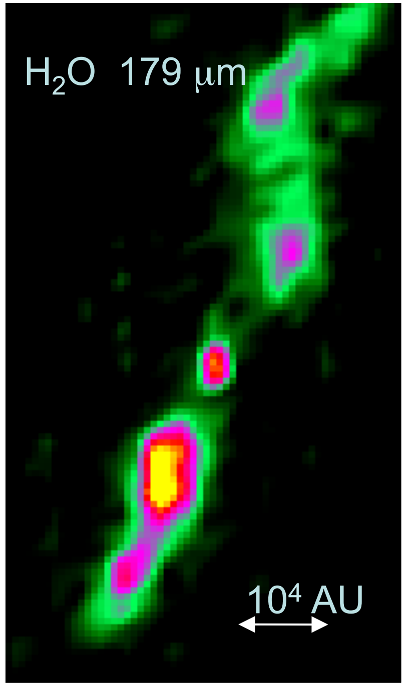


Water Emission in Outflow Shocks

B. Lefloch
IPAG (France)

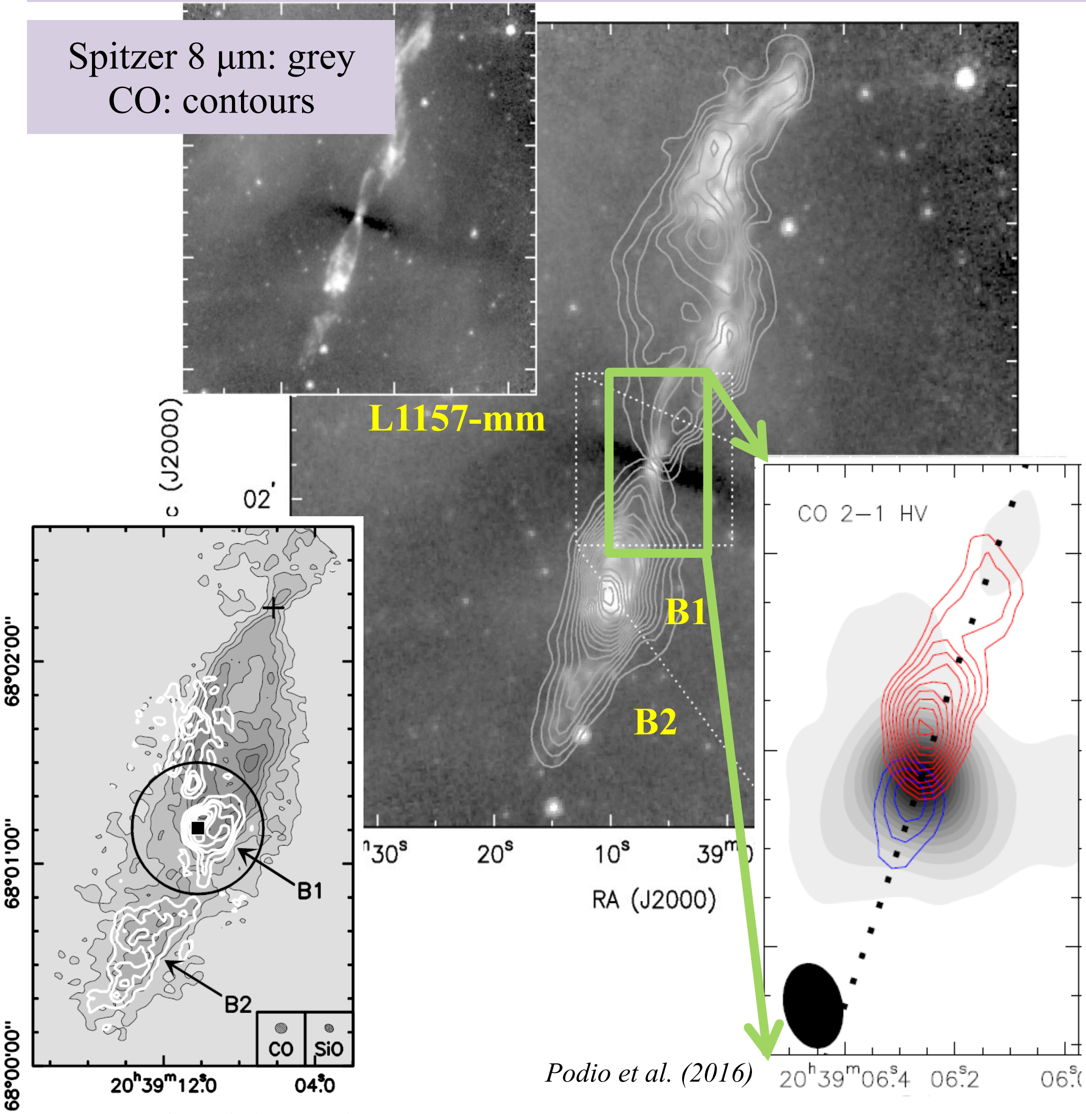


Thanks

To
M. Benedettini, G. Busquet, S. Cabrit, P. Caselli, E. Caux, C. Codella, C. Ceccarelli, A. Gomez-Ruiz, J. Holdship, I. Jimenez-Serra, A. Gusdorf, B. Nisini, L. Podio, S. Viti, M. Tafalla, M. Vasta, L. Wiesenfeld, and all my colleagues from the CHESS and WISH Teams

The Low-Mass Outflow Phenomenon

Bachiller et al. (2001), Looney et al. (2007), Neufeld et al. (2009)

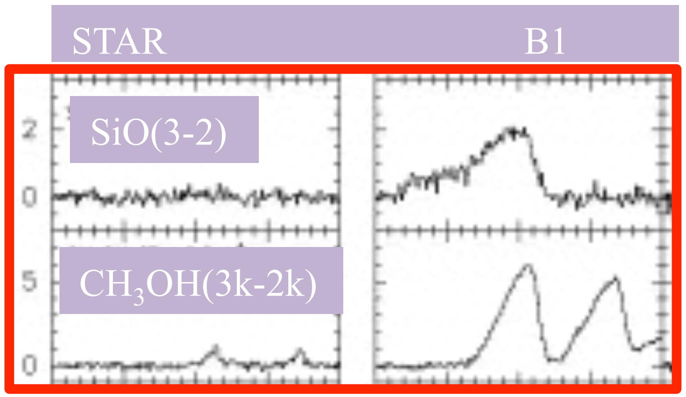


Gueth et al. (1996,98)

Three physical components

- **High-velocity wind**
- **Shock**
- **Bipolar outflow cavity**

Specific outflow shock chemistry



→ Evidence for grain mantle/core sputtering and dust shattering: CH_3OH/SiO
→ high-temperature gas phase reactions:HCN

