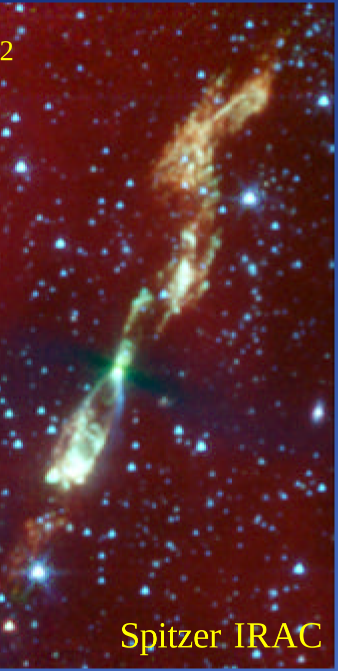
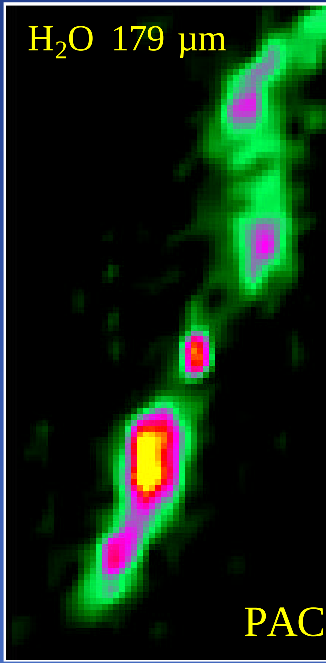


Protostellar Shocks in the Time of Herschel

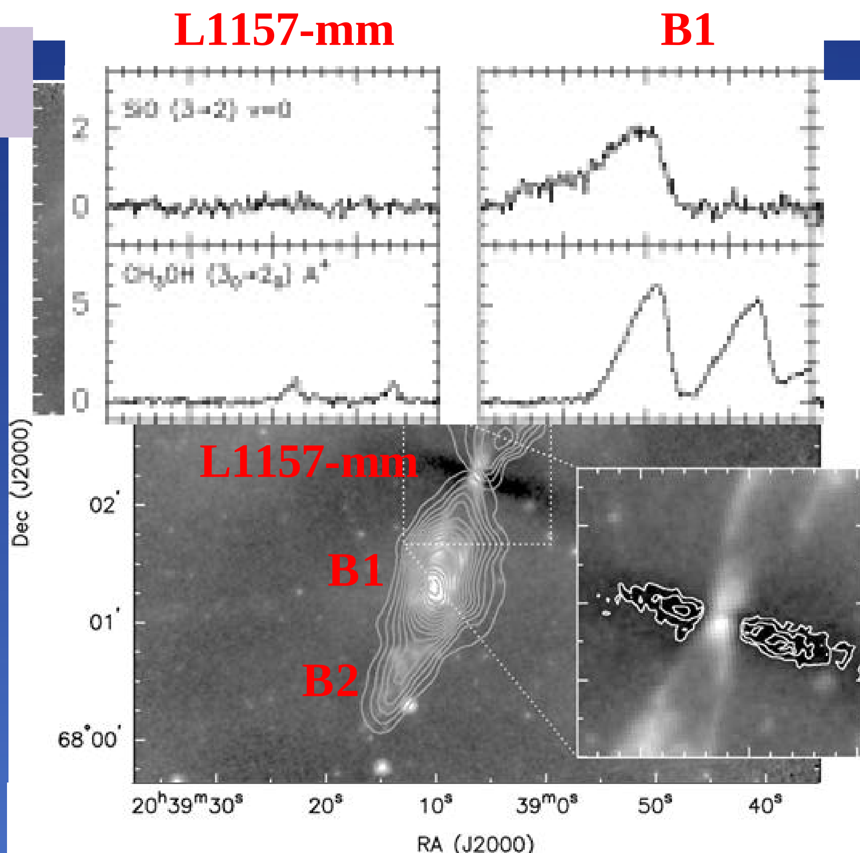


B. Lefloch (IPAG, Grenoble)
on behalf of

M. Benedettini (INAF), G. Busquet (INAF), S. Cabrit (LERMA), E. Caux (IRAP), C. Ceccarelli (IPAG), J. Cernicharo (CAB), C. Codella (Obs. Arcetri), A. Gomez-Ruiz (Obs. Arcetri), B. Lefloch (IPAG), B. Nisini (INAF), L. Podio (IPAG), K. Schuster (IRAM), S. Viti (UCL)

