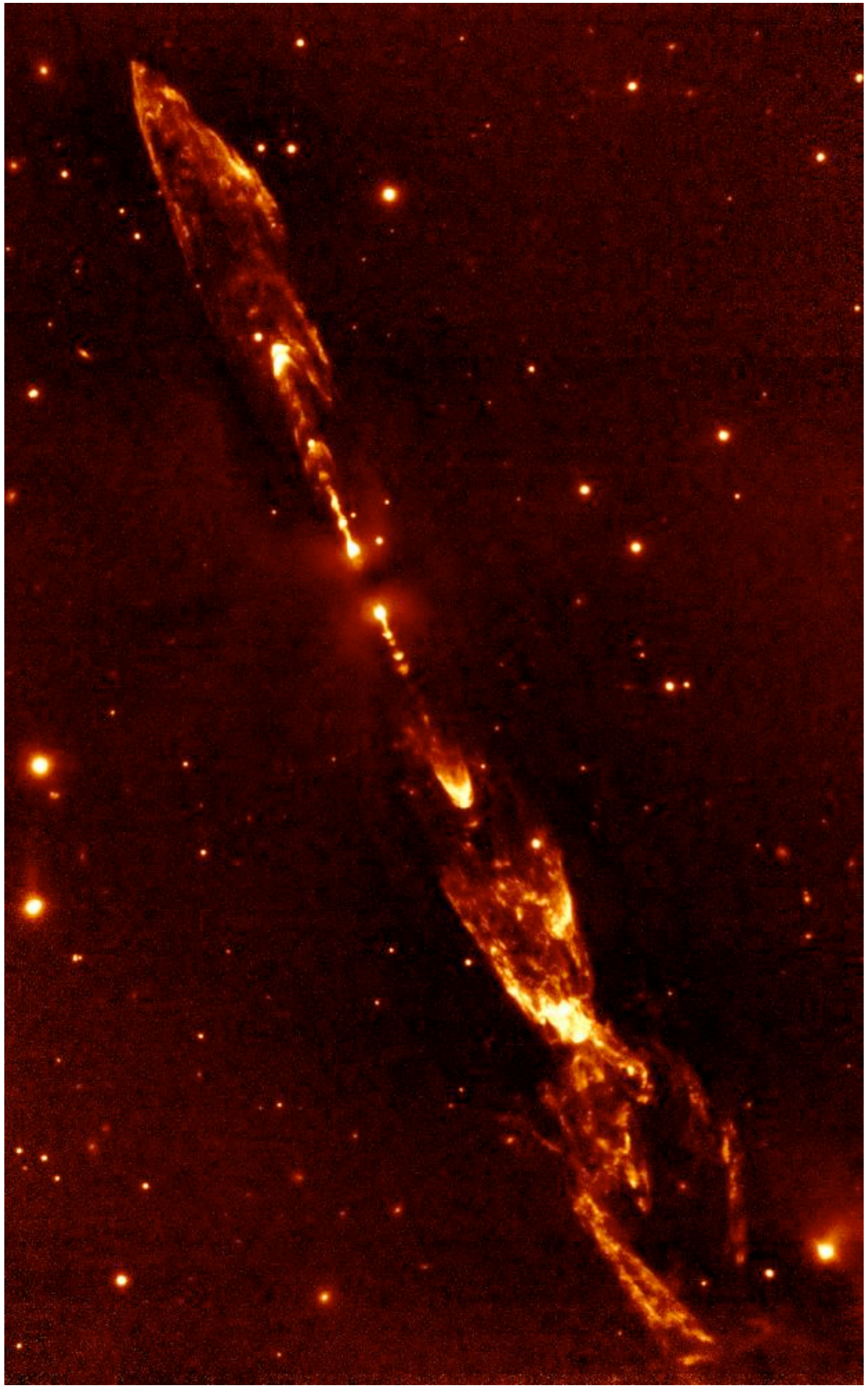

Protostellar outflows: Dynamics and chemistry

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cnrs

Outline

- General properties of outflows
  - Open issues
  - Swept-up flows and cavities
  - Molecular jets
- Shock modelling as a diagnostic tool
  - Total flow power
  - C vs J-type shocks vs. Obs
  - Shock chemistry vs. Obs
  - Jet chemistry
- Conclusions

General outflow properties

- Although unanticipated by early theories of star formation, outflows turned to be a ubiquitous phenomenon (Herschel confirmed!)
  - In all phases with accretion : from Class 0 to Class II
  - at all luminosities from < 0.1 $L_{\odot}$ to 10^5 $L_{\odot}$

- Tightly linked to accretion and very powerful: role in star formation ?
  - Limit the % of core mass going into star ?
  - Remove excess angular momentum from accretion flow? Cf. Simulations of rotating MHD collapse (eg. Banarjee & Pudritz 2006, Machida et al. 2009)

- Propagate over large distances (> 1 pc)
  - Modify cloud chemistry and dust properties ?
  - Source of turbulence for the ISM ?