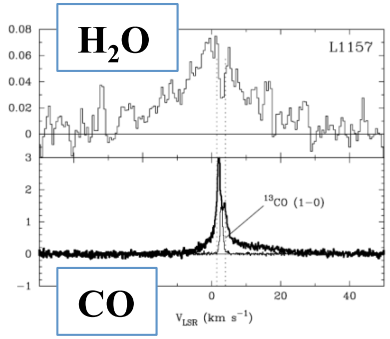
Previous results and questions

Shock Models predict a strong water enrichment in outflow shocks
(Neufeld & Kaufman 1996; Flower & Pineau des Forets 2010)

H_2O thermal line emission is a selective tracer of outflows
- **ISO**: water in *warm* outflow gas *(Liseau 1996; Giannini, 2001)*
- **SWAS, *Odin***: *o-H_2O 557 GHz*

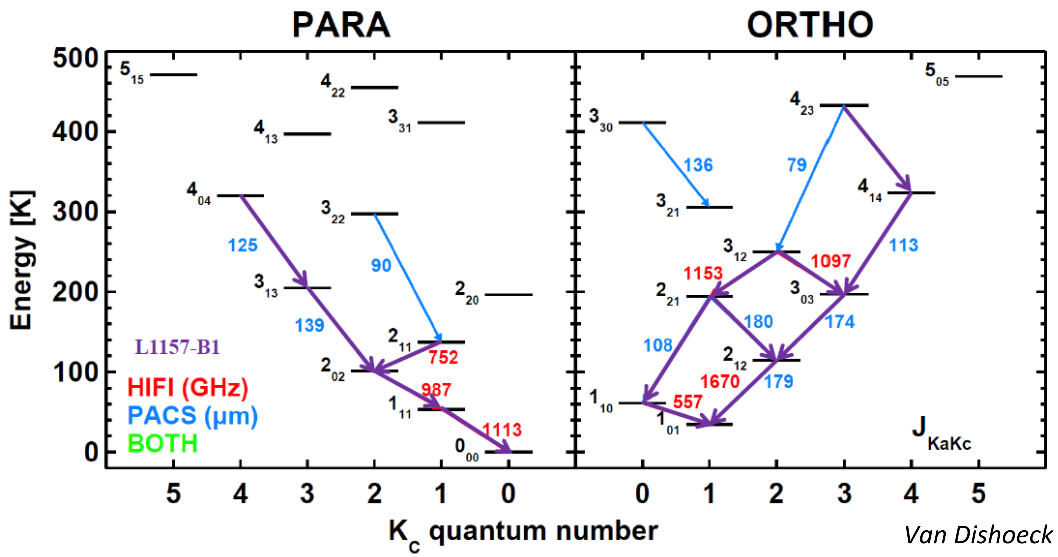
→ First resolved line profiles: high-velocity *wings* *(Franklin, 2008; Bjerkeli 2009*
→ First estimates of X(H_2O) in outflow/shocks : 10^{-7} to 10^{-4}

Angular resolution: several arcmin → only a global view on H_2O properties



Where is H_2O formed in outflows and by which processes: gas phase / dust grains ?
Which physical component(s) of the outflow are traced by H_2O ?
What is its role in the energy budget ?

The Promise of Herschel



Van Dishoeck et al. (2011)

Three assets to study outflow shocks:

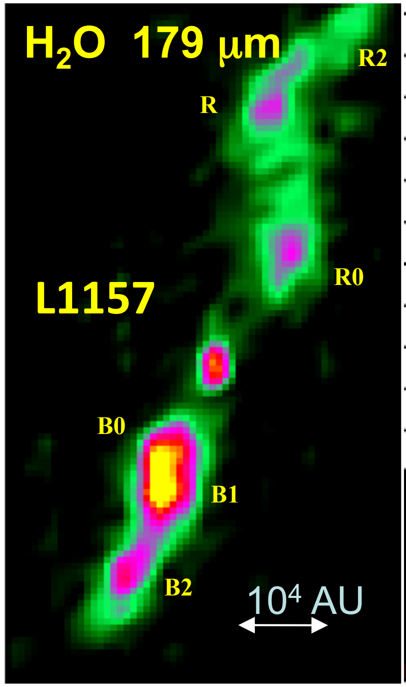
Both HIFI and PACS observed H_2O lines probing a wide range of excitation

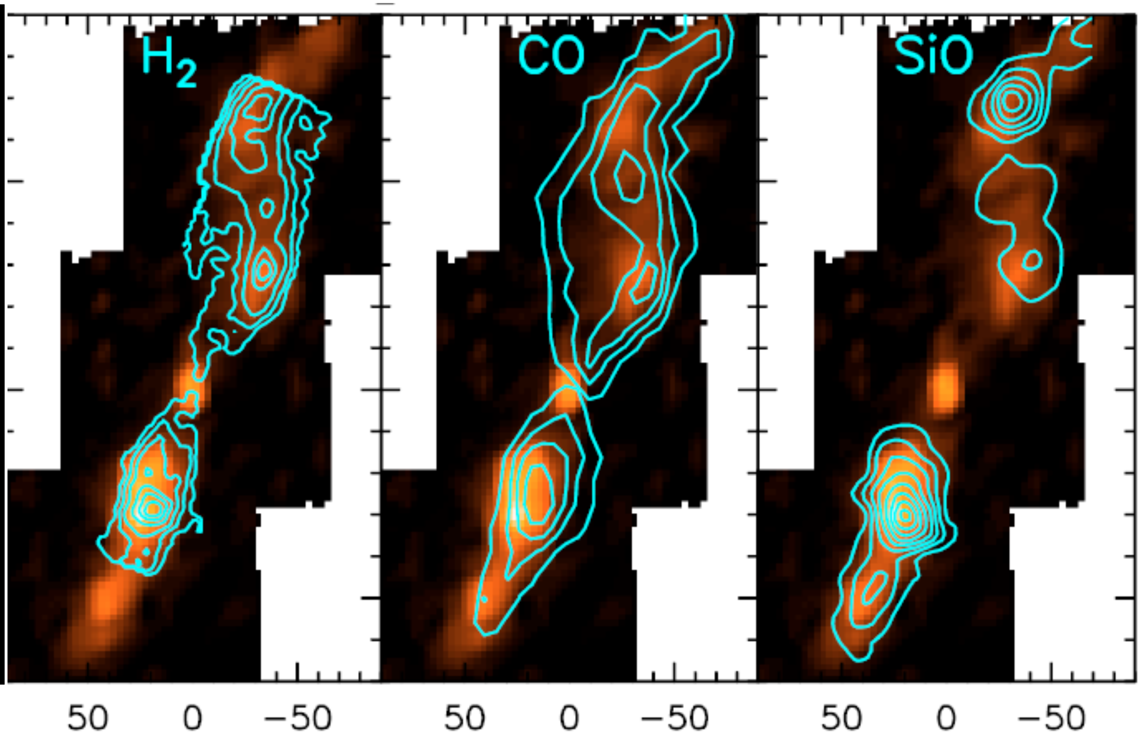
Angular resolution: 40” – 6” : comparable to ground based telescopes (IRAM, APEX)

