GH-2016: Molecular Astrophysics

Star-Formation: molecular composition of protostellar outflows/jets

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Outline

- Protostellar Outflows
- Chemically active outflows
- Molecular surveys in L1157-B1
- Other chemically active outflows
- Abundance enhancements
- Jet molecular composition

Star Formation Jets/Outflows

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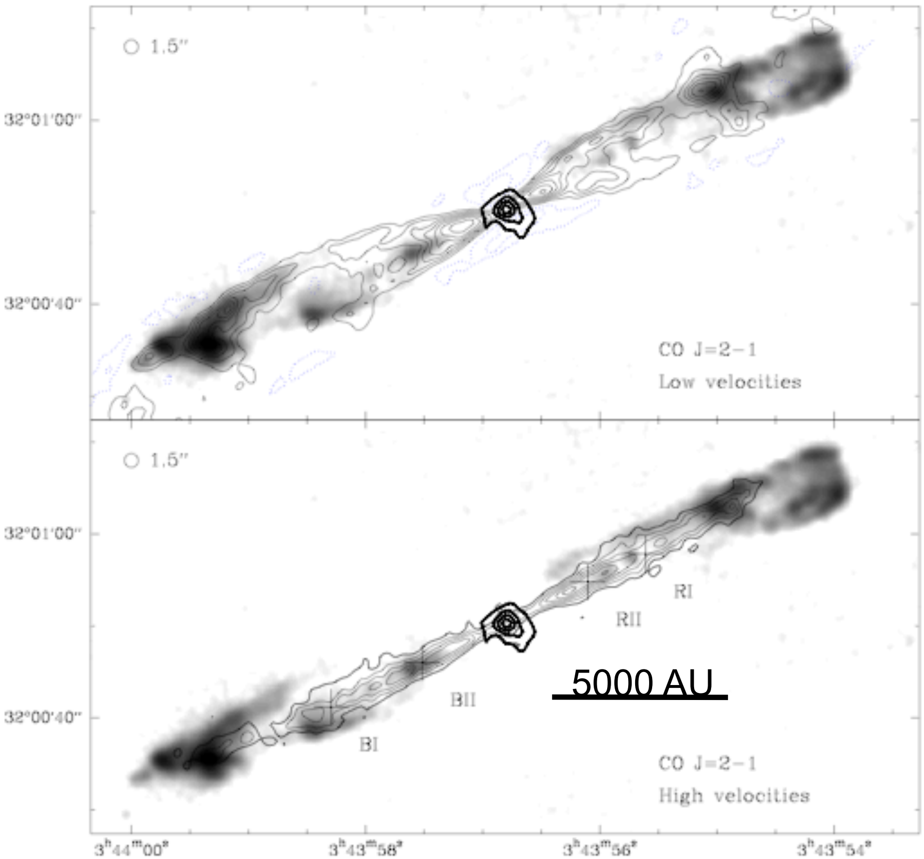


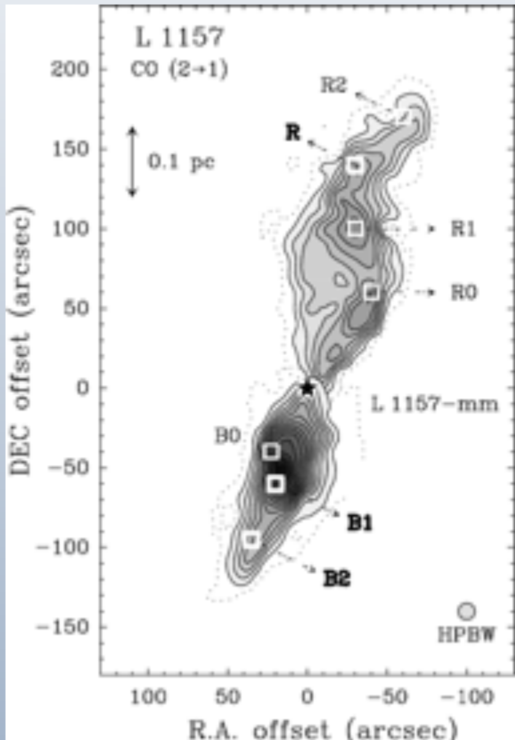
Gueth & Guilloteau, 1999

- Traditional studies in low-J CO (J=1-0 or 2-1)

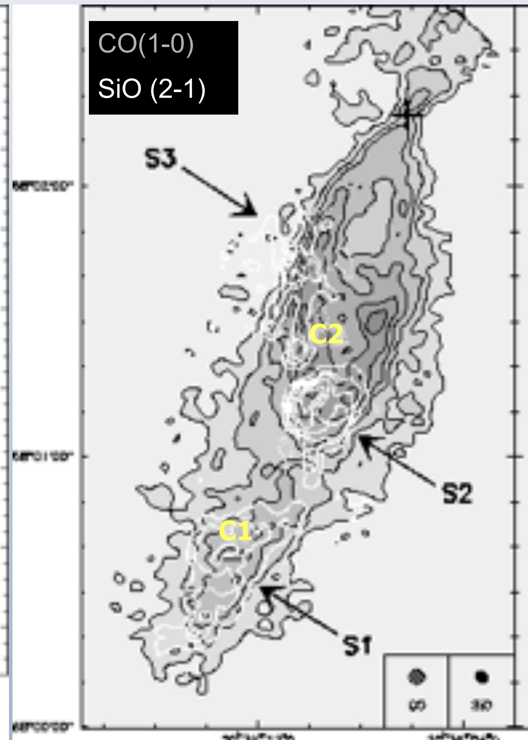
Two components:

- Standard high velocity (SHV): low collimation, cavity walls
- Extreme high velocity (EHV): Highly collimated, EHV wing + “bullets”
- “Bullets”: secondary peaks, compact clumps

L1157 chemically active outflow



Bachiller et al., 2001



Gueth et al., 1998

- L1157: dark cloud 440 pc distant (V_{LSR}=+2.7 km/s); Class 0 source with 11 L_{sun}
- Precessing bipolar outflow with a mean dynamical age of 15 000 yrs
- Strongest molecular line emission from the blue-lobe in several species
- Two cavities related with different ejection events (C1 older than C2)
- Prototype of chemically active outflows (shock chemistry)
- Chemical stratification along the lobe (Bachiller et al., 2001; Benedettini et al., 2007)

Different molecular tracers

- Single-dish detected ~ 30 molecular species in bipolar outflows (Bachiller et al. 2001)

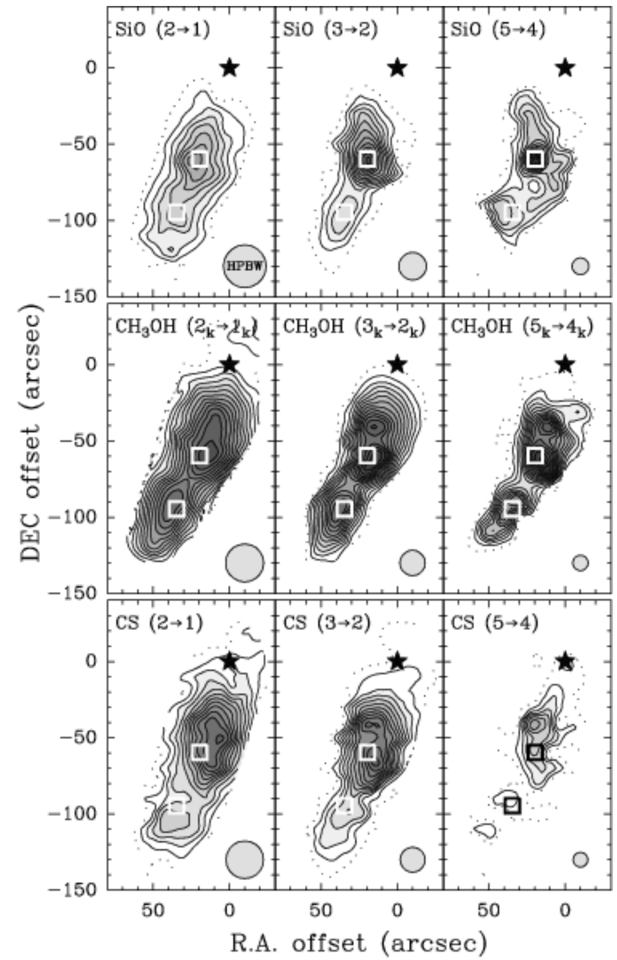
- Among the most prominent are SiO, CH_3OH, H_2CO, HCO^+, HCN, SO, SO_2, CS

- SiO one of the most important shock tracers

- Gradient in the chemical composition, possibly related with time-dependent shock chemistry

- However, for kinematical studies the CO molecule is still preferred, since this is a more chemically stable molecule