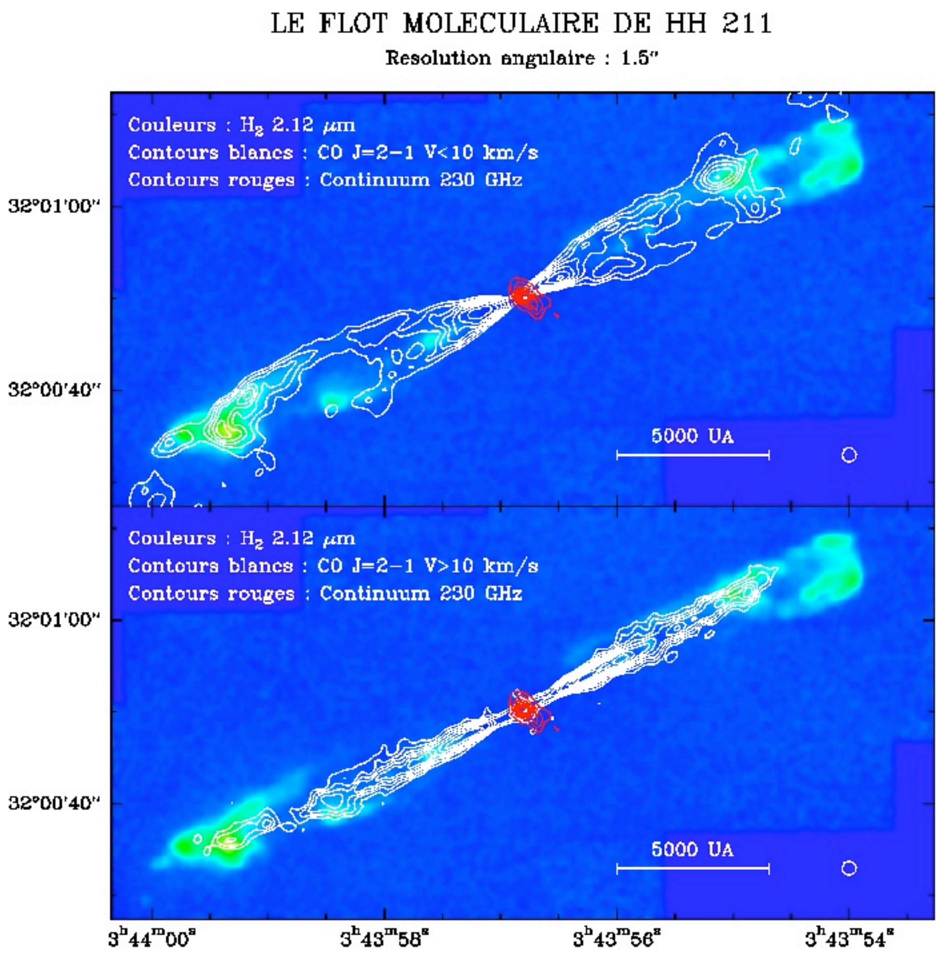
To answer these questions…

- To answer these questions one needs to clarify
  - primary wind origin (star ? disk ?), collimation, and interaction with disk and envelope
  - total wind power versus accretion/rotation power, and transfer of momentum to cloud
  - Outflow chemistry (gas and grains), shock geometry, and postshock mixing into cloud

Molecular CO outflows (Class 0/I)

- Interferometric maps ➔ Two velocity regimes, with different morphologies
  - Slow cavity (SHV) < 10 km/s
  - Fast jet (EHV) > 10-50 km/s.
  - jets seem less frequent in massive protostars

- Reviews on CO outflows:
  - Bachiller & Tafalla (1999) Richer et al. (2001), Arce et al. (2007)

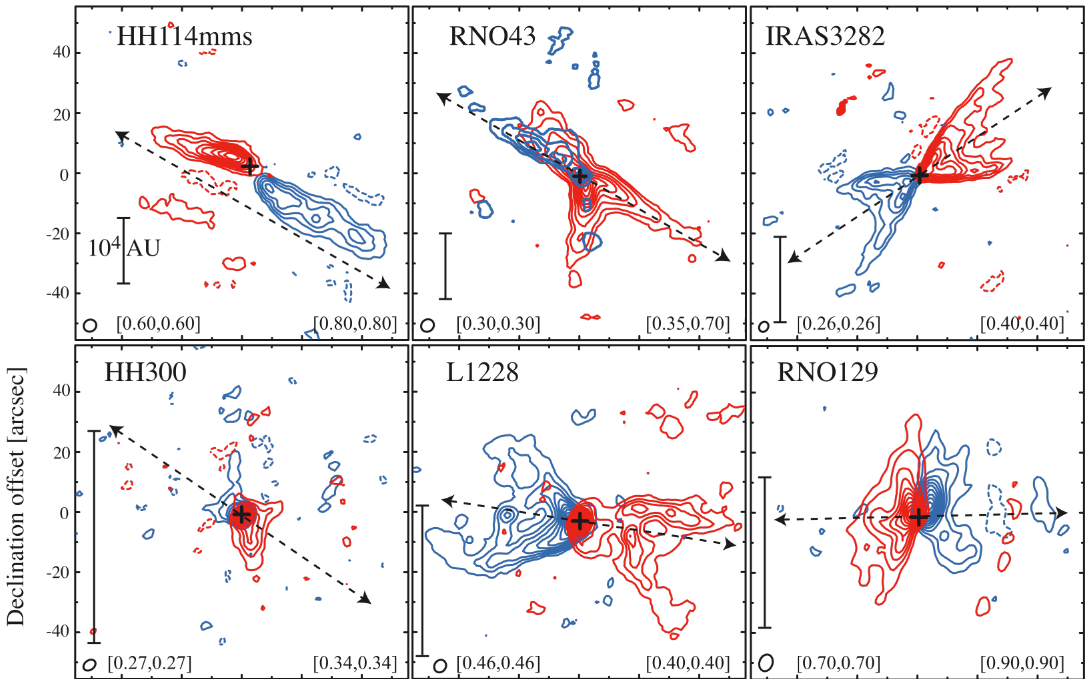


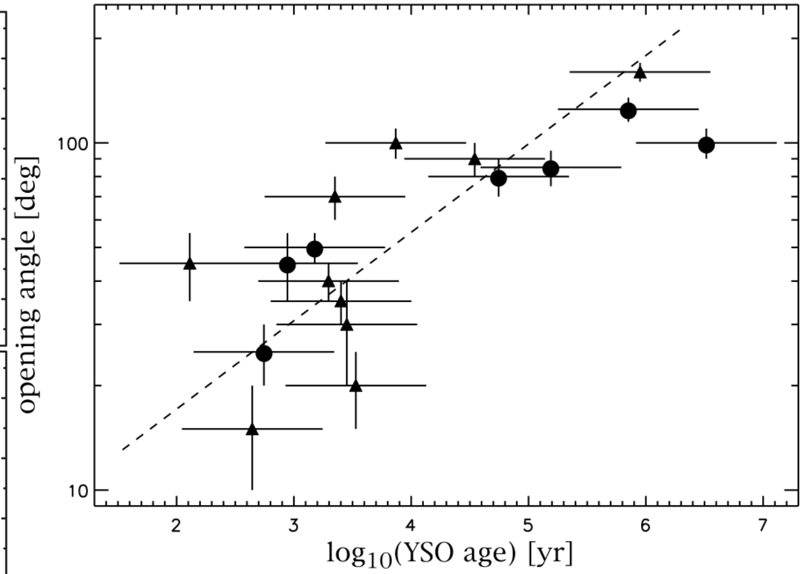
PdBI IRAM
Gueth et al. 1999

Outflow impact on envelope

(see Arce & Sargent 2006; Arce etal 2007 PPV)