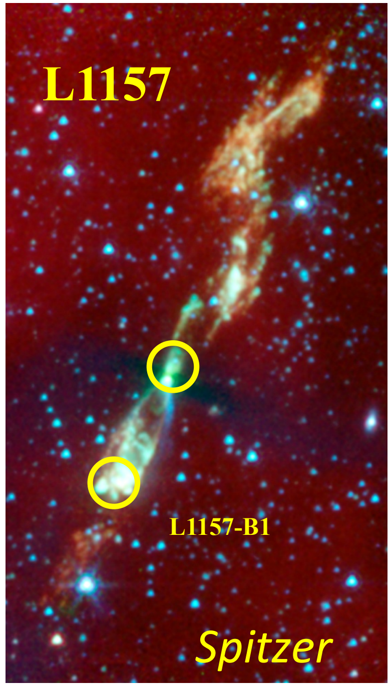
Spectral resolution down to ~ 1 MHz (HIFI) : kinematics of low- and high-excitation gas

Water Emission in Outflows

Also : Bjerkeli et al. (2013), Nisini et al. (2013), Santangelo et al. (2014)







Nisini et al (2010)

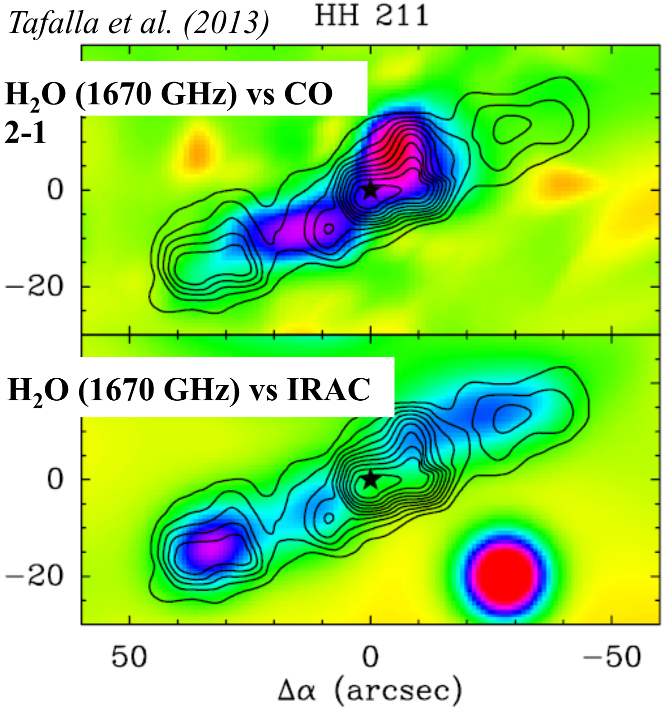
Strong water emission from the embedded protostar and the active shock regions B0-B2 and R0-R2 in the outflow.

H_2O peaks match the H_2 emission peaks (warm gas : 300K) , SiO (?), not with CO 2-1

+ ODIN/SWAS 557 GHz : H_2O from small size, water-rich clumps: X(H_2O) ~ 1(-4)

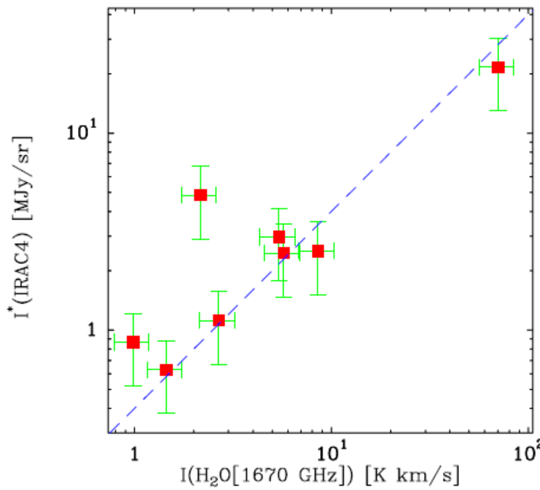
Water Emission in Outflows

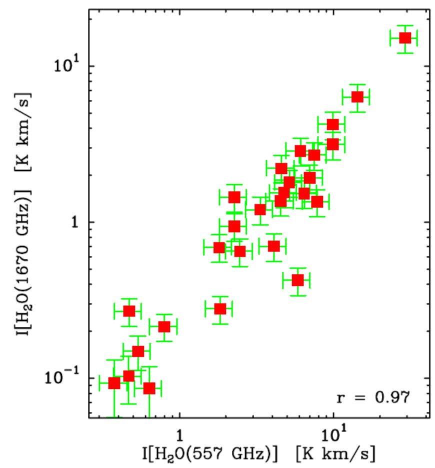
Tafalla et al. (2013)



Same for CepE, HH1, HH46-R, BHR71, HH54, L1448-C, L1448, L1157, VLA16293
Bjerkeli et al. (2012), Nisini et al. (2013), Santangelo et al. (2013), Busquet et al. (2014)

Outflow survey

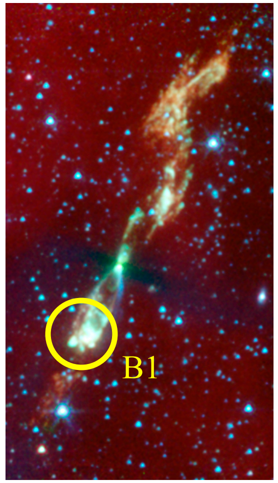




$I^*[\mathrm{IRAC4}]\ (\mathrm{MJy\ sr^{-1}}) = 0.4\ I[\mathrm{H_2O(1670)}]\ (\mathrm{K\ km\ s^{-1}})$.