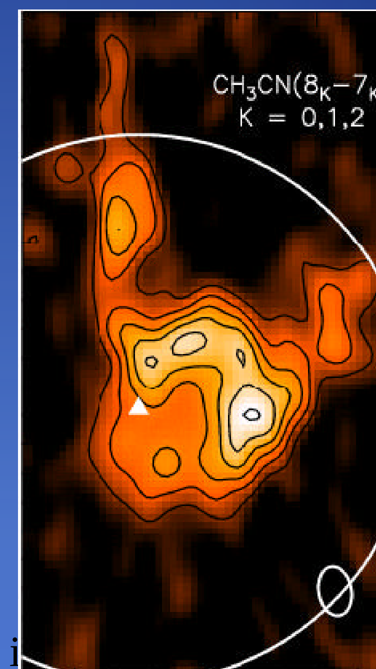
Protostellar Outflows and Shocks

Spitzer 8 µm: grey
CO: contours



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

Codella et al. (2009)



Distance: 250 pc
Driven source: Class 0 protostar (L1157-mm), L= 4-11 L_o
Most chemically rich outflow known so far
Precessing molecular outflow associated with several bow shocks seen in CO and i
Ideal laboratory to observe the effects of shocks on dust and gas chemistry
Benchmark for shock models (Gusdorf et al. 1998)

CHESS-Outflow

Don’t Miss C. Kahane’s Talk at 3p

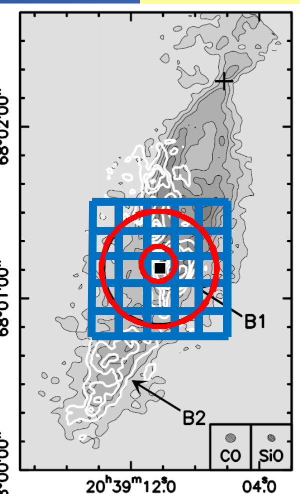
Herschel guaranteed-time Key Project CHESS (PI : C. Ceccarelli, IPAG) :
Chemical Herschel Surveys of Star Forming Regions

→ poster #42 A. Lopez-Sepulcre

To use the heterodyne receiver HIFI (480 – 1900 GHz) and PACS (55- 210 μm) to lead a comprehensive study of the typical protostellar bowshock L1157-B1 :

1 : to get a full description of the shock dynamics with a resolution similar to largest ground-based telescopes : physical conditions ? thermal structure ? role of *B* ?

2 : to explore the molecular complexity : hydrides? organic molecules ? molecular ions ?



Complementary observations with ground-based telescopes
- Mapping of selected molecular lines with the CSO (e.g. CO 6-5) and IRAM 30m (e.g. SiO 8-7)
- Full spectral line survey of the mm/submm bands (80 -350 GHz) with the IRAM 30m telescope (ASAI; C. Kahane’s talk)

CHESS-Outflow

The Team
S. Cabrit (LERMA), E. Caux (IRAP), C. Ceccarelli (IPAG), B. Lefloch (IPAG), **L. Podio (IPAG)**, K. Schuster (IRAM), M. Benedettini (INAF), **G. Busquet (INAF)**, C. Codella (Obs. Arcetri), **A. Gomez-Ruiz** (Obs. Arcetri), B. Nisini (INAF), S. Viti (UCL), J. Cernicharo (CAB)

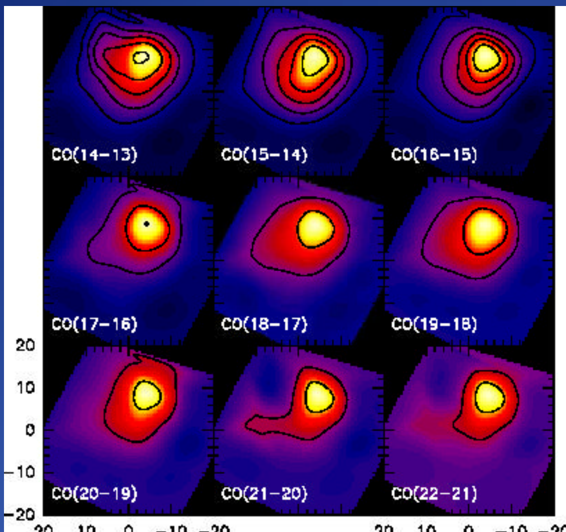
Collaborators : A. Faure (IPAG), F. Gueth (IRAM), **A. Gusdorf (LERMA),** L. Wiesenfeld (IPAG), P. Caselli (U. Leeds), F. Fontani (Obs. Arcetri)