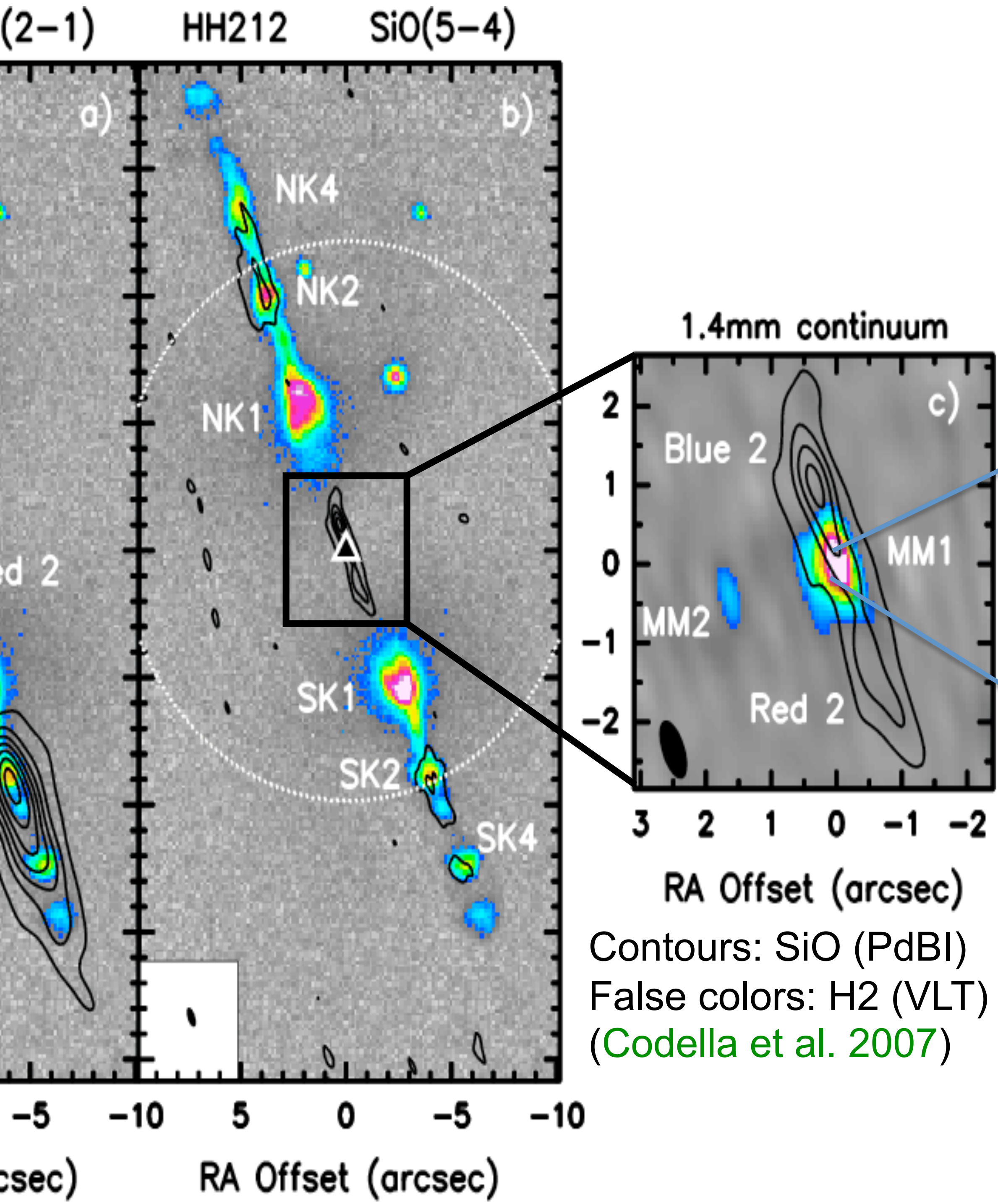
- Signs of interaction (V-gradients along flow) in dense gas tracers: entrainment rate of a few 10^{-6} Mo/yr;
- CO Cavity opening with « age » (Tbol, class) ➔ But it is the cause or consequence of infall decline ?