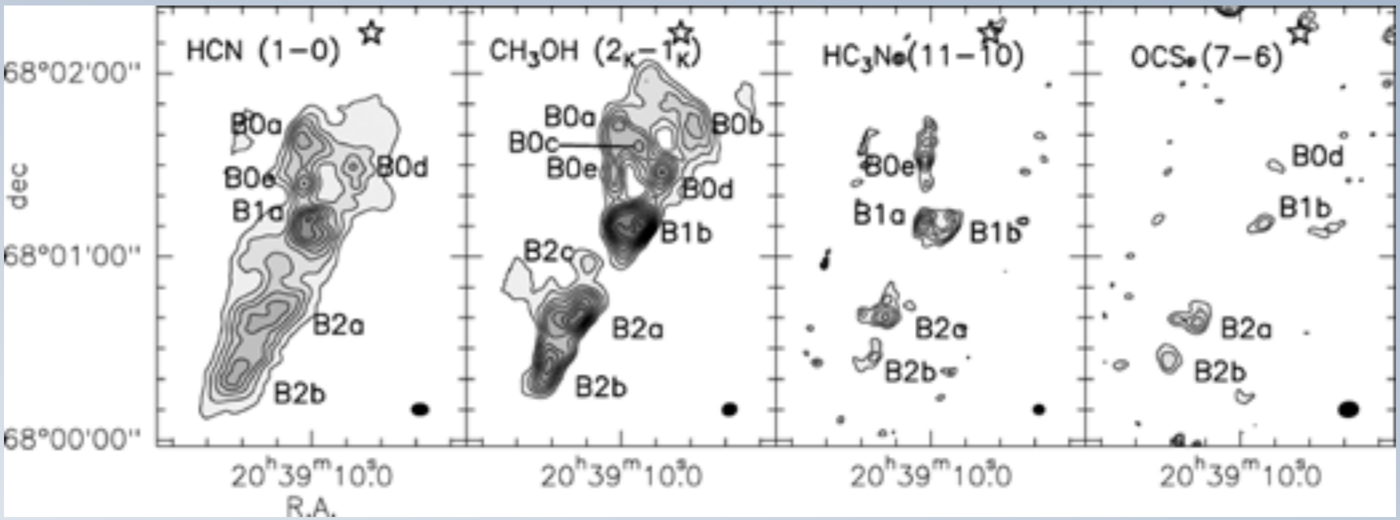
L1157



Bachiller et al. 2001

Chemical difference in the cavity

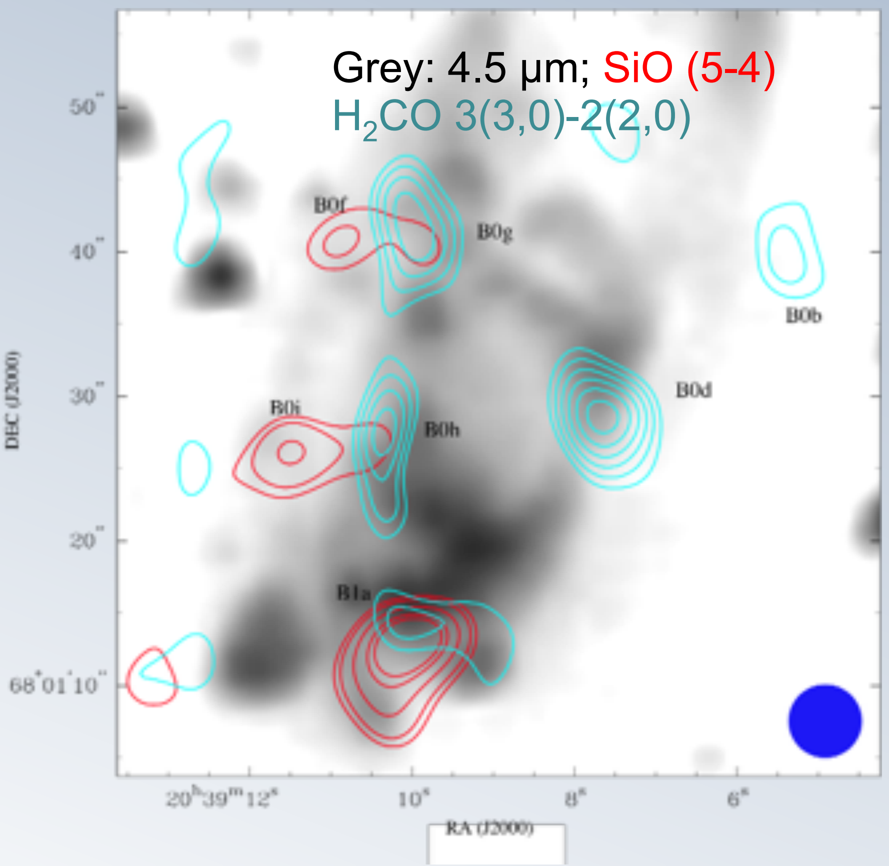
Benedettini et al. 2007



- Interferometric observations show emission from clumps cavities
- Eastern wall: HC_3N, HCN, CS, NH_3, and SiO
- Western wall: CH_3OH, OCS and ^{34}SO
- Peak displacements suggest physical & chemical inhomogeneities within the walls

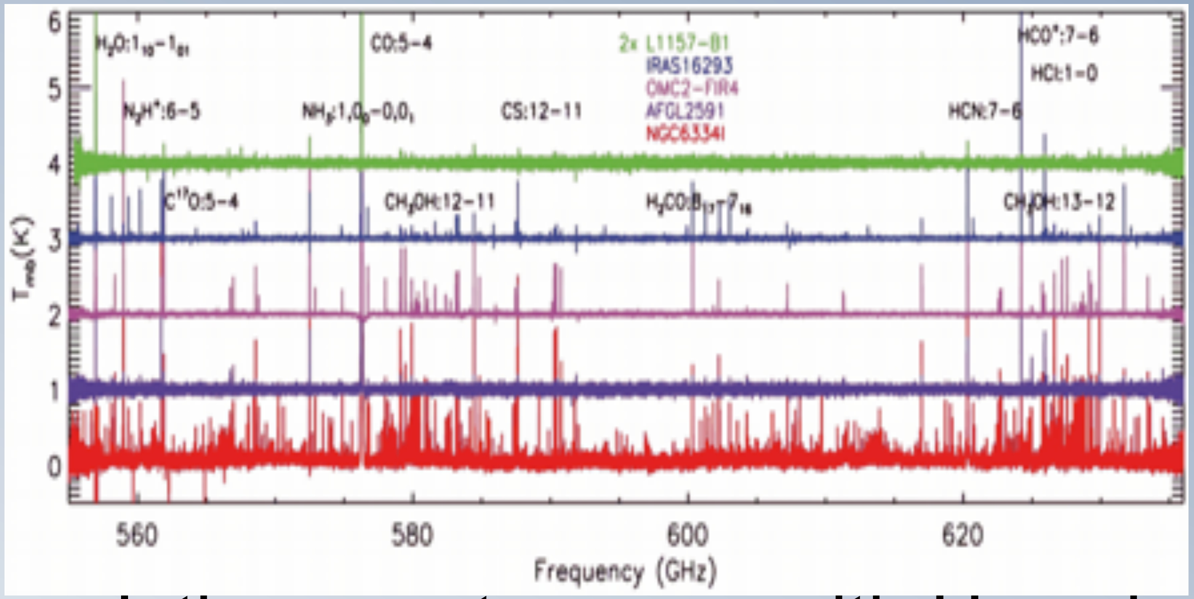
SiO vs. H_2CO

Gomez-Ruiz et al. 2013



- H_2CO tracing the cavity
- SiO clumps are likely tracing the last ejections events in L1157

Chemical survey of Star Forming Regions with Herschel (KP-CHESS)



- High resolution spectroscopy with Herschel/HIFI
- Deep observation in selected star forming regions: 1) shock (L1157-B1); 2) class 0 low-mass (IRAS16293); 3) intermediate-mass (OMC2-FIR4); 4) & 5) high-mass (AFGL2591 & NGC6334I)
- The chemical heritage of the star formation process

Number of species and lines

- Number of lines:
  - NGC6334I > 500
  - IRAS 16293 & OMC2-FIR4 ~ 70
  - AFGL 2591 & L1157-B1 <= 30
- Number of species:
  - NGC 6334I = 26
  - IRAS 16293 = 22
  - OMC2-FIR4 = 17
  - AFGL 2591 = 11
  - L1157-B1 = 8
- CH3OH: NGC 6334I rich and AFGL 2591 poor
- Deuterated molecules:
  - HDO & DCN only in IRAS 16293 & NGC 6334I
  - D2O only in IRAS 16293
- New species: H_2O^+, OH^+, H_2CL^+, D_2O, ND

Table 2. Species and number of detected lines in the 555–636 GHz.

Species	E_{up} (K)	(1)	(2)	(3)	(4)	(5)
H_2O	27–680	1	2	1	1	2
HDO	97	0	1	0	0	1
D_2O	29	0	1	0	0	0
CO	83	1	1	1	1	1
$C^{17}O$	83	0	1	1	1	1
HCO^+	119	1	1	1	1	1
$H^{13}CO^+$	119	0	1	0	0	1
HCN	119	1	1	1	1	1
$H^{13}CN$	119	0	1	1	0	1
DCN	119	0	1	0	0	1
HNC	119	0	1	1	0	1
CN	82	0	0	2	2	2
N_2H^+	95	0	1	1	0	1
NH_3	28	1	1	1	1	1
HCl	27	0	1	1	1	1
$H^{37}Cl$	27	0	1	1	0	1
CCH	117	0	0	2	0	2
H_2CO	120–530	4	8	8	0	8
CH_3OH	39–1050	17	35	47	3	345
$^{13}CH_3OH$	39–240	0	0	0	0	41
CH_3OCH_3	115–290	0	0	1	0	30
H_2S	160–415	0	2	0	0	4
CS	186	1	1	1	1	1
$C^{34}S$	175–200	0	2	0	0	2
SO	190–225	0	6	0	2	6
SO_2	80–210	0	10	0	0	15
others[c]		0	0	0	0	62
Total		27	86	71	16	558

Notes. Second column gives the upper level energy range of the detected transitions. Columns (1) to (5) refer to L1157-B1, IRAS 16293, OMC2-FIR4, AFGL 2591 and NGC 6334I respectively. In L1157-B1 the number refers to the list of lines reported in Codella et al. (2010).