French laboratories involved : IPAG, IRAP, LERMA + IRAM
European laboratories : CAB (Spain), INAF, Obs. Arcetri, Obs. Roma (Italy), UCL

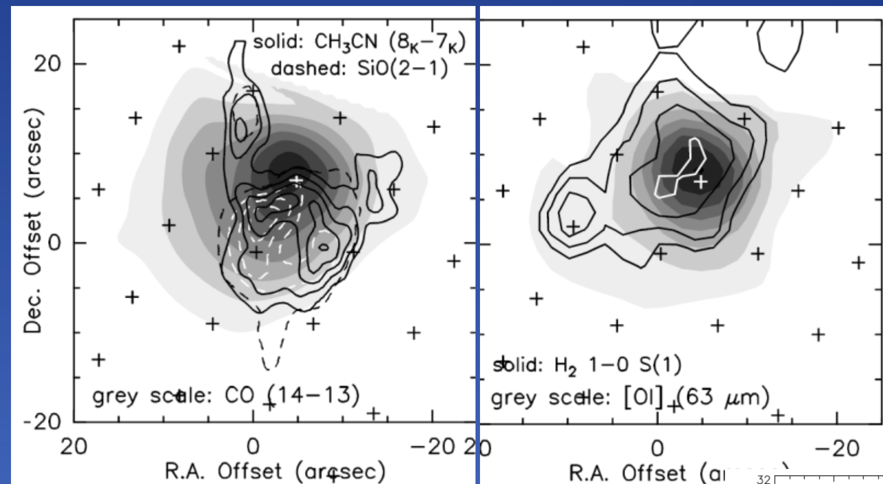
Funding : MEN (PPF), CNES, ANR FORCOMs, COST (Eu)

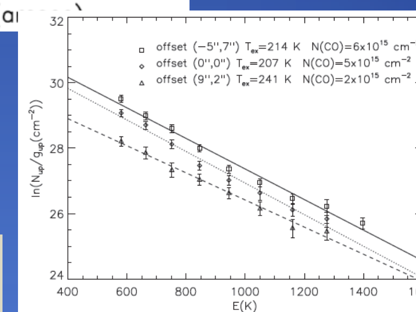
High-Excitation Gas in L1157-B1

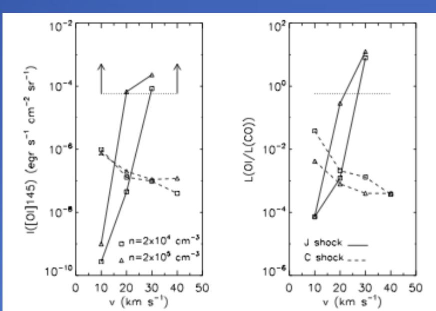
High-J CO line emission (E_{up}= 580 – 1400K)



Benedettini et al. (2012)







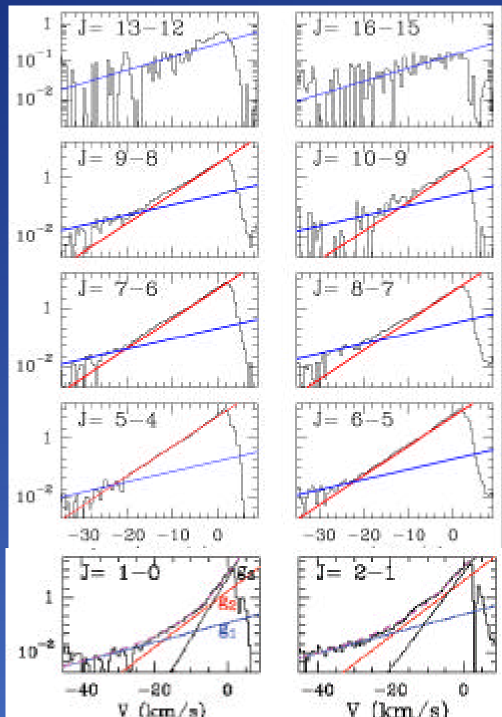
Flower & Pineau des Forets (2010)