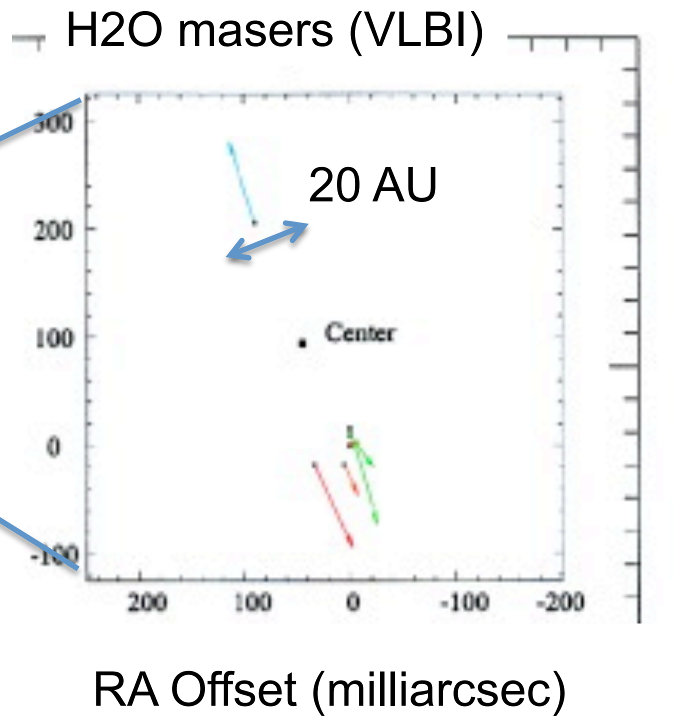


Arce & Sargent 2006

HH212 width

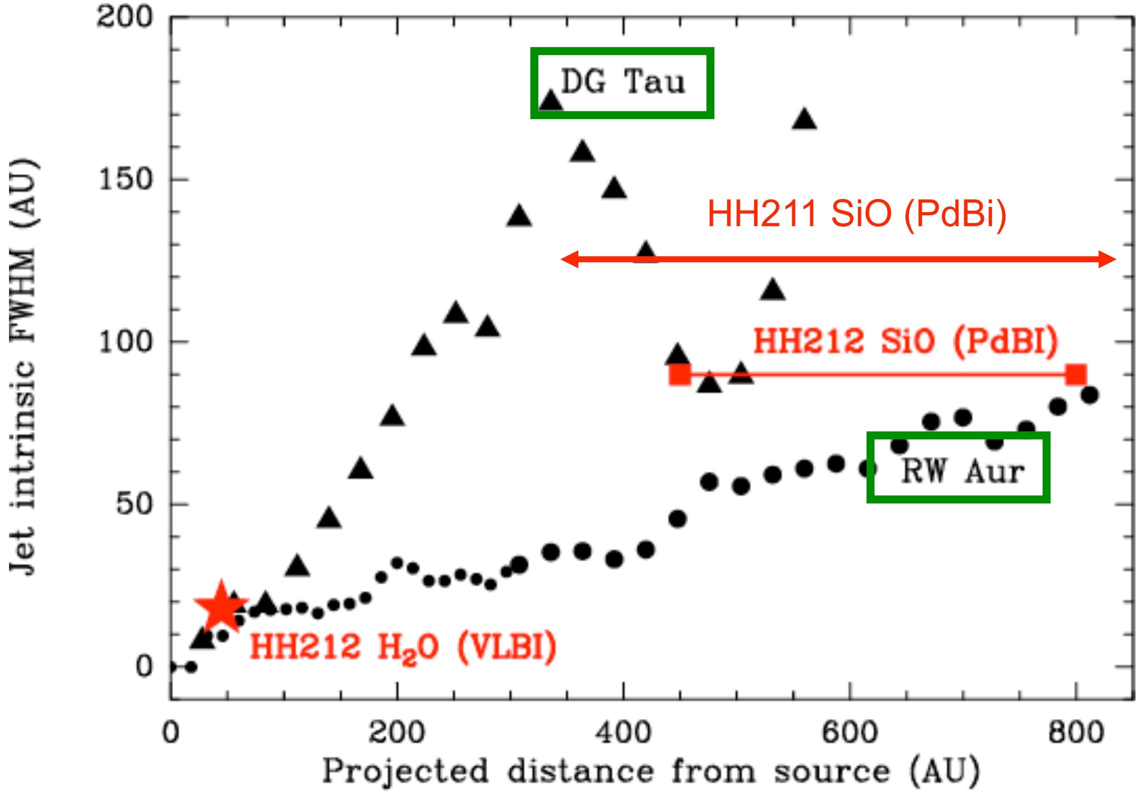


Contours: SiO (PdBI)
False colors: H2 (VLT)
(Codella et al. 2007)



(Claussen et al. 1998)

Molecular vs atomic jet width



Cabrit et al 2007

HH211 + HH212 : Class 0

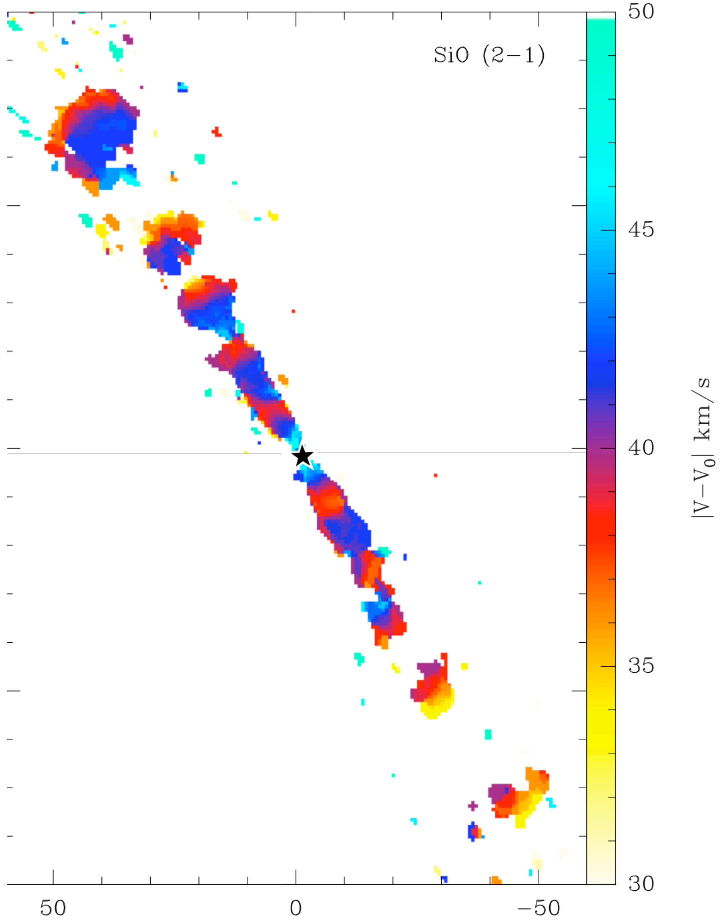
DG Tau + RW Aur: Class II
(Dougados et al. 2000)

Same collimation process from Class 0 to Class II = MHD

Jet appears collimated inside a radius of 10 AU at z = 50 AU

Molecular jet power

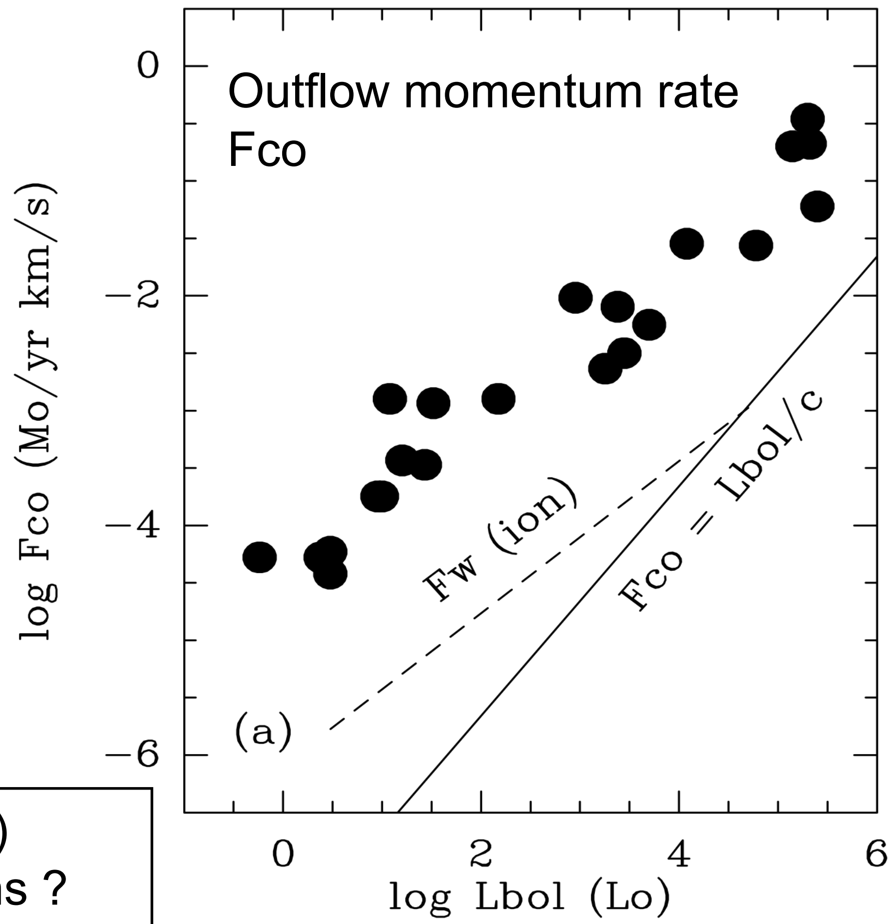
- Proper motions in HH212: Water masers ~ 60 km/s, H2 knots 150-200 km/s
- Deprojected bullet CO speed in HH111 = 240 km/s (Vrad = 40 km/s, i=80° from for optical)
  - Closely related to primary wind
- Bullets/knots = Internal shocks due to time variability
- Time-averaged mass-flux a few 10^{-6} Mo/yr = M(bullet)/dt
  - Lw = Mdot Vw^2 comparable to Lbol ! (Cabrit 2002, Lee etal 2010)
- Sufficient to push outflow ?
  - Wide-angle component necessary to expand cavity ?
  - How much additional power ?
  - Outer part of jet ? (X-wind, disk wind)