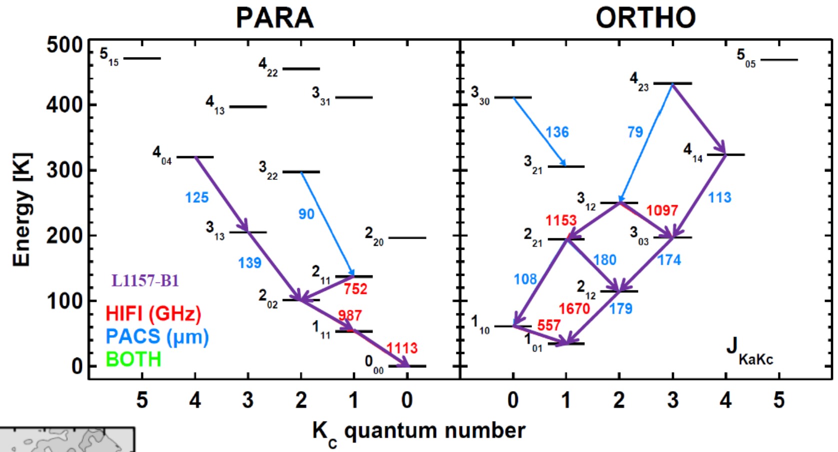
H_2O and the low-J CO lines trace different gas components
Close association between H_2O 557/1669 GHz and warm H_2 gas (300-500K)
Emission : narrow range excitation conditions

The outflow shock L1157-B1



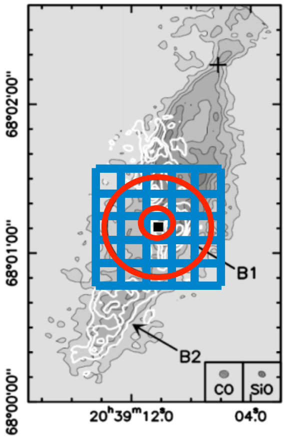
Prototype for outflow shock studies
HIFI/PACS Line survey in CHESS *(C. Ceccarelli et al. 2010)*

→ Shock Physical and Chemical structure



The most complete water line set obtained for a shock
13 transitions : 9 HIFI , 7 PACS
9 ortho/5 para

+ High-J CO, CS, HCN, …
+ OH, NH_3, HDO

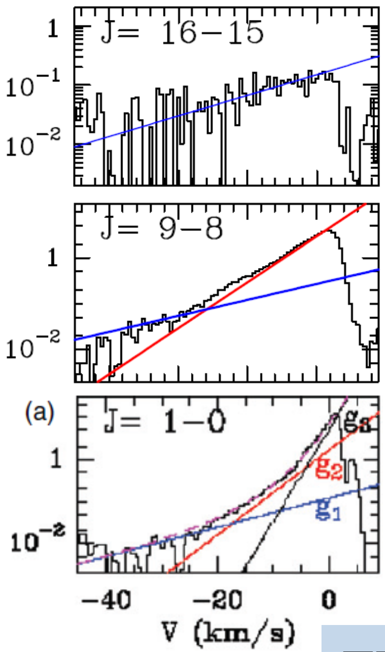


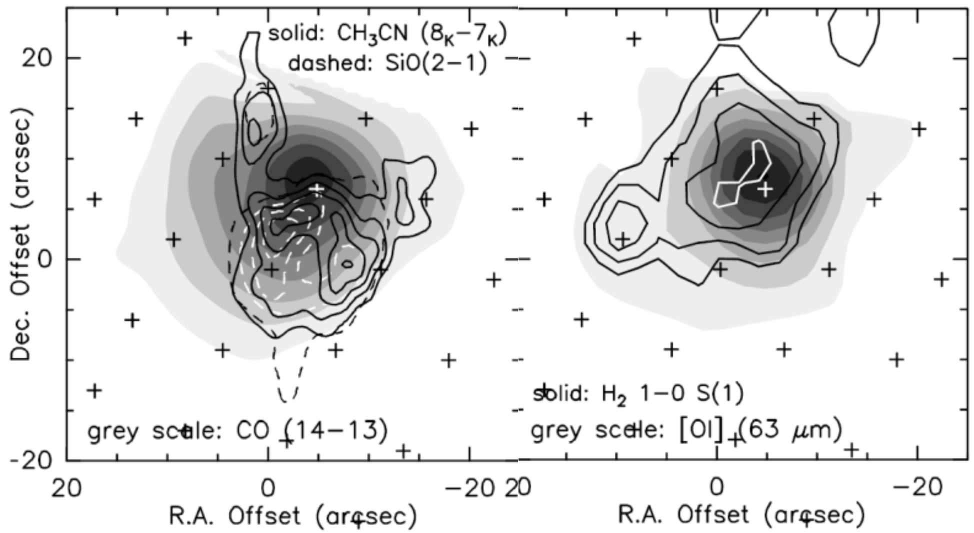
Complementary data

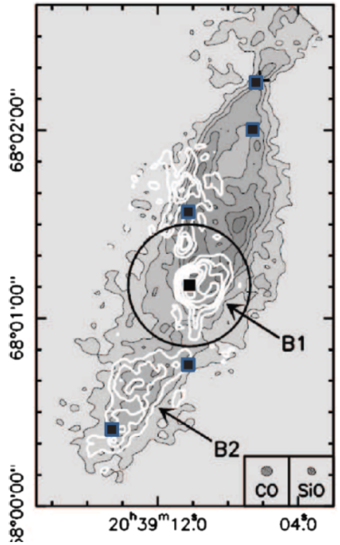
- IRAM 30m line survey of L1157-B1 : 80 – 350 GHz
- Sub/Millimeter line emission maps: IRAM 30m, PdBI, CSO
- IRAC Spitzer H_2 maps

Physical Structure of L1157-B1

CO







Lefloch et al. (2012)

Three shock components with specific spectral signatures: T α exp(v/v_0)

Double Shock structure

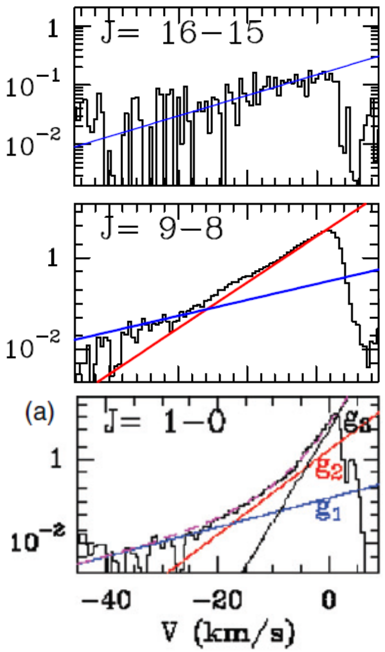
- B1 outflow cavity walls
- the jet impact region against B1 cavity