CHESS observations of protostellar outflow L1157

Herschel/HIFI+PACS and complementary IRAM-30m single pointing observations on the main shock B1

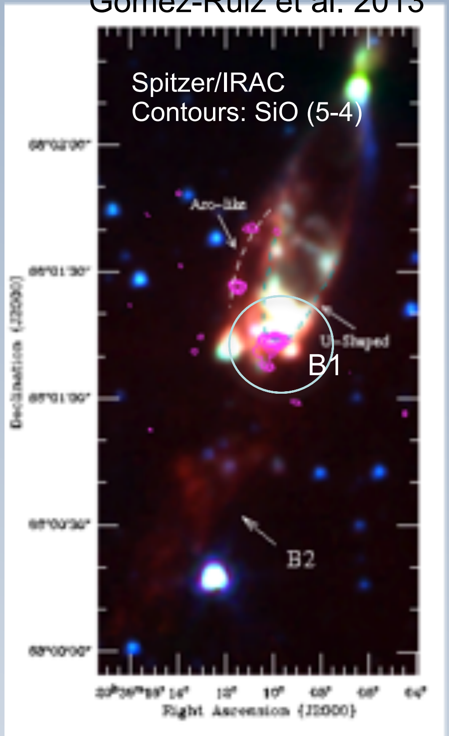
27 lines detected, most of them up to Vlsr -10 km/s; CO up to -40 km/s

CO, H_2O, CH_3OH, CS, SiO, H_2CO, HCN, among others, show prominent emission at outflow velocities

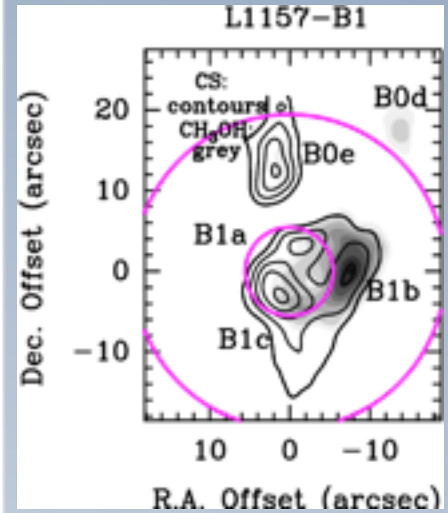
Spatial information is very important to constrain the models of the molecular emission

We need maps at least from the lower frequency transitions

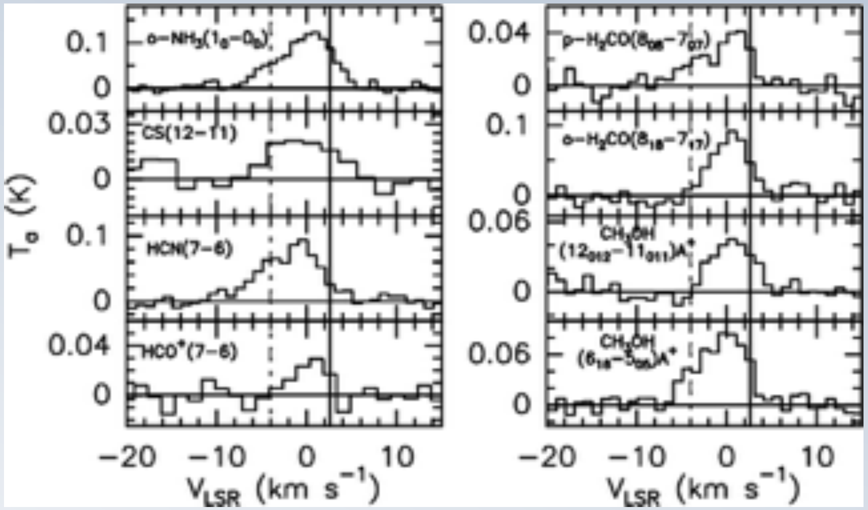
Gomez-Ruiz et al. 2013



Codella et al. 2010

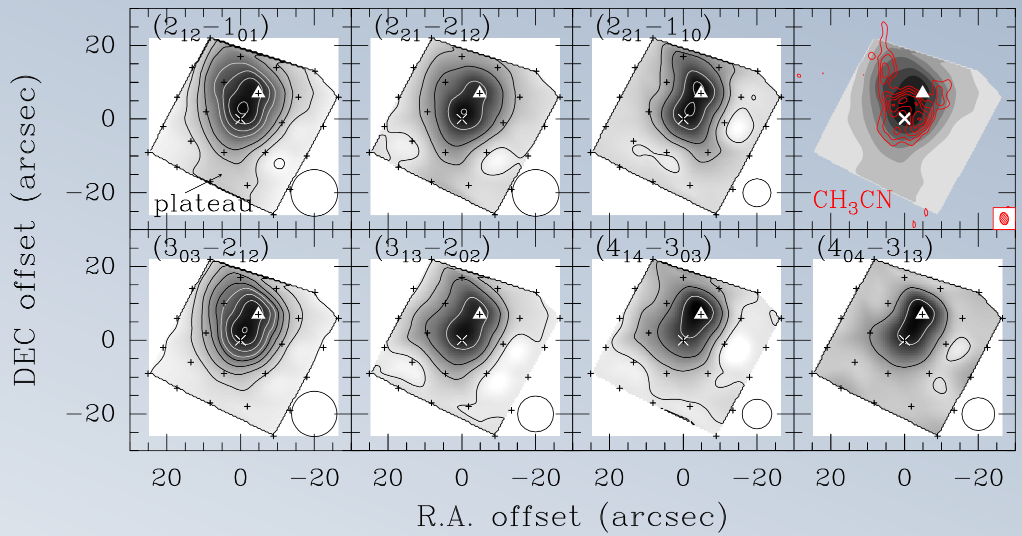


Codella et al. 2010



Water in L1157-B1

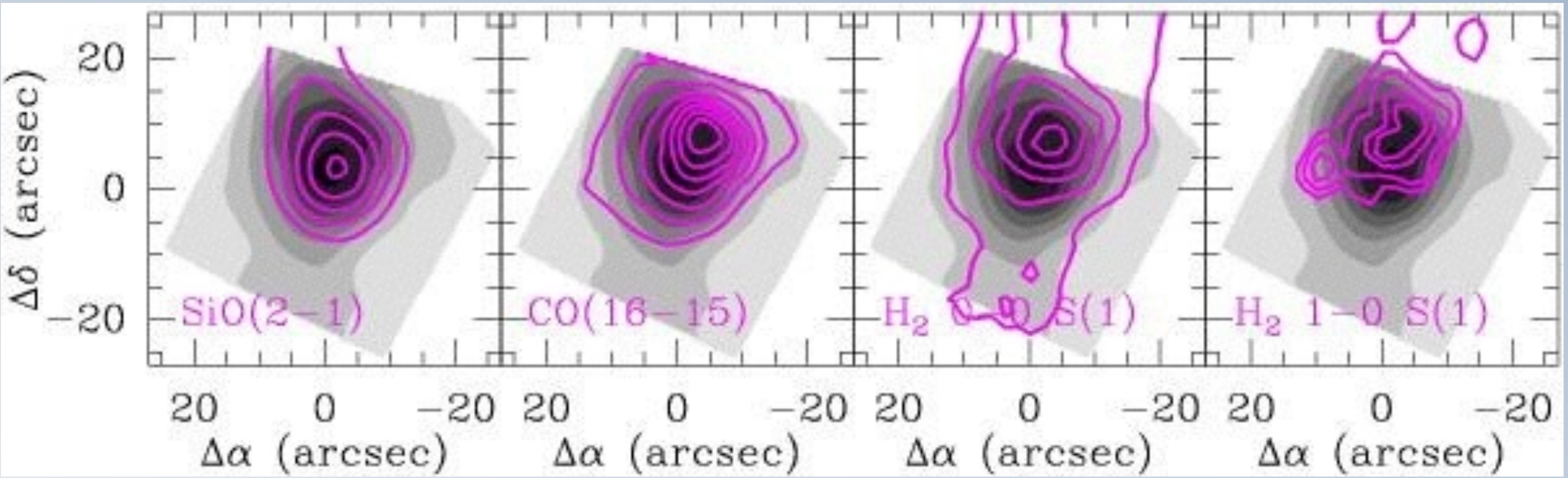
Busquet et al. 2013



- H2O predicted as one of the main cooling agents in shocks, along with H2 and CO
- 13 H2O transitions detected: 7 with PACS (5 ortho, 2 para) and 8 with HIFI (5 ortho, 3 para). Eup < 320 K
- Water distribution with little variation at the different transitions, typical size (FWHM) 10”