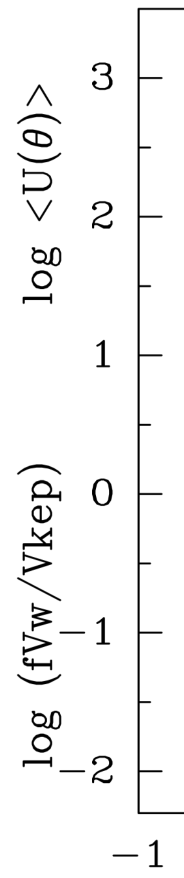


Santiago-Garcia et al 2009

Constraints on total wind power ?

- M(co) >> M* ➔ Mostly swept up : Integrated P and Ek deposited by « primary wind » over time
  - Momentum injection *rate Fco* correlates well with Lbol (Cabrit & Bertout 1990)
  - If momentum conserved , suggests Mw / Macc ≥ 0.1 and Lw up to Lbol (cf. Richer et al. 2001)
  - effect on star formation ?



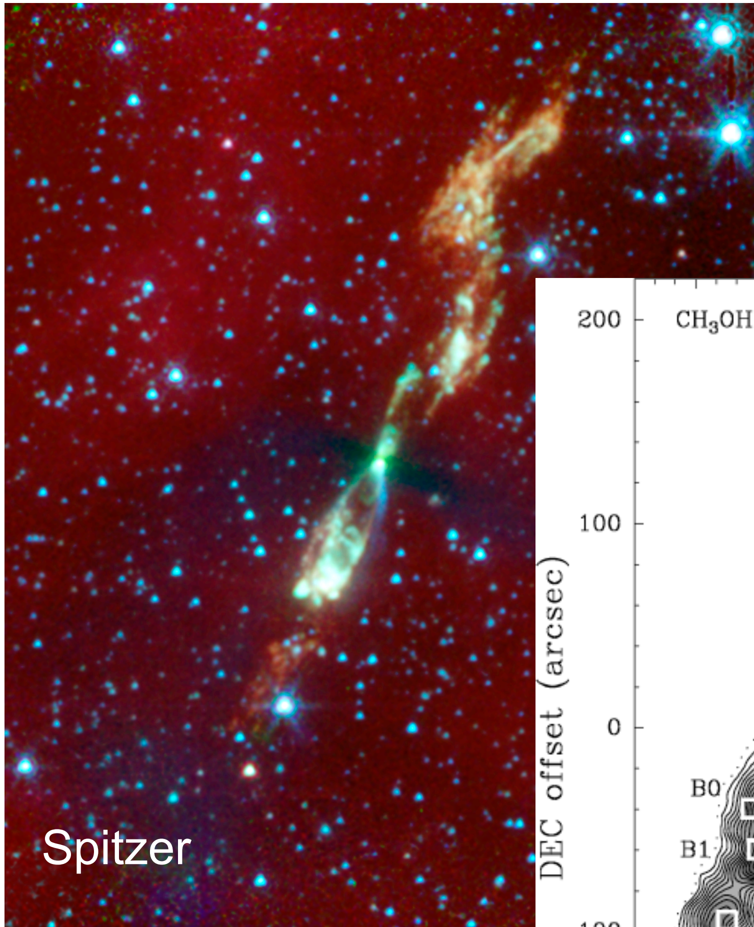


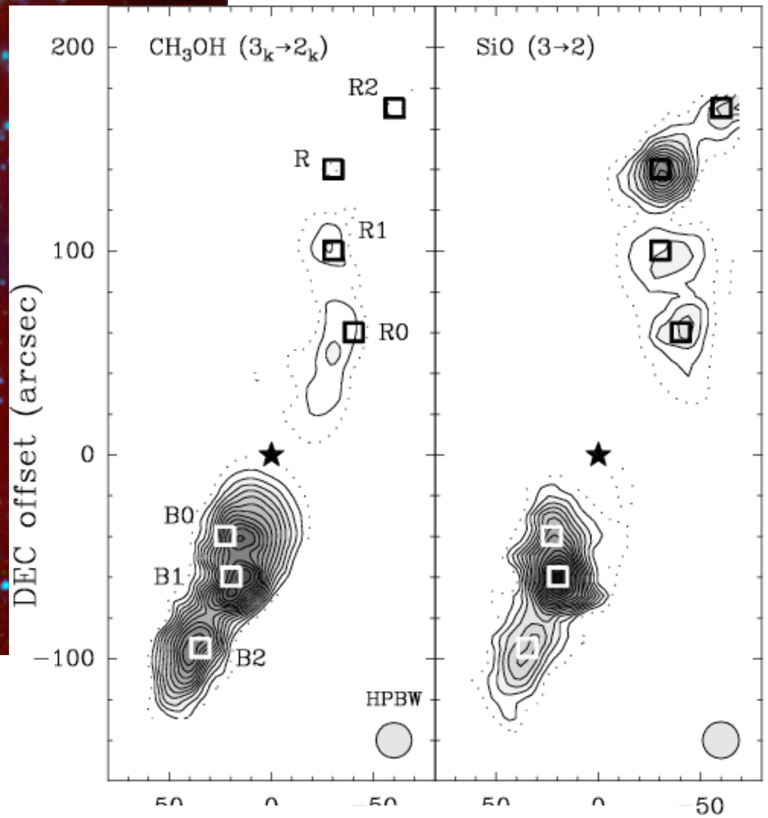
- Concerns (cf. Downes & Cabrit 2003, 2007)
  1- Wrong CO ages / inclination corrections ?
  2- Missing momentum in dissociated gas ?
  3- Momentum-driven or energy-driven cavity?