Cavity associated with previous ejection : B2

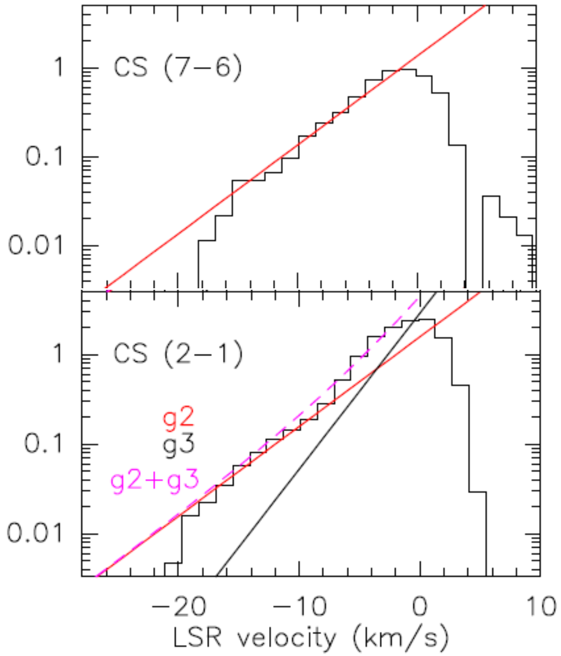
Physical Structure of L1157-B1

Three shock components with specific spectral signatures

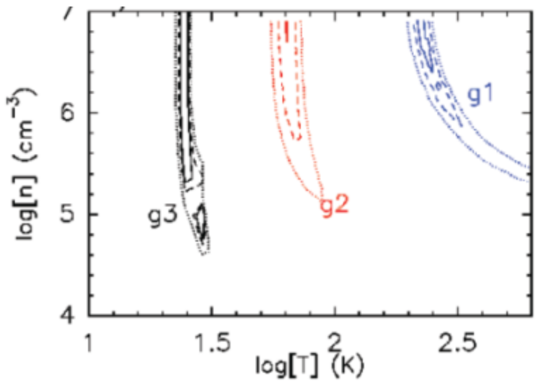
Lefloch et al. (2012)

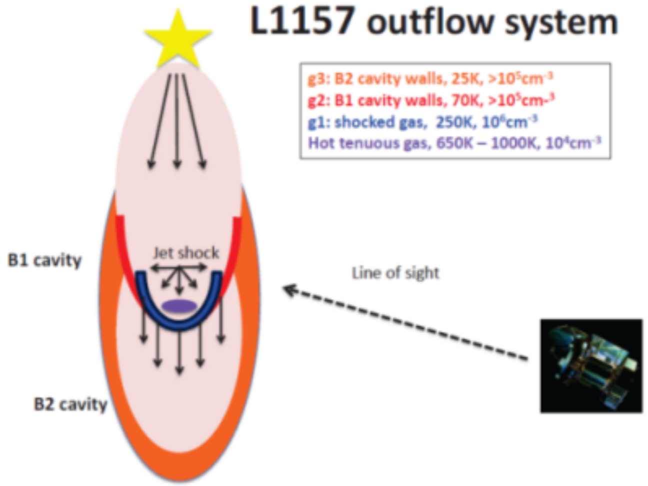


Gomez-Ruiz et al. (2015)



Spectral signatures are essentially independent for a wide range of species



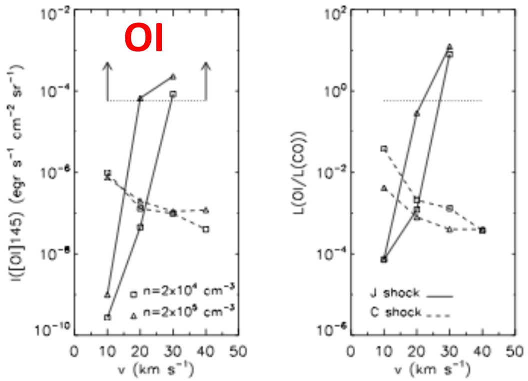


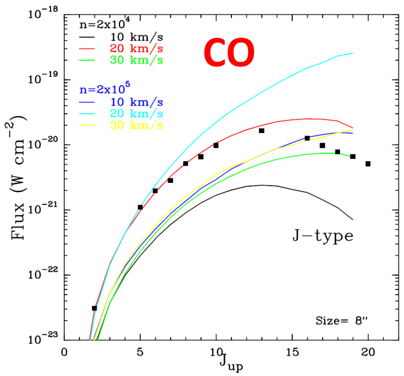
Physical conditions are homogeneous:
Isothermal, uniform density

Physical Structure of L1157-B1

Jet Impact Shock region

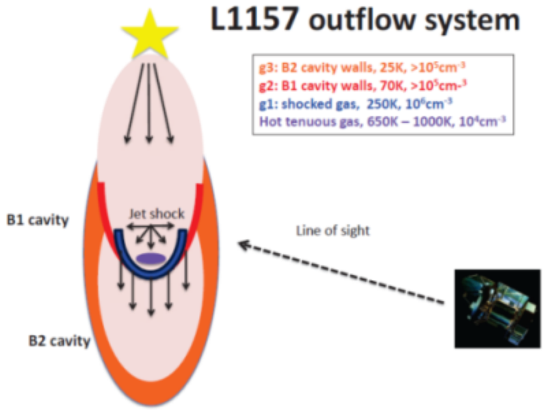
Bright OI emission and CO are consistent with a J-type shock





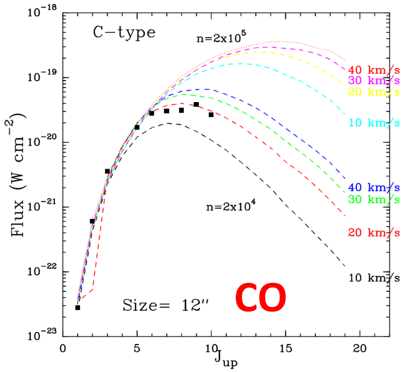
Flower & Pineau des Forets (2010)