H_2O vs. SiO

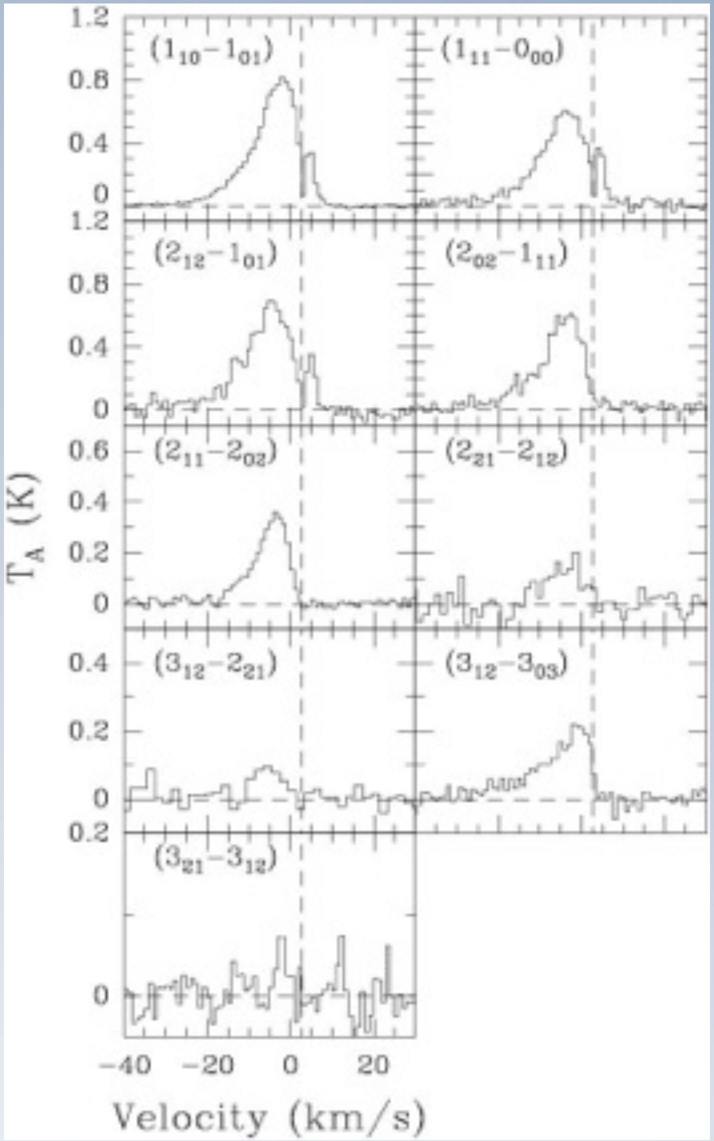
Busquet et al. 2013



- Good match between H2O and SiO
- Some overlap with CO and H2

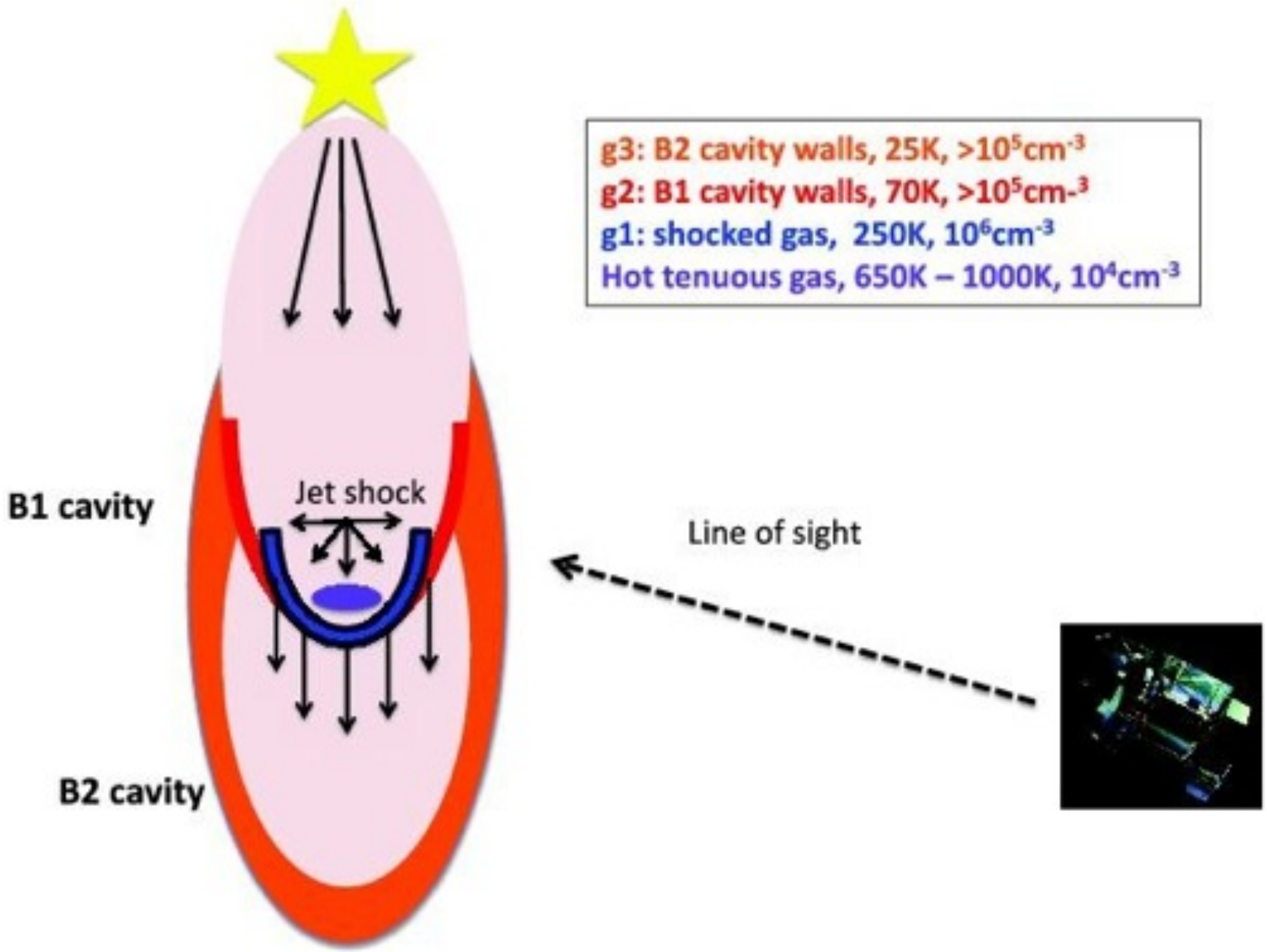
H_2O line profiles

- Broad lines, FWHM of 10 km/s. Some cases with Vlsr up to -30 km/s
- o-H2O (3_12 – 3_03) profile similar to CO (16-15), therefore g1 component
- 1666 and 1113 GHz lines peak at -5 km/s, while 752 and 988 GHz at -3 km/s
- Absorption at cloud velocity in low-energy transitions, likely from the protostellar envelope
- Red-shifted emission at the rear part of the cavity



Temperature/density structure

Busquet et al. 2013



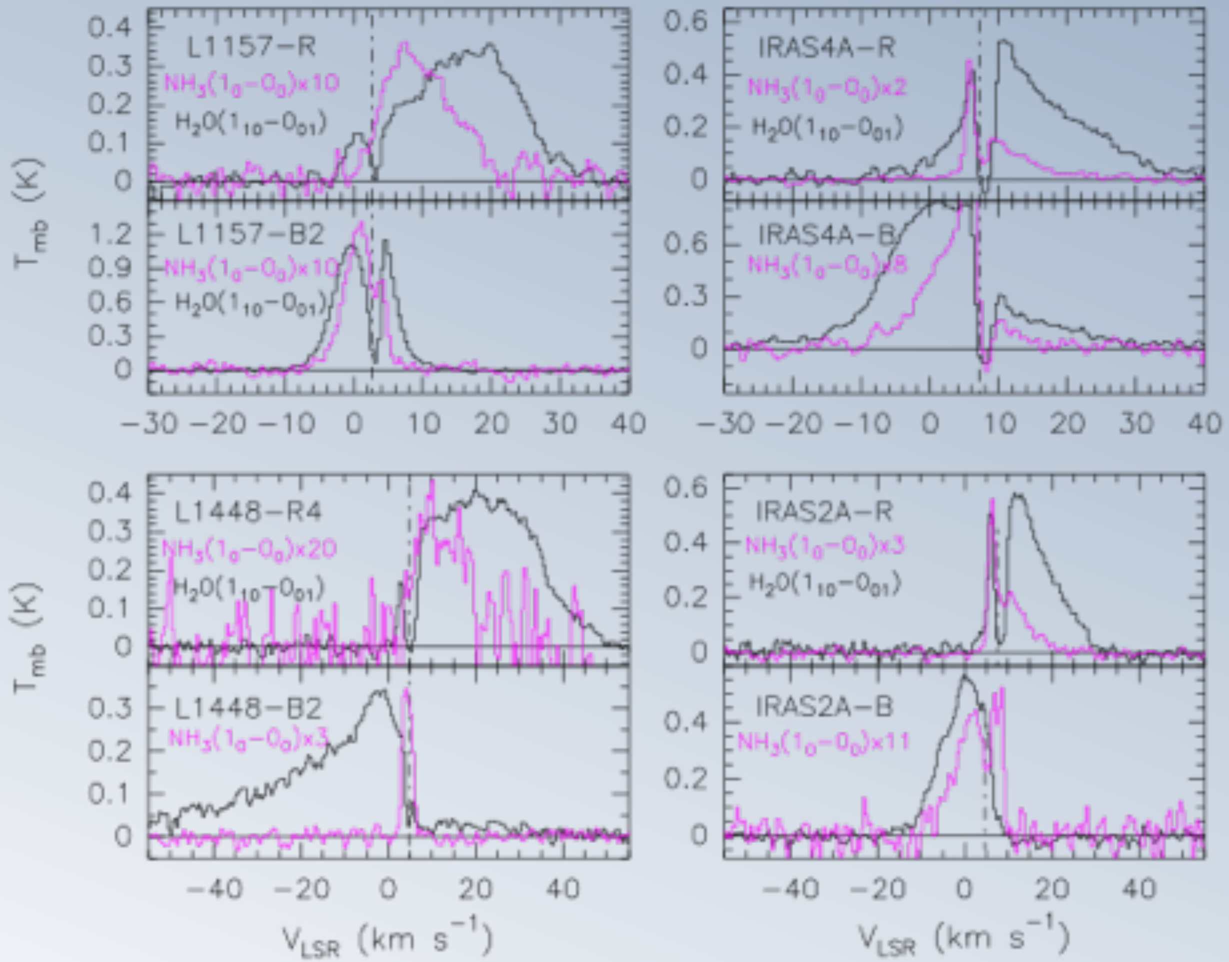
H_2O abundances and line cooling

Table 4. Physical conditions of the shock components accounting for the water line emission in L1157-B1.