Need to study outflow entrainment process directly

Evidence for shocks in outflows

- Localized heating
  - H2 emission: T 2000 K – 800 K
  - NH3: 100 K
  - CO high-J: 300 K
- Chemical enhancements by orders of magnitude
  - « Grain » species: SiO, CH3OH, H2CO, NH3
  - Gas phase: SO, SO, HCN, CS..
- Water !
  - SWAS, ODIN, Herschel



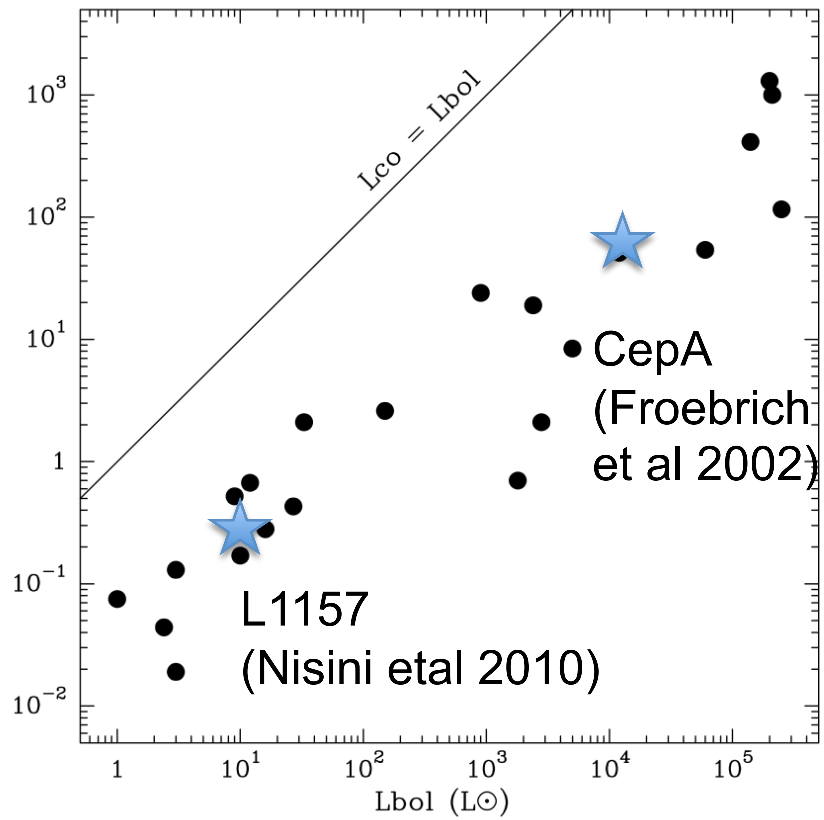


L1157 (Bachiller et al. 2001)

Molecular cooling budget in flows

- ISO : first measures of main molecular coolants in shock heated gas (cf. Giannini et al. 2001):
  - Lrad (CO + H_2O + H_2) ~ Lmech (CO cavity)
  - ➢ outflow age $t_{co} = R_{co}/V_{max}$ is ok
  - ➢ Concern 1 (tco) removed..

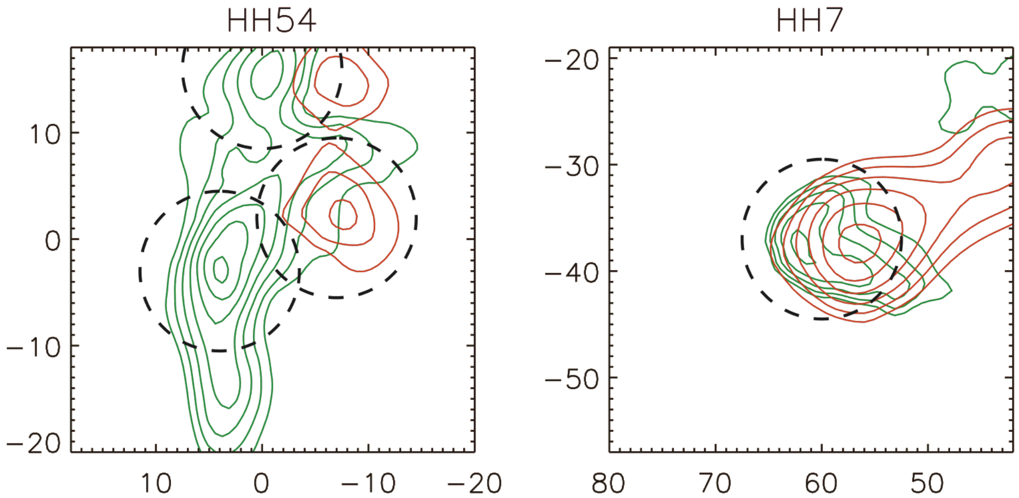
Lmech(co) = ½ Mco Vco² / tco



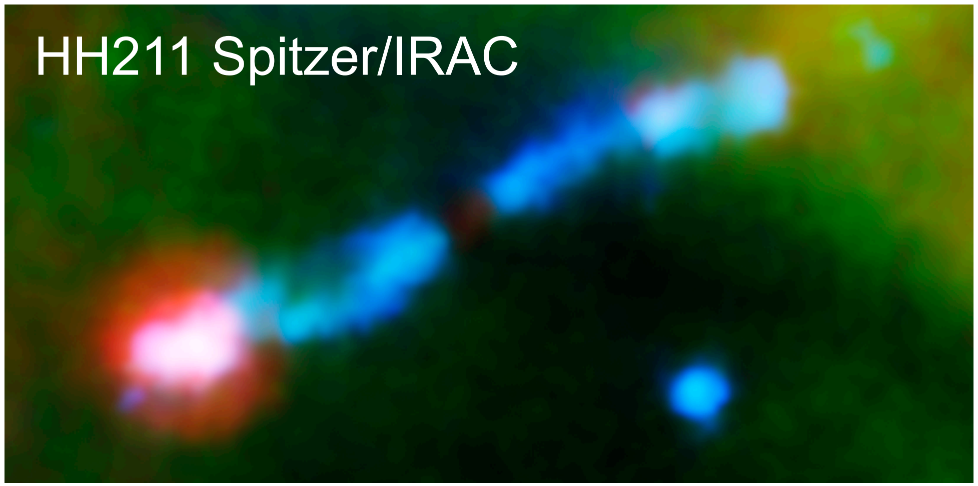
Location of dissociative shocks

- Spitzer: Fe+, Si+, Ne+ , OH (photodisso H2O)
- Offset behind bowshock : radiative wind shock (40-80 km/s)
- Confirm momentum-conserving jet-cloud interaction
  - Concern 2 removed
- NB: Herschel: [OI] at 63mic as mass-flux probe in dissociative shocks
  - but mind contribution of internal jet shocks..
- Dissociative shocks restricted to flow axis:
  - Concern 3 removed ?