$n(H_2) = 10^4$ cm^{-3}
V_s= 20-30 km/s



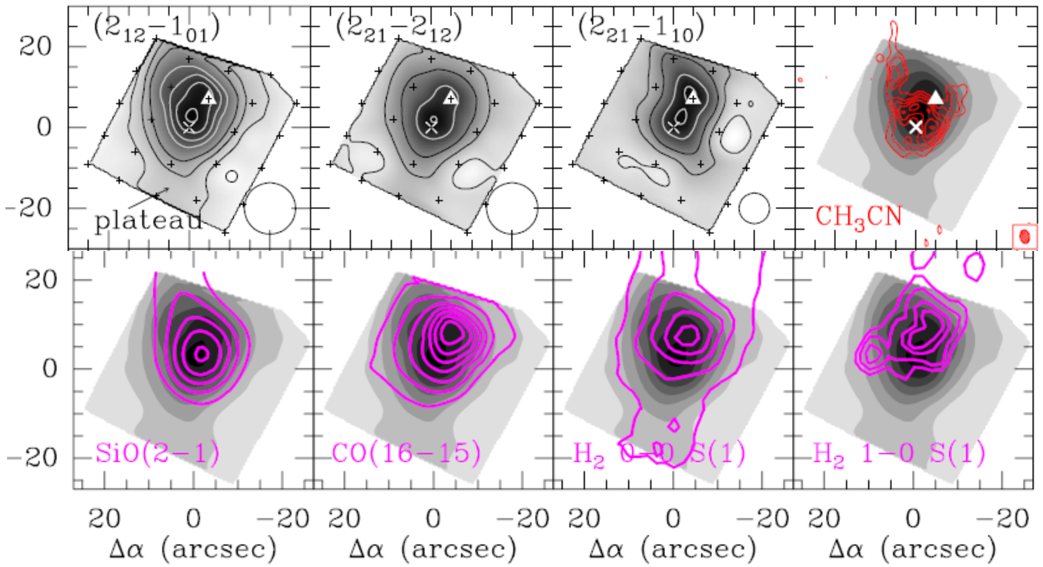
B1 Outflow cavity

Bright CO emission is consistent with a C-type shock



$n(H_2) = 10^4$ cm^{-3}
V_s= 20 km/s

Water Emission in L1157-B1

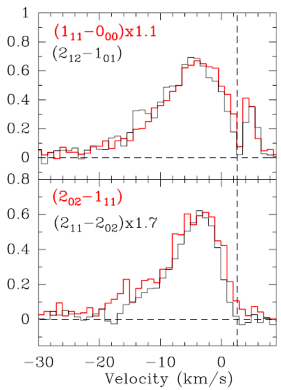


Bowshock

Emission detected over the bowshock

Emission peak shifted wrt high-excitation gas: CO (16-15), H_2 1-0 S(1)

Two contributions at apex and jet shock ?



HIFI line profiles : Two physical components

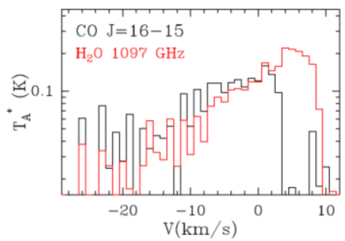
1669, 1113, 557 GHz

987, 752 GHz

Comparison H_2O – CO line profiles

H_2O 1097 GHz / CO 16-15 does not vary with velocity

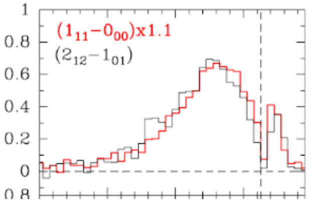
No evidence for X(H_2O) increase with velocity



Water Emission in L1157-B1

The Two-Temperature model

1 – Warm, Dense Component

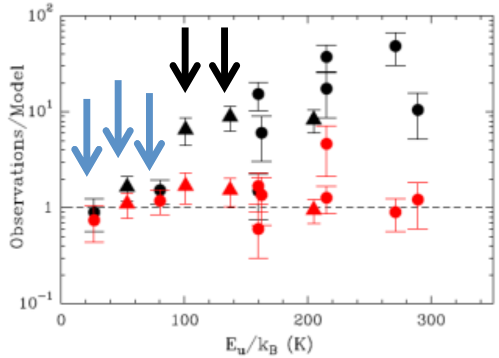


T=250K, n(H_2)=2x10^6 cm^{-3}, size= 10”, N(o-H_2O)= 2x10^{14} cm^{-2}

→ best-fit for o/p H_2= 0.5 (Spitzer: 0.6, *Nisini et al. 2010*)

→ best-fit for o/p H_2O= 3

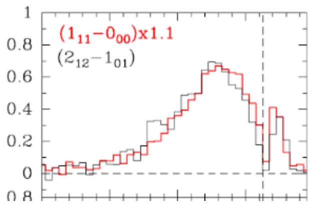
Warm Component Emission from the jet impact shock region



Water Emission in L1157-B1

The Two-Temperature model

1 – Warm, Dense Component

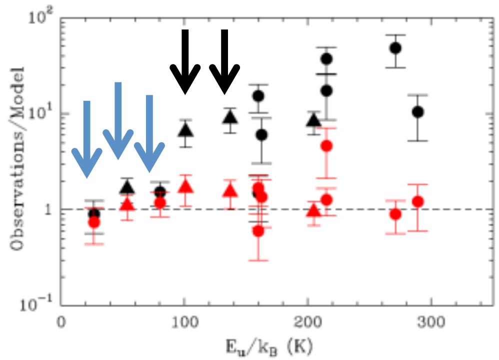


T=250K, n(H_2)=2x10^6 cm^{-3}, size= 10”, N(o-H_2O)= 2x10^{14} cm^{-2}

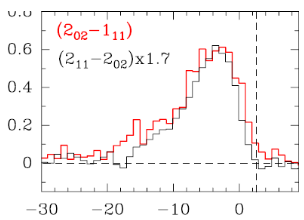
→ best-fit for o/p H_2= 0.5 (Spitzer: 0.6, *Nisini et al. 2010*)

→ best-fit for o/p H_2O= 3

Warm Component Emission from the jet impact shock region



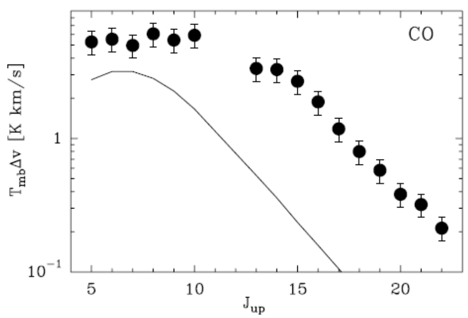
2 – Hot, Diffuse Component



T= 1000K, n(H_2)= 2x10^4 cm^{-3} , size= 2.5”
N(o-H_2O)= 9x10^{16} cm^{-2}

Higher-T solutions for higher o/p H_2 ratio
T=1000K, o/p-H_2= 3 is consistent with Spitzer

This high-T component is not detected in the PACS CO lines

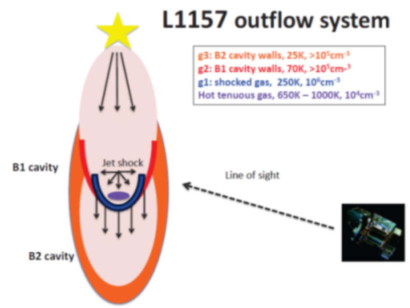


Temperature distribution similar to that observed in H_2 with Spitzer:
Stratification in the post-shock gas ?