Comp.	T_{kin} (K)	$n(H_2)$ (cm^{-3})	$N(H_2O)$ (cm^{-2})	$N(H_2)$ (cm^{-2})	$X(H_2O)$	Size ($''$)	$L(H_2O)$ ($L_\odot$)	$L(CO)$ ($L_\odot$)	$[H_2O]/[CO]$
Warm	250–300	$(1–3) \times 10^6$	$(1.2–2.7) \times 10^{14}$	1.2×10^{20}	$(0.7–2.0) \times 10^{-6}$	10	0.002	0.004	0.03
Hot	900–1400	$(0.8–2) \times 10^4$	$(4.0–9.1) \times 10^{16}$	3.3×10^{20}	$(1.2–3.6) \times 10^{-4}$	2-5	0.03	0.01	1

- H2O abundance in hot comp. is two orders of magnitude higher than warm comp.
- In warm comp. water contribution to line cooling is 50% of the CO luminosity
- For the hot comp. the far-IR cooling of H2O dominates over CO
- Far-IR cooling of the bow-shock appears to be equally dominated by both H2 and the hot water component
- Total far-IR cooling from B1 is 0.05 Lsun

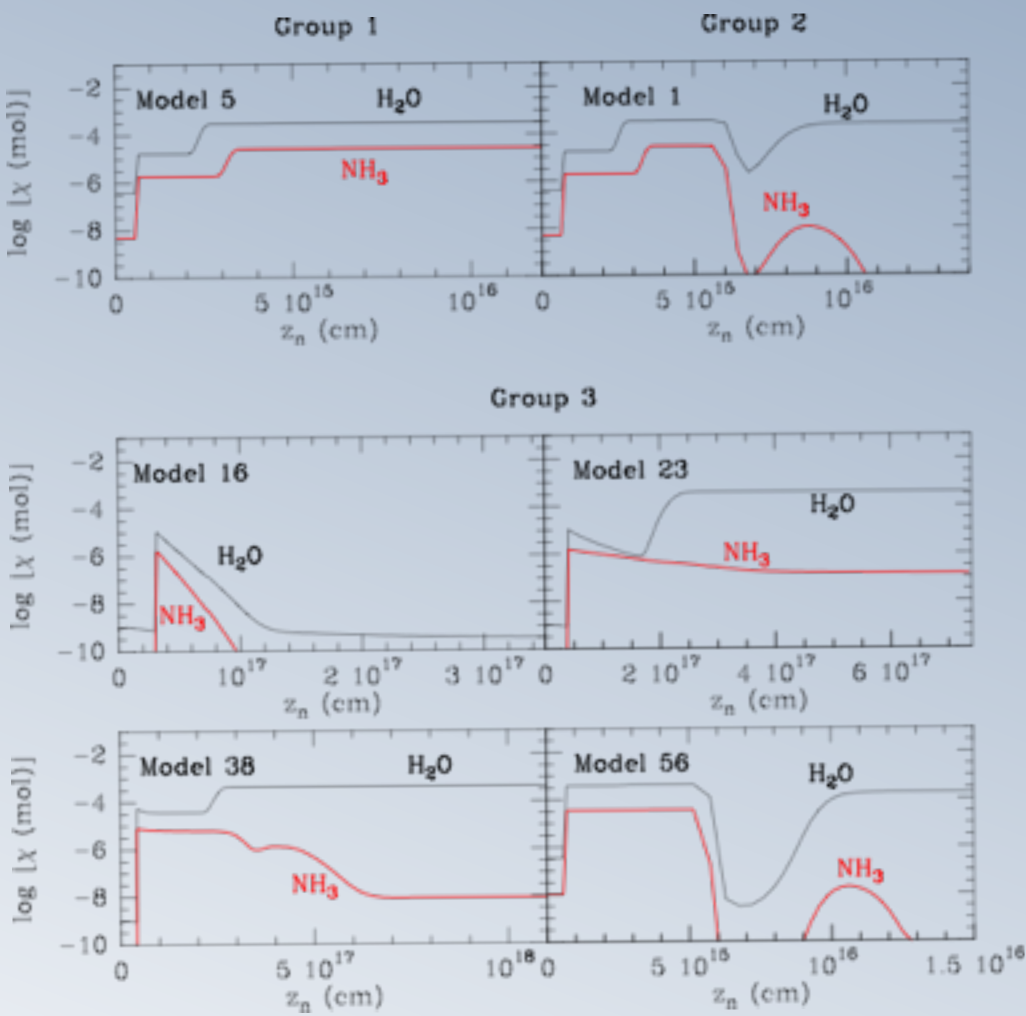
Ammonia vs water



Gómez-Ruiz et al. 2016

Chemical models: core evolution+shock

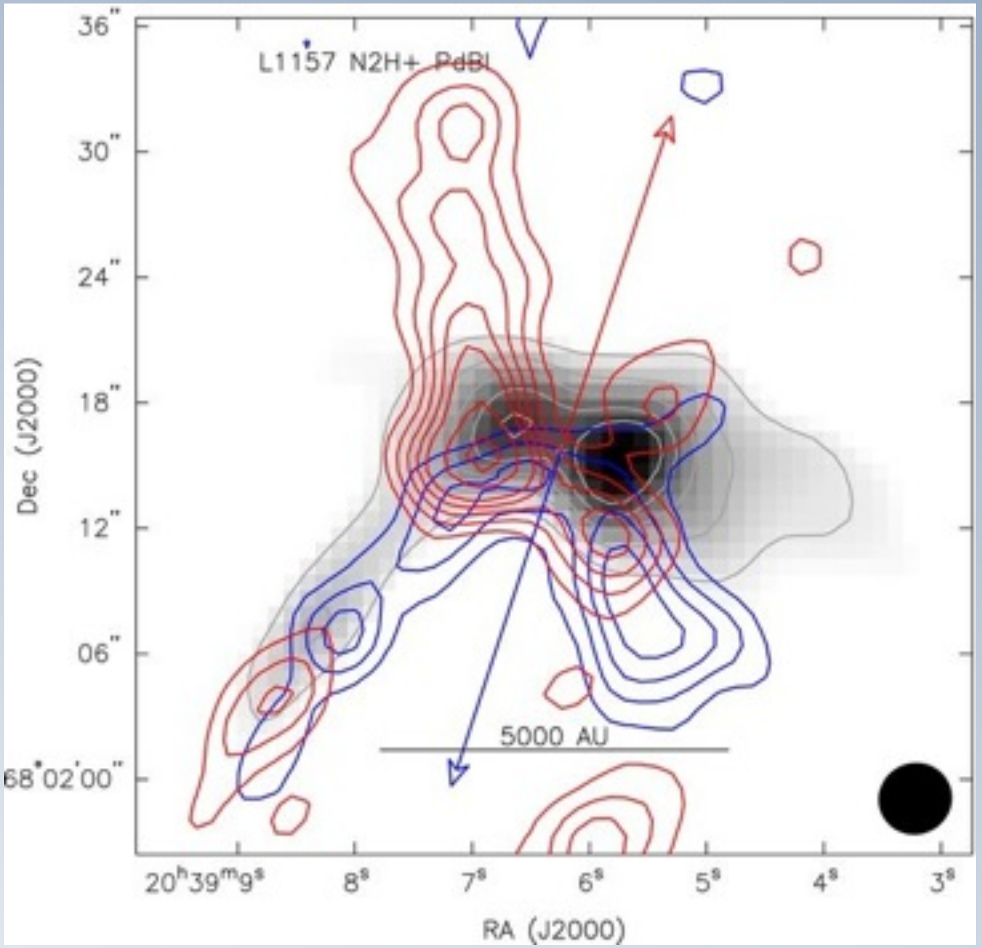
- Group 1: H_2O and NH_3 are both either abundant, or otherwise (L1157-B2, IRAS2A-B,)
- Group 2: NH_3 decreases 'earlier' in the postshock gas, i.e. at lower velocities (1448-B2,L1448-R4, IRAS4A-R, IRAS4A-B, IRAS2A-R, L1157-R,)
- Group 3: no clear trend (L1157-B2, IRAS2A-B)



Gómez-Ruiz et al. 2016

N_2H^+ (diazenylium)

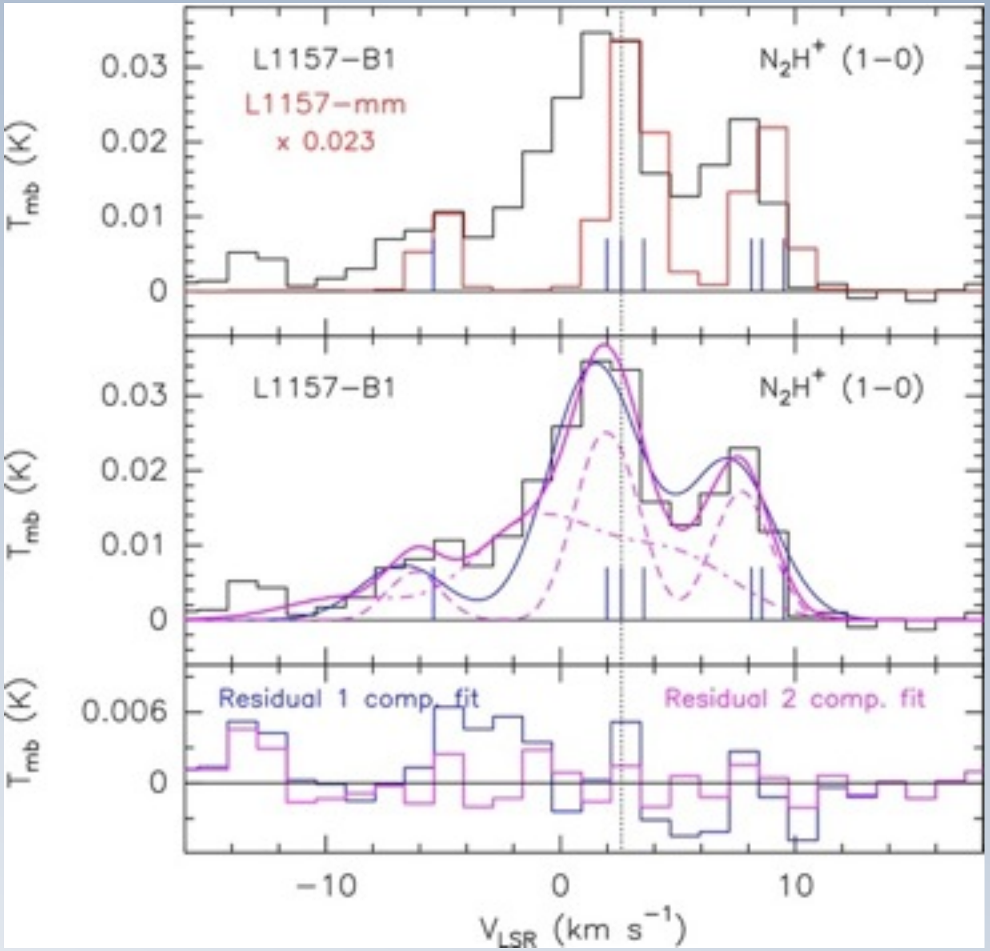
- Standard tracer of cold & quiescent pre-stellar environments (e.g. Caselli et al. 2002)
- Tobin et al. (2013) found narrow line emission tracing envelope, but elongated along the outflow cavity walls
- Outflow entrainment or shock near the driving protostar?
- Is there any role of N_2H^+ in shock chemistry??