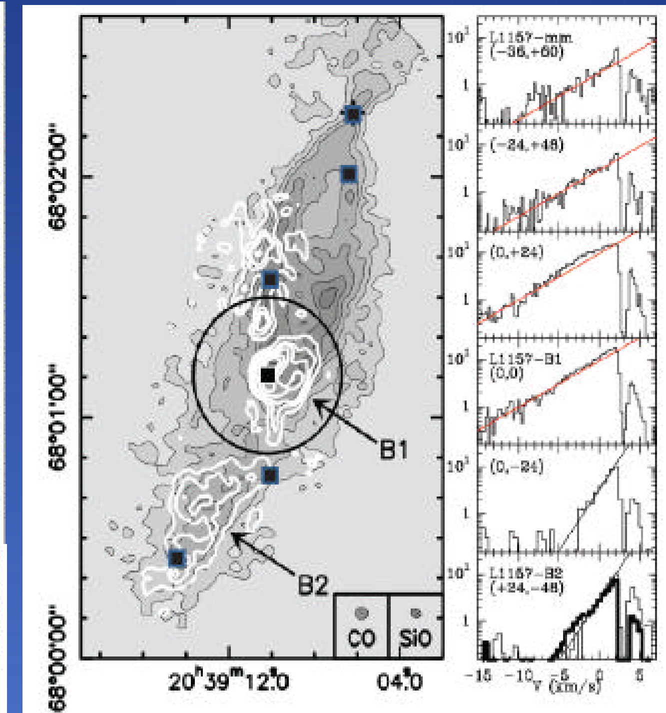
High-excitation component : CO, OI, OH
→ Size : 7" , upstream of the apex
→ Gas at LTE with Trot= 210K

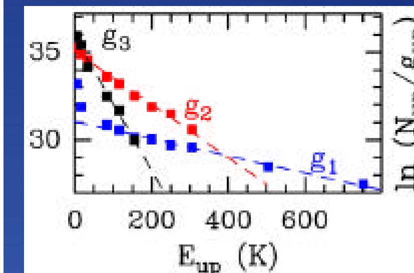
Comparison with shock models for OH, OI + Spitzer
→ **dissociative J-type shock**, which could trace the jet impact on outflow cavity

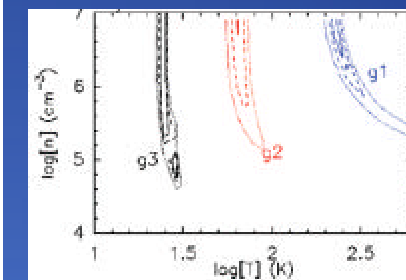
Jet-Driven Bowshock Signatures

Lefloch et al. (2012)









g_1 : J-type shock (210K)
g_2 : B1 cavity walls (70K
g_3 : B2 cavity walls (25K

The CO emission is the sum of the contributions of shocked gas components g_1, g_2, g_3 modelled as exp(-|v/v_0|)

- different range of J_{up} : excitation conditions
- g_i is independent of J_{up} : isothermal
- different velocity ranges but all peak at low-vel.

Origin of the Molecular Emission

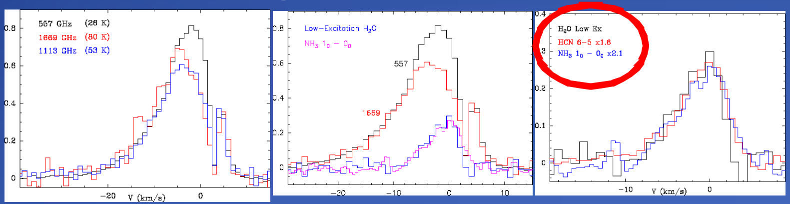
17 Species detected with HIFI and PACS

- **CO, ^{13}CO, C^{18}O, *CI* , HCO$^+$**
- **H_2O, OH, OI, *HDO***
- **H_2CO, CH_3OH (50% lines)**
- **NH_3, HCN , HCl , NO, H_2S, CS, SiO**

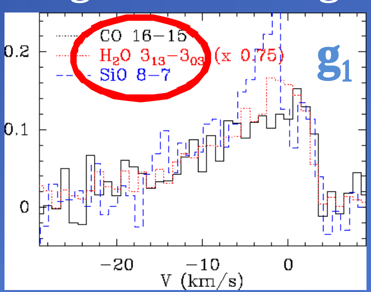
First detection in an outflow : HCl

A not so large variety of line profiles in each component

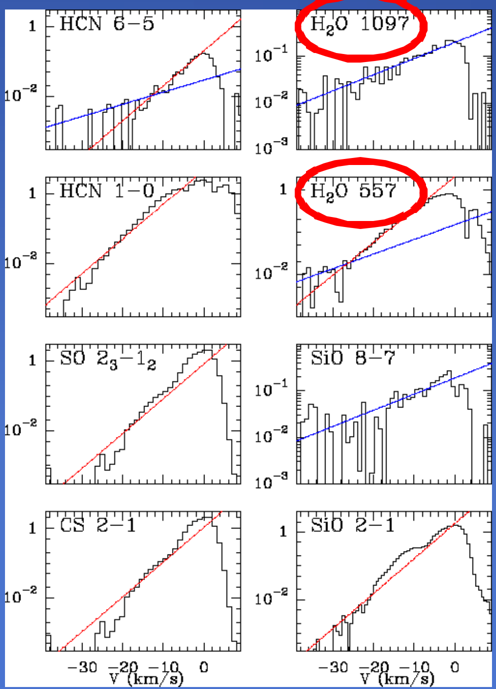
Low-excitation gas **Molecular-rich gas**