Water Abundance and Line Cooling

	Tk (K)	$n(H_2)$ (cm^{-3})	$X(H_2O)$	Size (")	$L(H_2O)$	L(CO)
Warm	250-300	(1-3)(6)	(0.7-2.0)(-6)	10	0.002	0.004
Hot	900-1400	(0.8-2)(4)	(1.2-3.6)(-4)	2.5	0.03	0.01

L(OI)= 3×10^{-3} L_o L(OH)=4×10^{-4} L_o $L(H_2) \simeq 0.03\ L_o$ *(Nisini et al. 2010)*



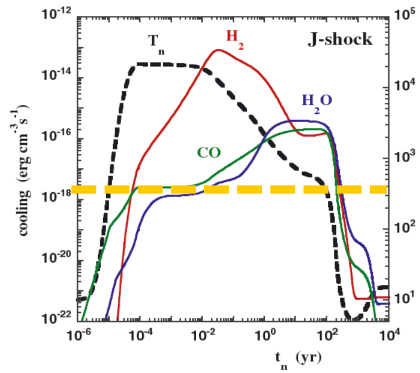
Warm component

Partly dissociative J-type shock : **Low $X(H_2O) \sim 10^{-6}$**

$L(CO) \sim L(OI) \sim L(H_2O)$

Similar results by Tafalla (2013); Bjerkeli et al. (2012)

Flower & Pineau des Forets (2010)



Hot component

High $X(H_2O) \sim 10^{-4}$: C-type shock ? *(Kaufman & Neufeld 1996)*

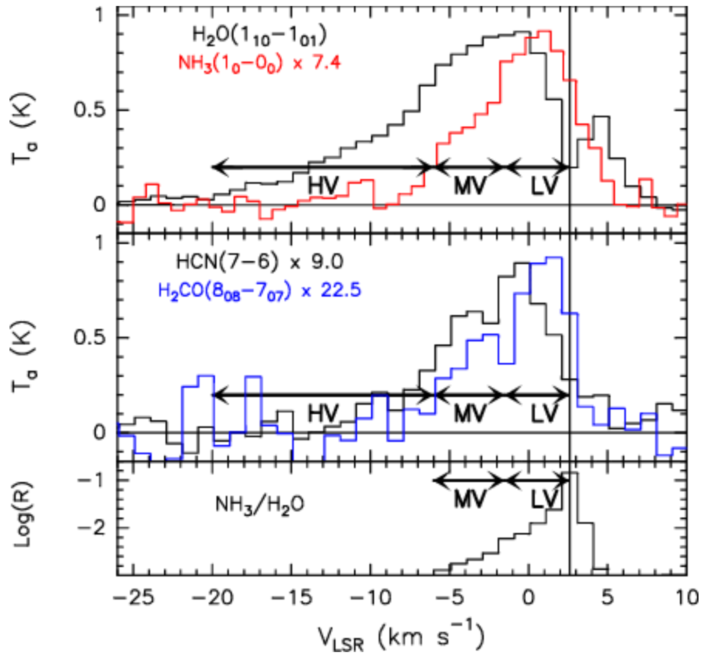
All O not locked up in CO is converted to H_2O

$L(H_2O) \sim L(H_2) > L(CO)$

See also L1448 study by Santangelo et al. (2013)

NH_3/H_2O: Shock temperature diagnostics

Codella et al. (2010)



NH_3/H_2O decreases as a function of velocity

Codella et al. (2010) : Different formation mechanisms :
NH_3 is released by grain mantles
H_2O water is released by grain mantles + high-T reactions in the warm shocked gas

Viti et al. (2011) : Destruction of NH_3 in the shock

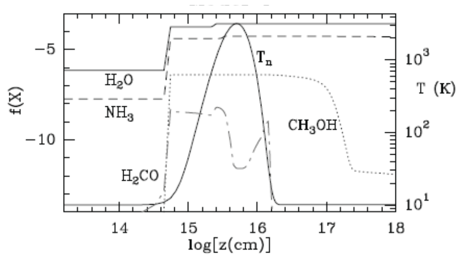
NH_3 is initially frozen onto dust grains, released in gas phase when passing through the shock. For T_{kin} > 4000K,

$$\mathbf{H + NH_3 \rightarrow NH_2 + H_2}\ (E_{act} = 5000K)$$

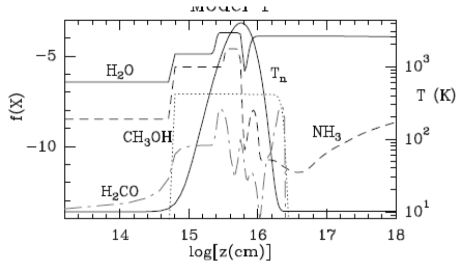
UCL_CHEM +
Parametric shock code
(Jimenez-Serra 2008)

NH_3/H_2O could help constraining the shock parameters

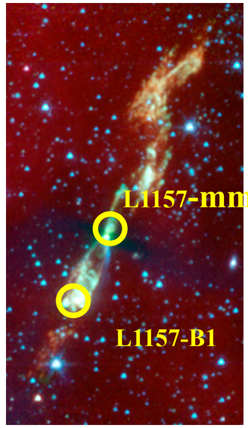
n(H_2)= 5x10^4 cm^{-3}, V_s= 35 km/s



n(H_2)= 5x10^4 cm^{-3}, V_s= 40 km/s



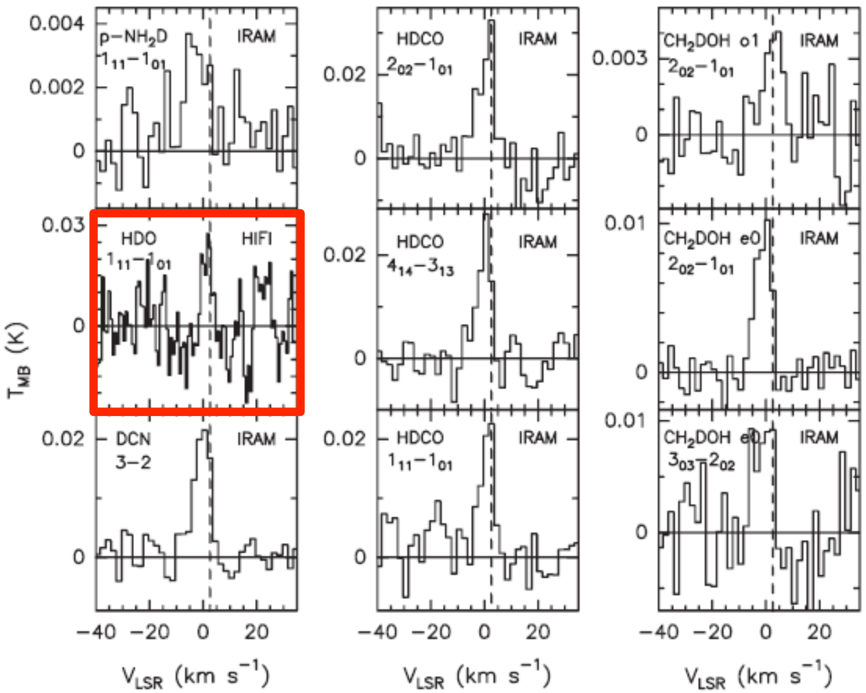
Deuterated Water



Stark (2004): HDO outflow emission in I16293-2422
Codella et al. (2010): HDO detected in the cavity walls of L1448 outflow