Tobin et al. 2011

N_2H^+ (1-0) spectrum at B1

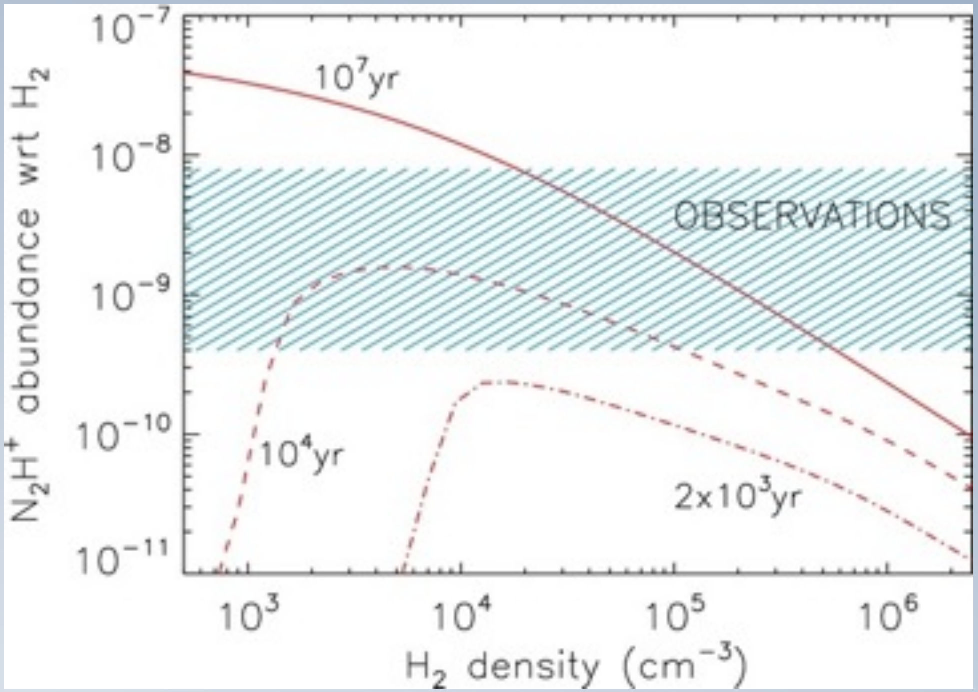
- IRAM-30m profile broader (4.3 km/s) than emission from central region (0.6–0.8 km/s)
- Two gaussian components needed to reproduce line profile: broad & narrow
- The profile is consistent with g2 and/or g3 components, i.e. B1 and/or B2 cavities
- $X(N_2H^+)$ = 2 – 8 x 10^-9 : consistent with values at L1157-mm



Codella et al. 2013

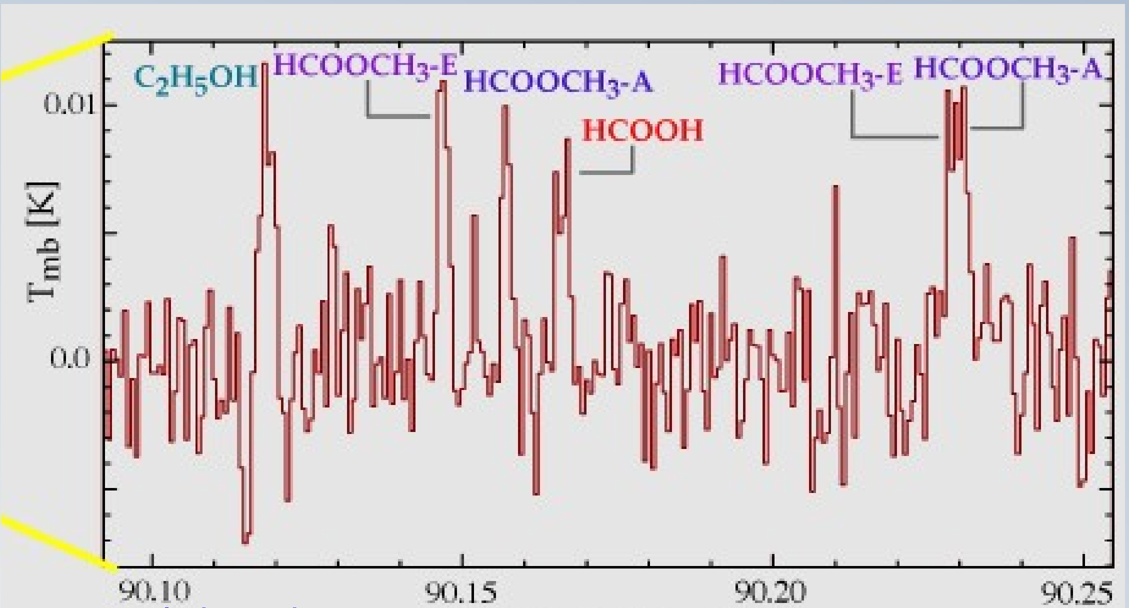
Chemical models

- ASTROCHEM code and parametric shock model
- Observed abundance matched by a model of cold, quiescent, and relatively old (> 10^4 yr) gas, no need of a shock
- N_2H^+ formed in gas phase and shock passage does not increase abundance
- N_2H^+ is a fossil record of the pre-shock phase (i.e. detection due to increase in column density)



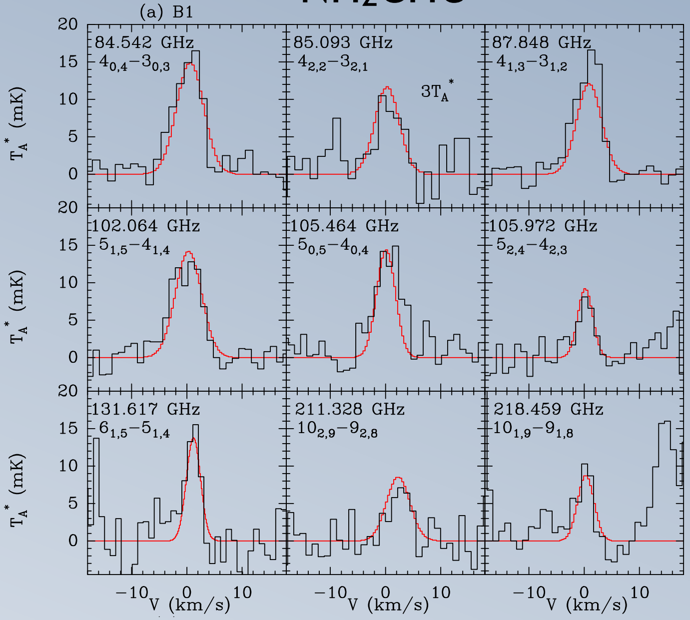
Codella et al. 2013

Complex/pre-biotic molecules



Arce et al. (2008)

NH2CHO



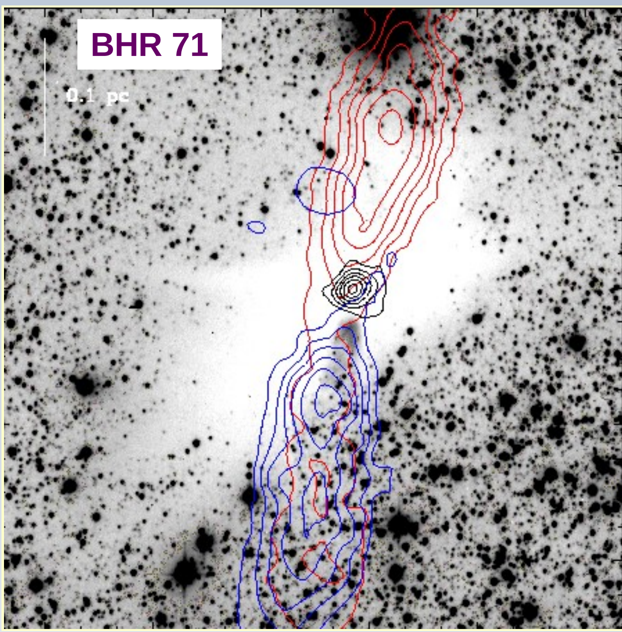
Mendoza et al. 2014

Formamide: Mendoza et al. 2014; Acetaldehyde: Codella et al. 2015; PO: Lefloch et al. 2016