High-excitation gas

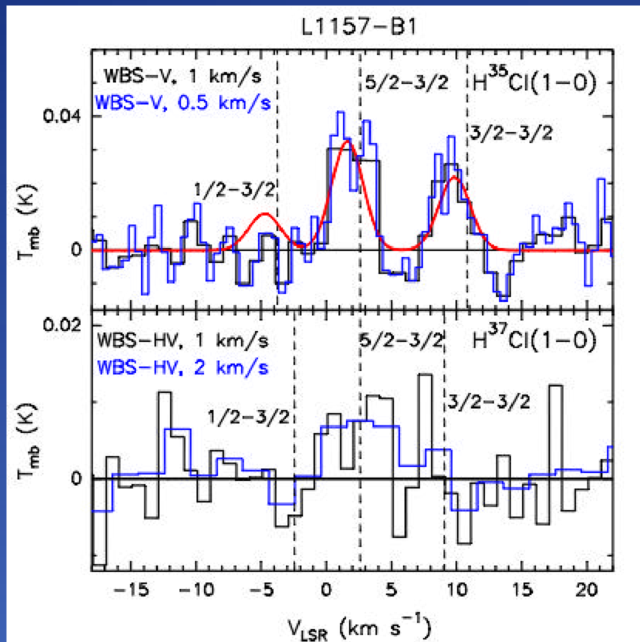


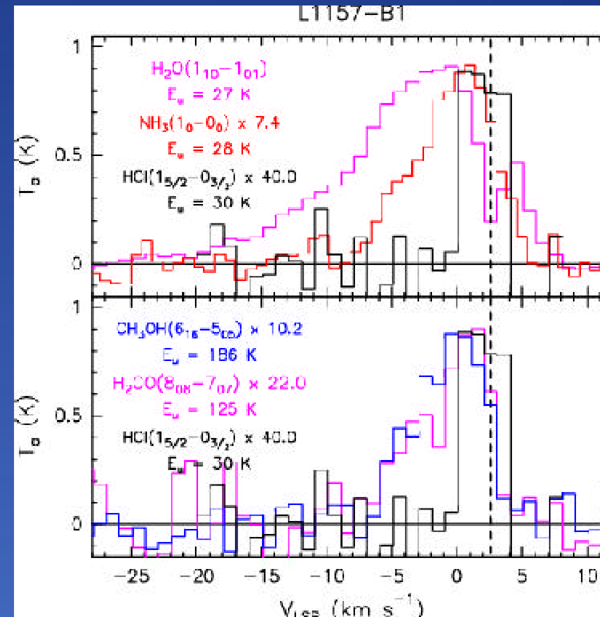
H_2O, high-J CO and SiO trace the same gas



Multiple excitation components

HCl Emission in Shocks





From Observations and Non-LTE modelling → $x(HCl)=(3\text{-}6)\times10^{-9}$
Like in protostars previously observed with HIFI and CSO