Search for Deuterated isotopologues in L1157-B1

Codella et al. (2012)



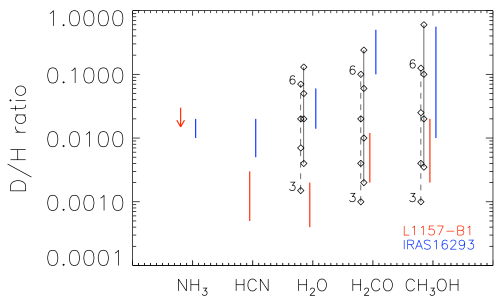
CH_2DOH, HDCO, DCN, HDCS, NH_2D,
HDO $1_{11} - 0_{00}$

Shock age : 2000-4000yr
→ **A record of ice mantle formation**

Lower deuteration for H_2O and HCN

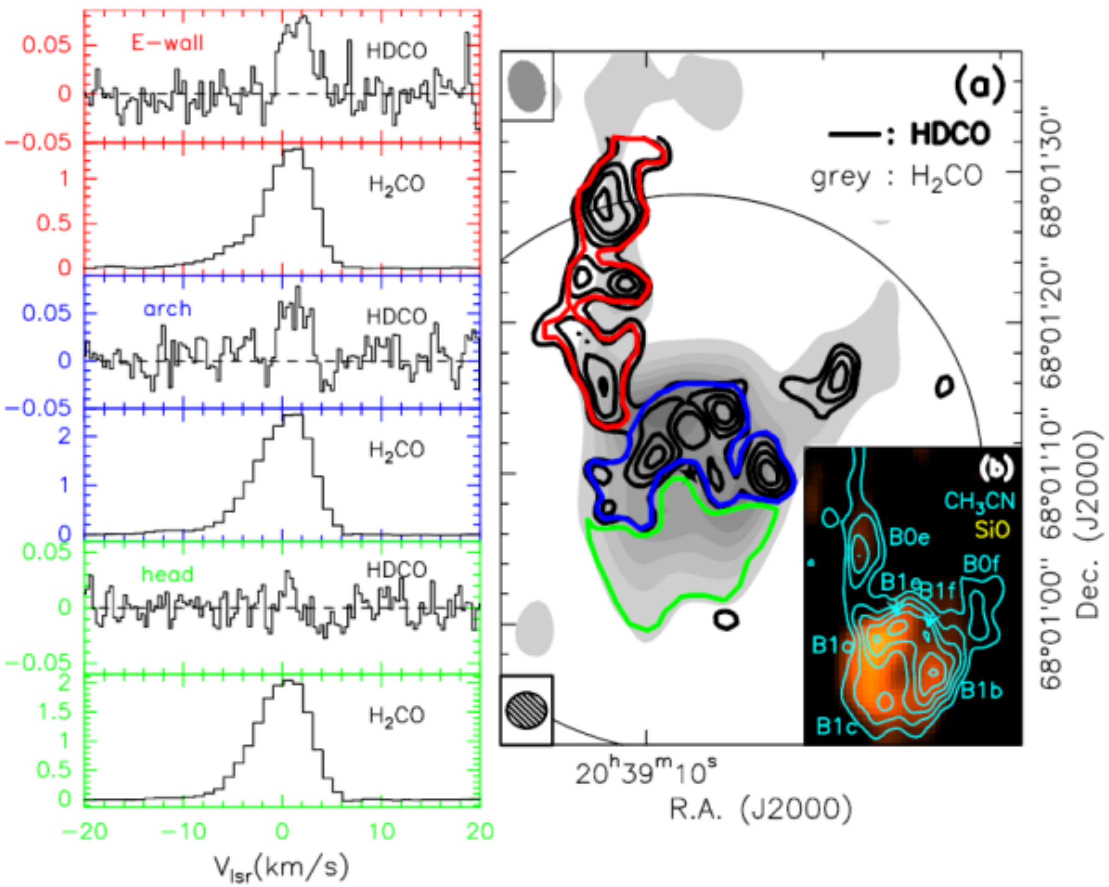
H_2O : D/H= $(0.4\text{-}2)\times10^{-3}$

GRAINOBLE *(Taquet et al. (2012) :* Ice formation scenario in L1157
1 - low-density phase (10^3 cm^{-3}) : H_2O ice formation
2 - higher-density phase (10^4 cm^{-3}) : H_2CO and CH_3OH ices form

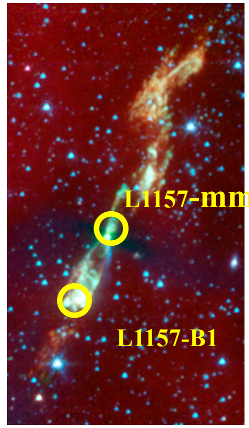


Fossil Deuteration

Deuteration as seen with the PdBI at 2.5”



Fontani et al. (2014)



Deuterated formaldehyde is associated with shocked gas in the cavity walls and the arch
→ SPUTTERING

Extended Formaldehyde emission :
Tip of bowshock → gas phase formation

D-fractionation : 0.04 (arch) to 0.15 (walls)
D-fractionation on mantle grains in the arch: ~ 0.11

Conclusions

Herschel has allowed us to probe the structure of molecular shocks: double shock (jet, cavity). Shock models succeed approx. in accounting for their physical properties based on CO SLED.

H_2O 557/1669 GHz lines trace a warm (300-500K), dense gas component detected in H_2 with Spitzer and high-J CO (not low-J): very good correlation morphology and intensity.
Low water abundance ($X \sim 10^{-6}$) and physical properties are well accounted for by J-type shock components of small size.

Detailed shock studies share similar conclusions :
Modelling of the H_2O emission requires in general a multi-temperature distribution:
A second, compact component of hot (1000K) and less dense gas is required to account for H_2O SLED. This component may be detected (or not) in the high-J CO lines.
It dominates H_2O production in L1157-B1 shock region ($X \sim 10^{-4}$).

→ The exact physical relation between these components remains to be understood: stratification in the post-shock region ?

$X(NH_3)/X(H_2O)$ abundance is sensitive to T_{max} in the shock and could be used to constrain the shock parameters.
HDO studies are a useful tool to determine the history of ice mantle formation in the cloud.

Thank You