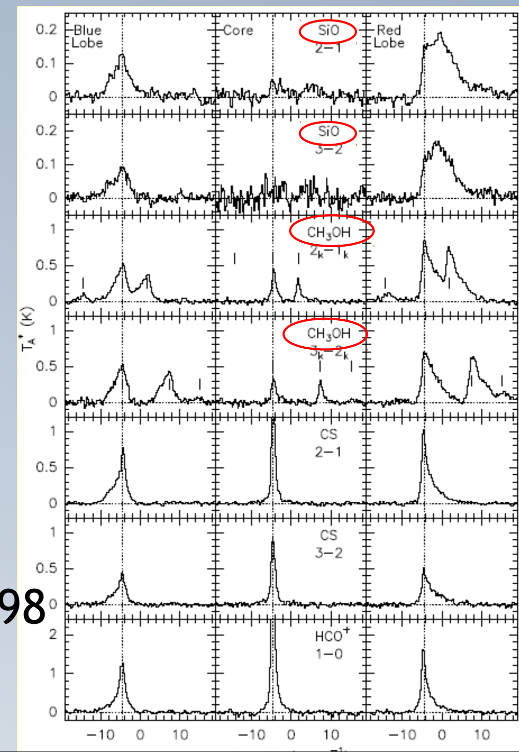
Spectral surveys in L1157-B1

- 3mm line survey with Nobeyama 45m (Yamaguchi et al. 2012)
- Herschel/HIFI survey ~500-2000 GHz + complementary IRAM-30m (CHESS: Ceccarelli et al. 2010)
- 1, 2, 3 mm survey with IRAM-30m (ASAI: Lefloch & Bachiller)

Other chemically active outflows

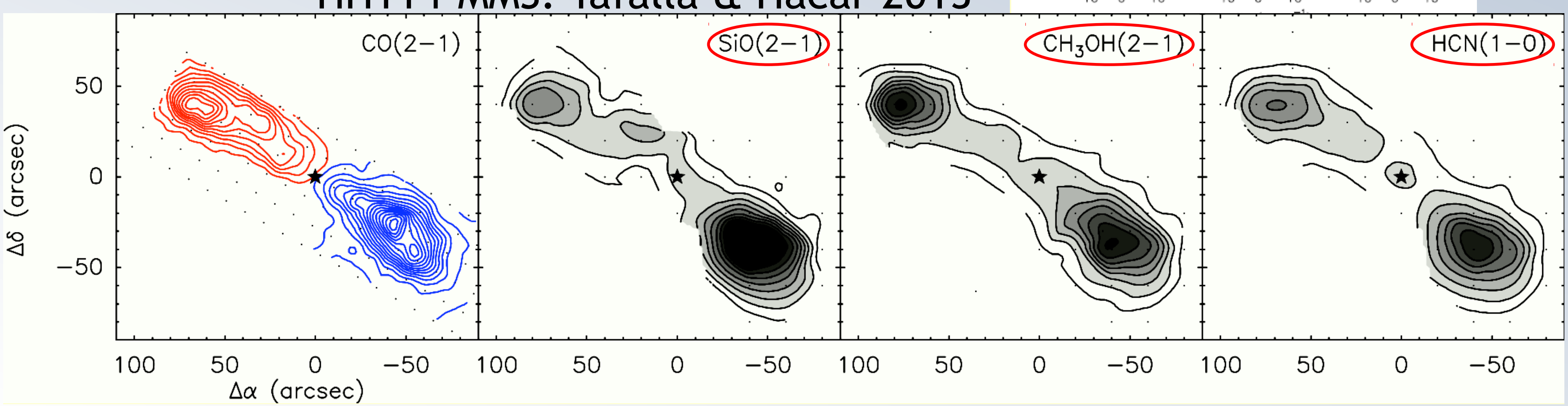


Bourke+2001

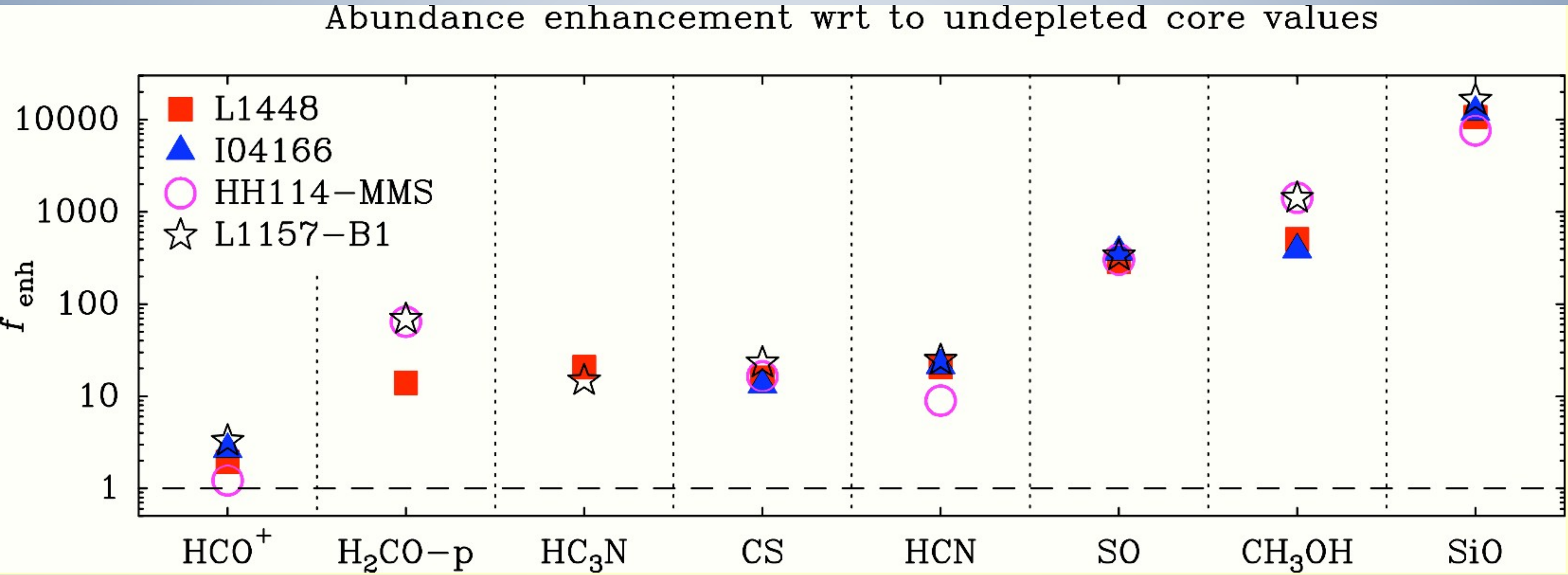


Garay+1998

HH114-MMS: Tafalla & Hacar 2013



Abundance enhancements

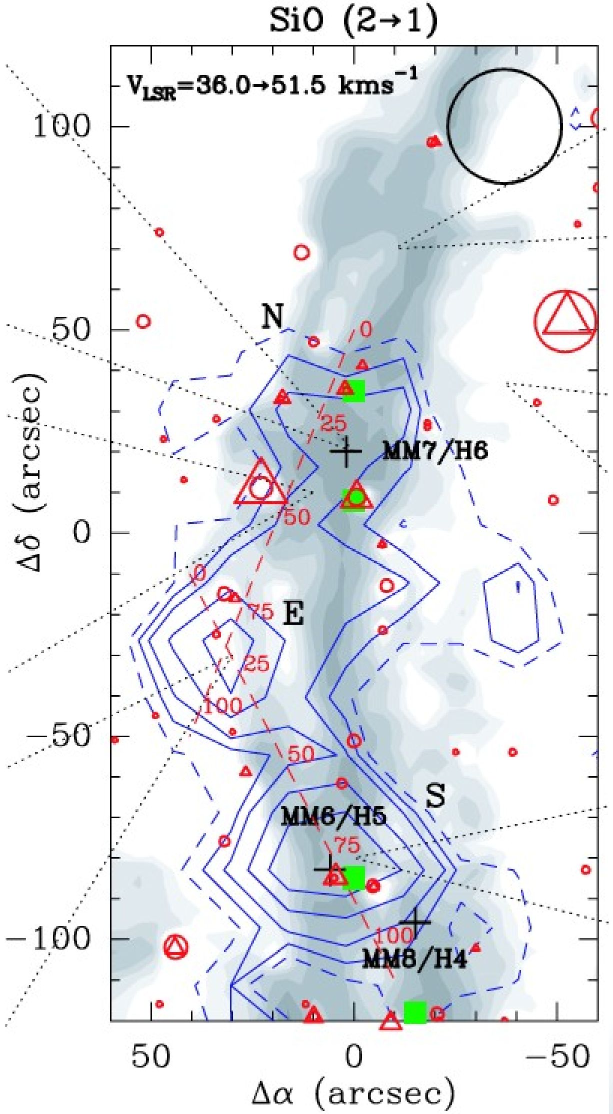


Tafalla et al. 2010

Systematic behavior suggesting “simple” shock chemistry
Prominent enhancement of SiO, SO, CH3OH
No global chemical model simultaneously fits all molecular data