…but the violent shocks in L1157-B1 should have liberated Chlorine

Something is missing…

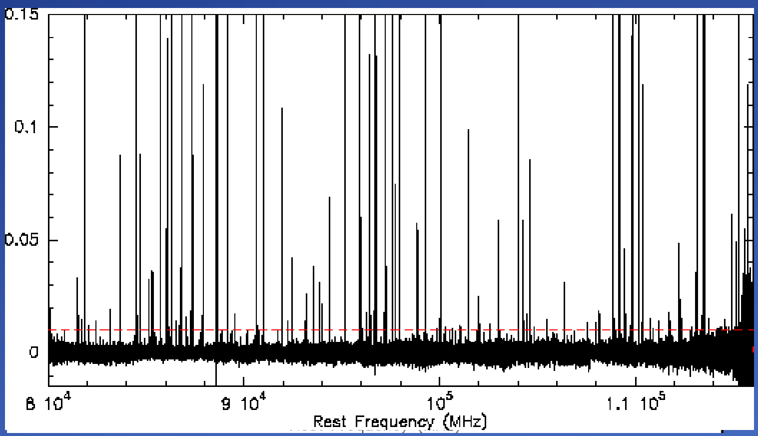
Molecular Complexity

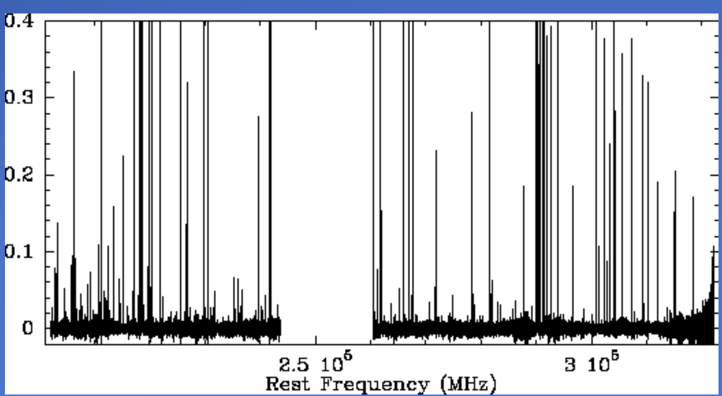
Don't Miss
C. Kahane's Talk at 3p

80 – 116 GHz : s = 1-2 mK / 0.4 MHz
129 – 172 GHz : s = 3-5 mK / 0.4 MHz
200 – 320 GHz : s = 3-5mK / 0.4 MHz
329 – 350 GHz : s = 5mK / 2 MHz

Protostellar shock line surveys of L1157-B1 at IRAM

L1157-B1





New detections in an outflow shock:

Molecular Ions : HCS^+, N_2H^+, $H^{13}CO^+$

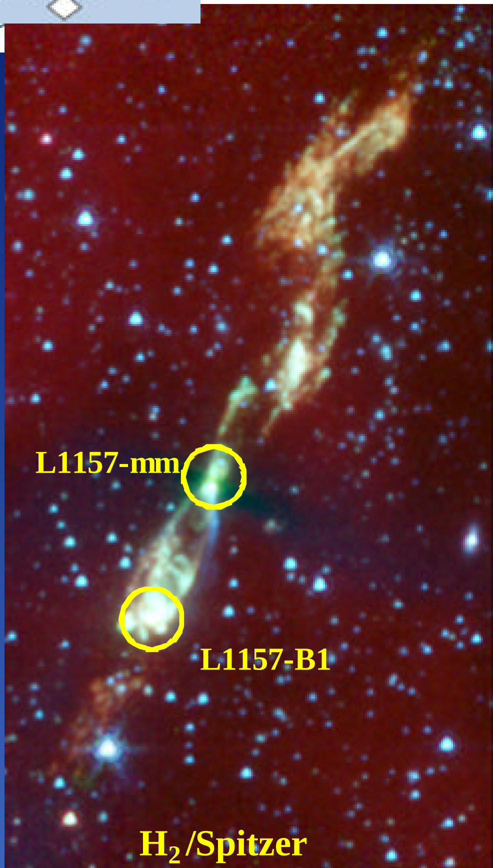
N-bearing : NS, NO, PN(2-1)

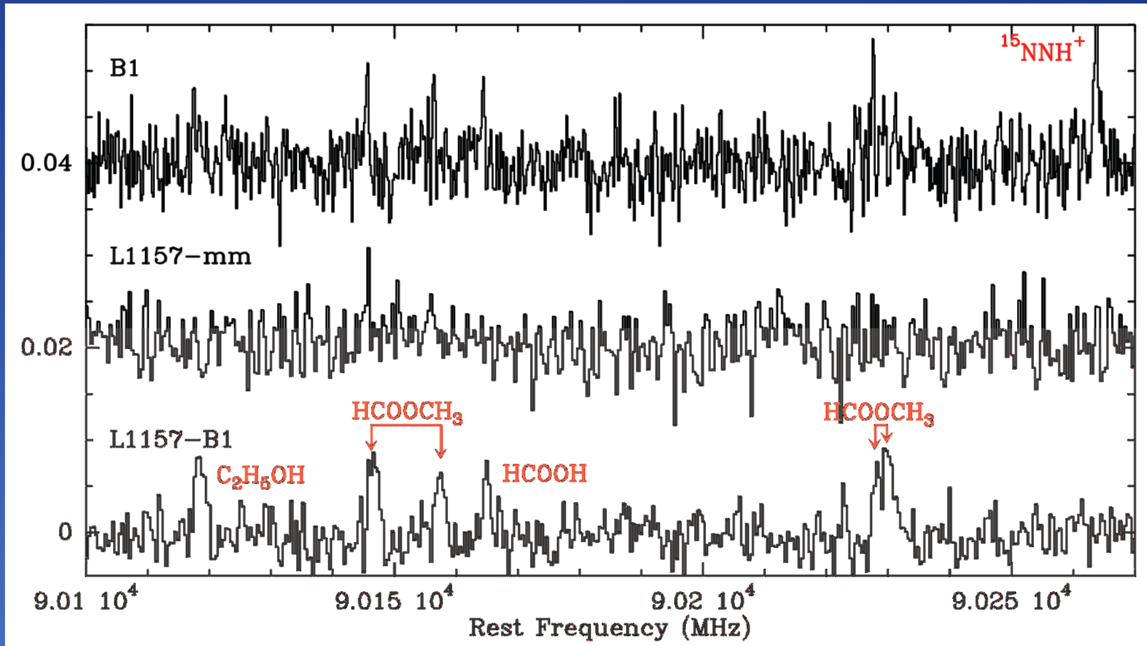
C-bearing : CCS, CCH, c-C_3H_2, HC_3N, HC_5N