Green : H2, Red = Ne+ or Si+



Neufeld et al 2006



Testing shock physics & chemistry
Molecular shock model
(Flower & Pineau des Forêts, 2003, 2010)

- Plane-parallel (1D), multi-fluid model

- Integrate steady MHD equations & non-equilibrium chemistry & heating (ion-neutral drift) & cooling (atomic and molecular radiation) along shock

- ro-vibrational level populations of H_2 , H_2O, CO, CH3OH, integrated in parallel

- 136 species included, 1040 reactions

- Grain physics – sputtering of mantles and erosion of core

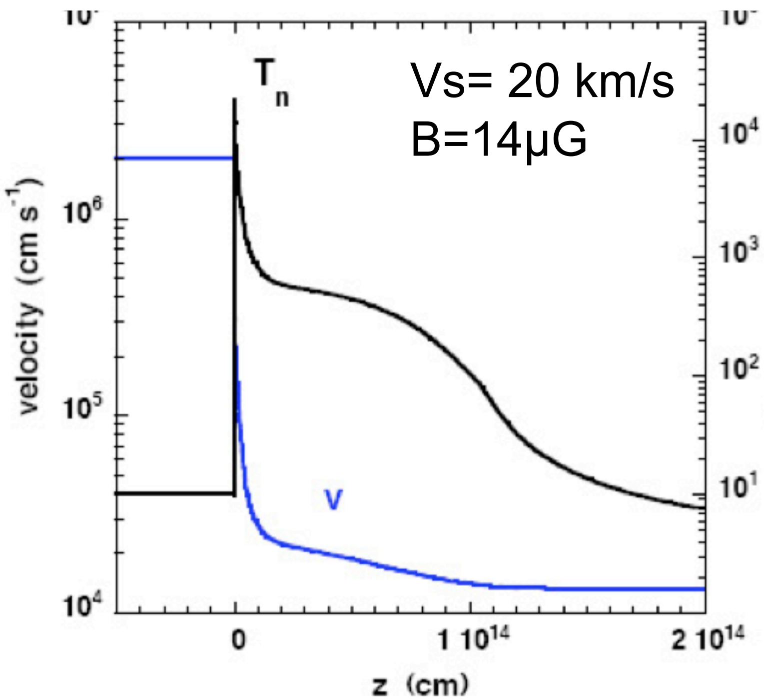
- Grain-gas collisions: narrower & hotter shocks than Kaufman & Neufeld (1996)

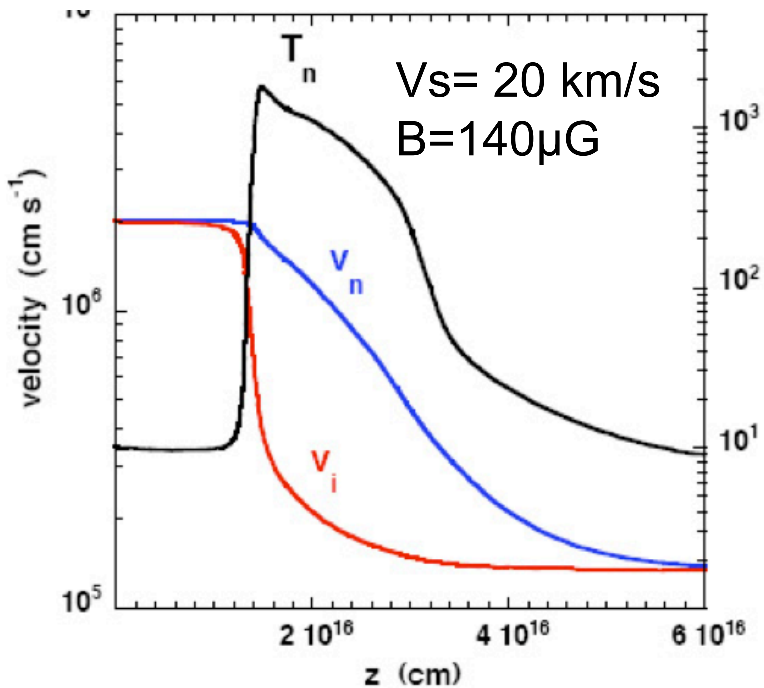
J-type vs C-type shocks

Draine (1980), Flower et al. (1985), Smith (1991), Kaufman & Neufeld 1996

• **V > Vcrit (B)**
J (Jump)-shock = monofluid
Fast dissipation by n-n collisions
High Tmax α V^2

• **V < Vcrit(B)**
C (Continuous)-shock = multifluid
Slow dissipation by n-i collisions
Lower Tmax (H_2 cooling)