SiO: prominent shock tracer

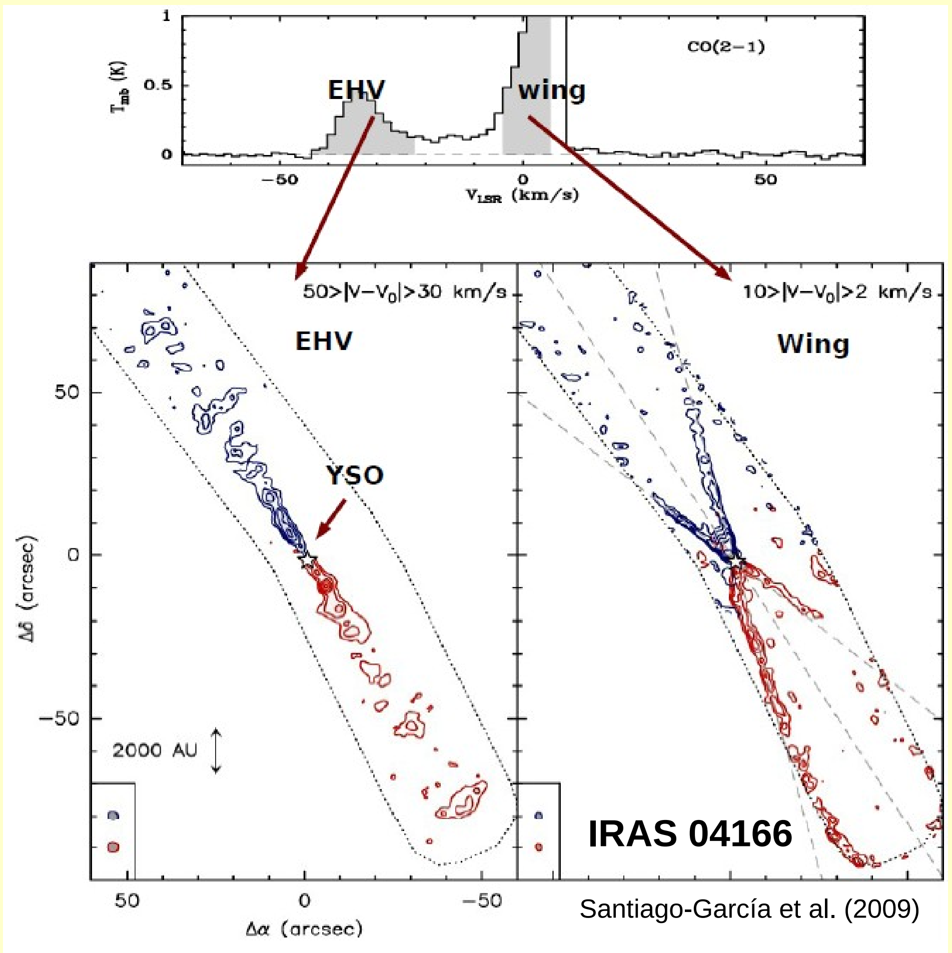
- Sensitive shock tracer: enhancements > 10^4 (ambient abundance < 5e-12; Ziurys et al. 1989)
- Release of Si from grains (and mantles) in C or J shocks (e.g. Gusdorf et al. 2008)
- Parsec scale SiO emission in IR-Dark Clouds: multiple outflows or cloud shocks?



Jiménez-Serra et al. 2010

Extreme High Velocity

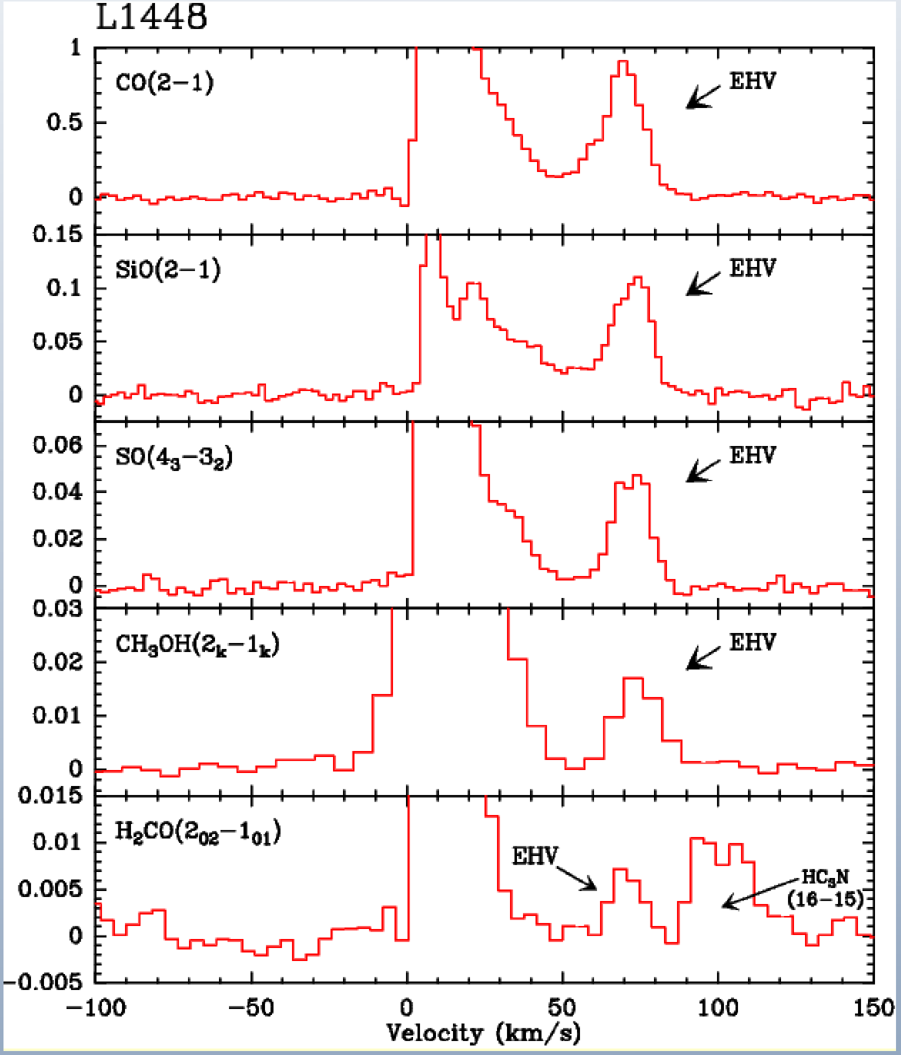
- EHV gas seen as secondary peaks
- Weaker than the "standard" high velocity tracing the cavity
- Related with the jet gas



Santiago-García et al. (2009)

Chemical composition of EHV

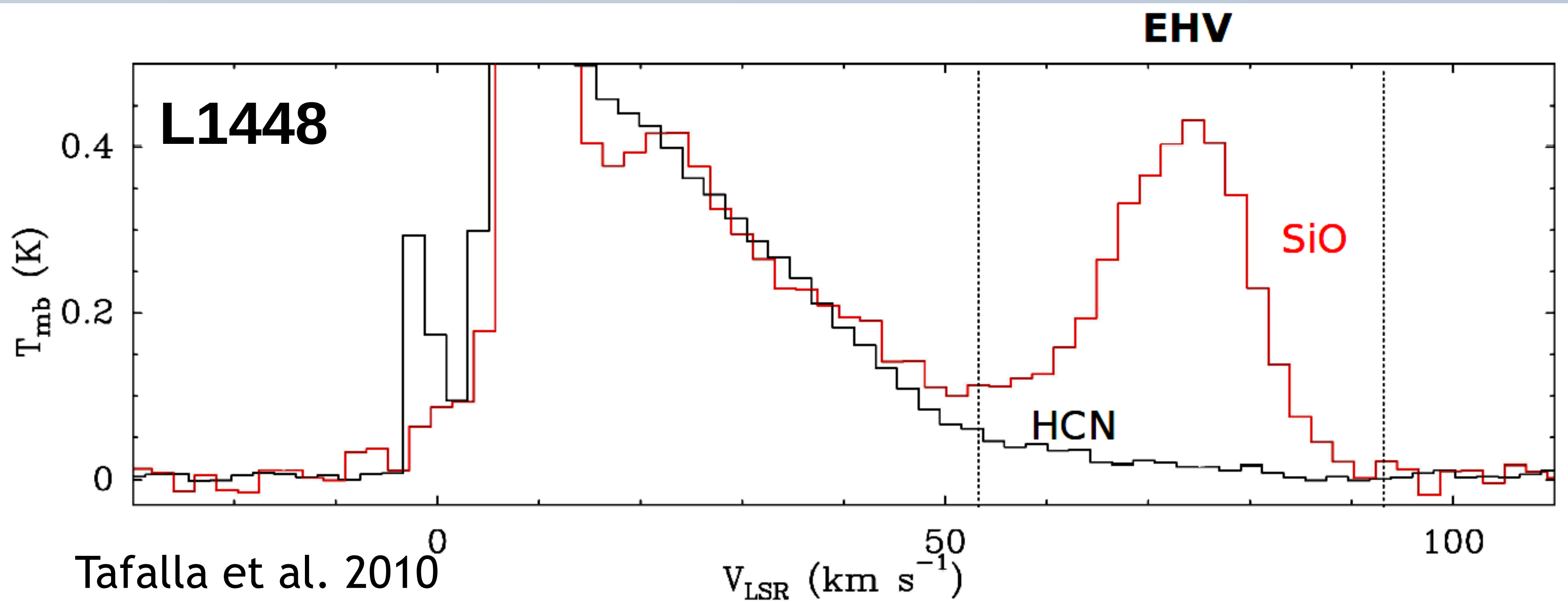
- IRAM-30m survey in L1448 & IRAS 04166: CO, SiO, SO, CH_3OH, H_2CO
- Herschel detection of H_2O EHV gas (Kristensen et al. 2011)



Tafalla et al. 2010

EHV gas in Oxigen-rich

- EHV gas dominated by Oxigen-bearing molecules
- C-bearing molecules significantly depleted : SiO/HCN ~ 20 from "wing" to EHV



Tafalla et al. 2010

Summary

- Shocks in outflows have an important impact in the chemistry of the ISM
- Molecular emission from shocks are also important to study the dynamics of protostellar outflows
- Accelerated ambient gas (standard high velocity) subject to numerous surveys (L1157): clear trend of abundance enhancements; consistent with shock models
- Jet gas (EHV) no well explored, but evidence of O-rich chemistry

http://shocks2016.faj.org.pl