D-bearing : CH_2DOH, DCN, NH_2D, HDCO, HDCS

Which molecular complexity ?

Molecular Complexity





Early Class 0

Class 0

Shock

Arce et al. (2008

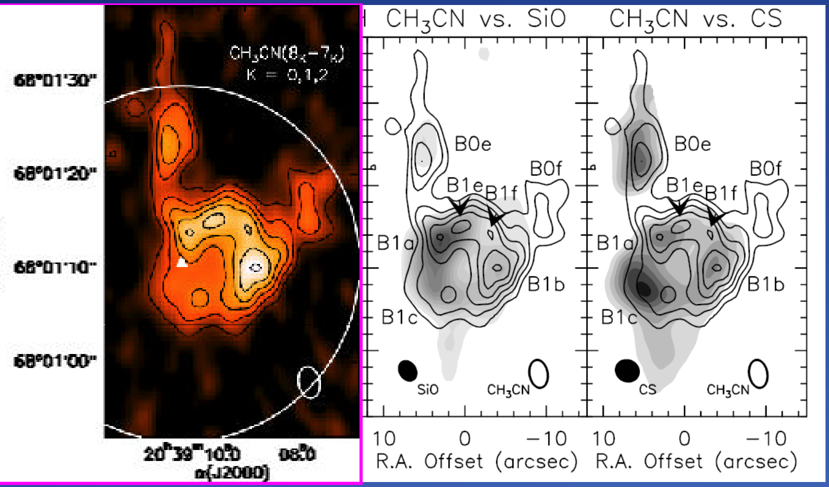
COMs are efficiently produced in the protostellar shock L1157-B1
No evidence of hot corino around the protostar L1157-mm

COMs identified: CH_3OH, H_2CO, CH_3CHO, HCOOH, $HCOOCH_3$, NH_2CHO, CH_2CO, CH_3CH_2OH, CH_3OCHO, CH_3CN

TABLE 2
ESTIMATES OF TEMPERATURE, COLUMN DENSITY, AND ABUNDANCE

Molecule	T_{rot} (K)	N (10^{13} cm^{-2})	$X = N/N_{...}$ (10^{-9})
$HCOOCH_3$-A[a]	27 ± 4	15 ± 4	11 ± 3
$HCOOCH_3$-E[a]	18 ± 13	12 ± 11	8 ± 7
CH_3CN[a]	110 ± 50	0.1 ± 0.05	0.07 ± 0.0
HCOOH[b]	10	8	5
C_2H_5OH[c]	25[d]	10	7

Complex Organic Molecules in L1157



Clump	T_{rot} (K)	N_{CH_3CN} (cm^{-2})	N_{CH_3OH}[a] (cm^{-2})	[CH_3CN]/[CH_3OH] (10^{-3})
B0e	57	8 10^{12}	6 10^{15}	1.3
B0f	–[b]	–[b]	–[a]	–
B1a	67	1 10^{13}	4 10^{16}	0.3
B1b	73	1 10^{13}	5 10^{16}	0.2
B1c	132	2 10^{13}	4 10^{16}	0.5
B1e	92	4 10^{13}	–[a]	–
B1f	55	2 10^{13}	–[a]	–

Association with shocked gas
Trot : higher at apex, lower in wings

Which formation mechanism ?

Gas phase model : grain mantle evaporation of H_2O, H_2CO, CH_3OH, NH_3 followed by warm gas phase reactions

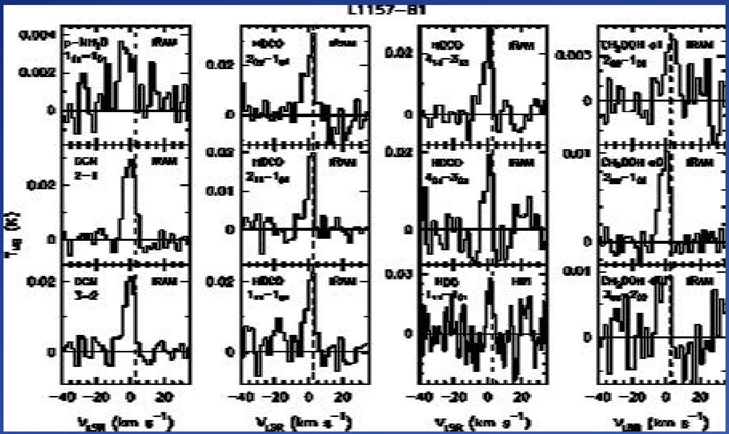
CH_3CN : low CH_3CN/CH_3OH wrt Hot Core Chemistry → gas phase formation (HCN, CH_3+)
Note : Max Col density is *not* at the apex but in the post-shocked gas

In B1 : n(H_2) high, T high… but
→the shock parameters are such that t_{cool} (100 K) < a few 10^3 yrs << Timescale for gas phase models (Millar 1991).

Grain surface chemistry: complex molecules are formed on icy mantles and subsequently released. $HCOOCH_3$,

Fossil Deuteration in L1157-B1

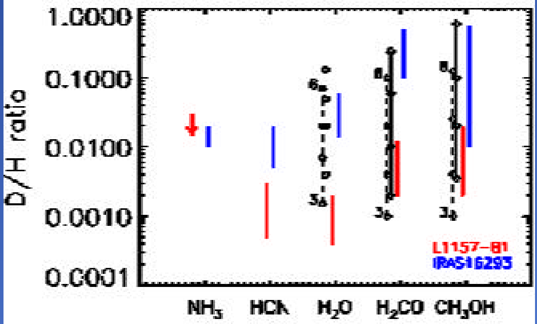
Codella et al. (2012)



A total of 11 emission lines (E_{up} <63 K) :
CH_2DOH(3), HDCO (6), and DCN (2)

Two tentative detections :
p-NH_2D (S/N = 3) and HDO (S/N = 4)

Osamura et al. (2004) :
Methanol, formaldehyde, and water provides us with a fossil record of the pre-shock gas conditions



High deuteration for CH_3OH, H_2CO : (0.5-1)%
Lower deuteration for H_2O and HCN : < 0.1%

Deuteration in L1157-B1 is systematically 10 times lower than in protostellar cores (IRAS16293).

First low-density phase (10^3 cm^{-3}), when water ice formed, followed by a phase of increased density, when CH_3OH and H_2CO ices formed.

Comparison with predictions for molecule formation (H_2O, H_2CO, CH_3OH) and D-enrichment predictions from model GRAINOBLE gas-grain surface chemistry

See V. Taquet's Talk

Abundances consistent with formation of H_2O, H_2CO, CH_3OH on icy grain mantles.

Conclusions

Protostellar Shocks Shine !

The exploitation of the Herschel + IRAM survey is just starting …

What we have learnt

Herschel shows that protostellar shocks play an important role in the chemistry of SFRs.

They enrich the molecular complexity of their environment, which can now be explored with the current mm/far-IR instruments: alcools, C-chains, molecular ions, etc…

Shock dynamics are more complex than what we expected. Comparison with state-of-the-art models is encouraging.

More is coming

H_2O !
N-bearing species (Poster #39 R. Le Gal)
S-bearing species
Molecular Ions : HCO^+ , $H^{13}CO^+$, HCS^+ , …
H_2CO and CH_3OH
Complex Organic Molecules

Conclusions

Looking to the future

More case studies are needed
→ Herschel (SPECSO)
→ IRAM 30m (ASAI) and PdBI

Shock dynamics
NOEMA and ALMA will be able to resolve the structure of shocks and we suspect interesting results !

JWST (SPICA ?) : high-resolution spectroscopy of near/mid-IR H_2 lines will trace the shocked gas kinematics : a novel view !

Molecular Complexity in the inner protostellar regions
NOEMA, ALMA will investigate the impact of shocks on the inner protostellar regions (100 AU) and will clarify the nature of the hot corino (COM-rich) region around protostars