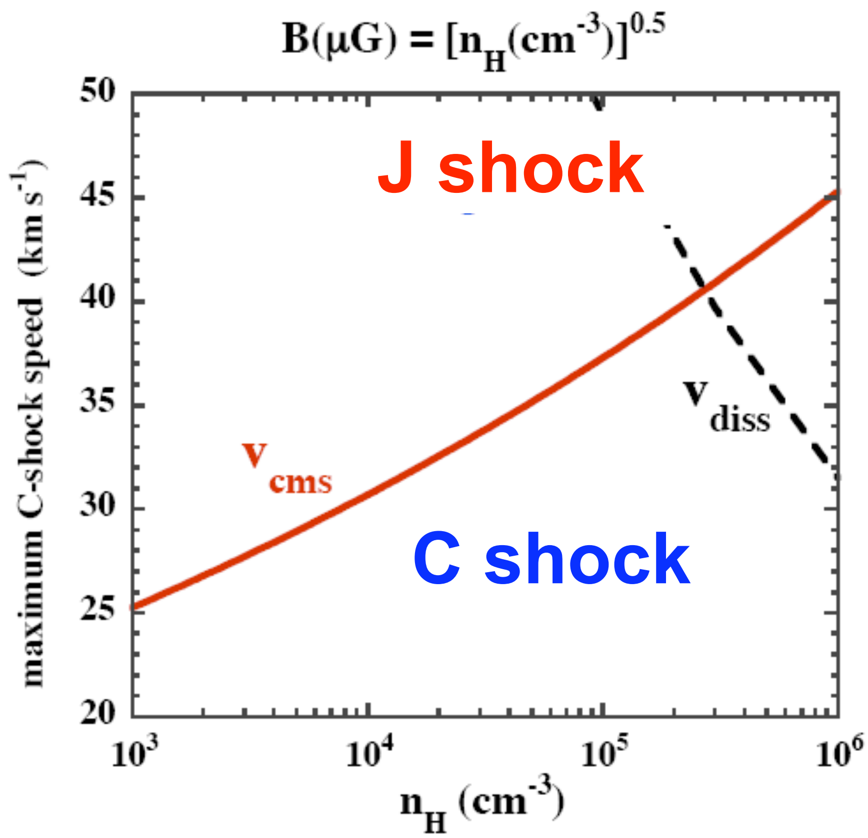


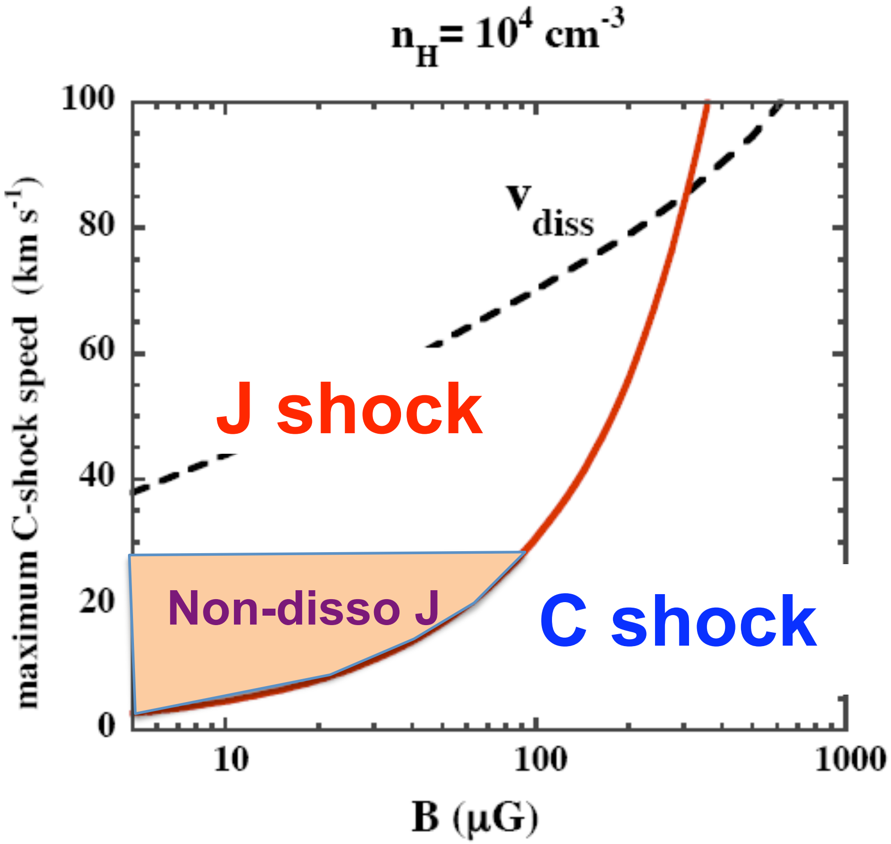
Maximum Velocity for C-shocks

Maximum critical velocity for C shocks

- $V_s < V_{diss}$ dissociation of H_2 *(Le Bourlot et al 2002)*
- $V_s < V_{cms} \propto B_\perp$ magnetosonic speed in charged grains

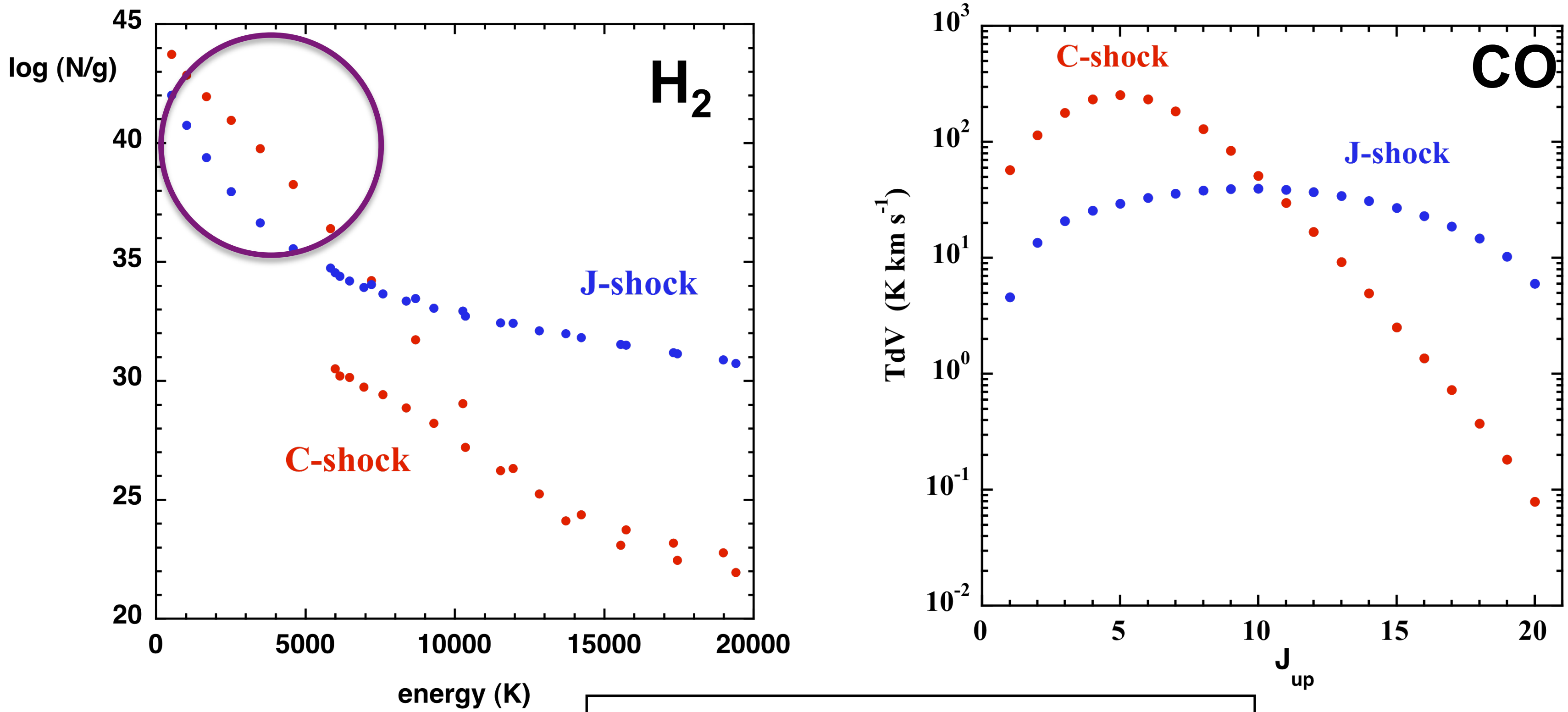
(Flower & Pineau des Forêts 2003)





Molecular cooling diagnostics

- molecular cooling budget similar in C-shocks and **non-dissociative** J-shocks with V < 25 km/s *(Flower & Pineau des Forêts 2010)*
- But different distribution among lines

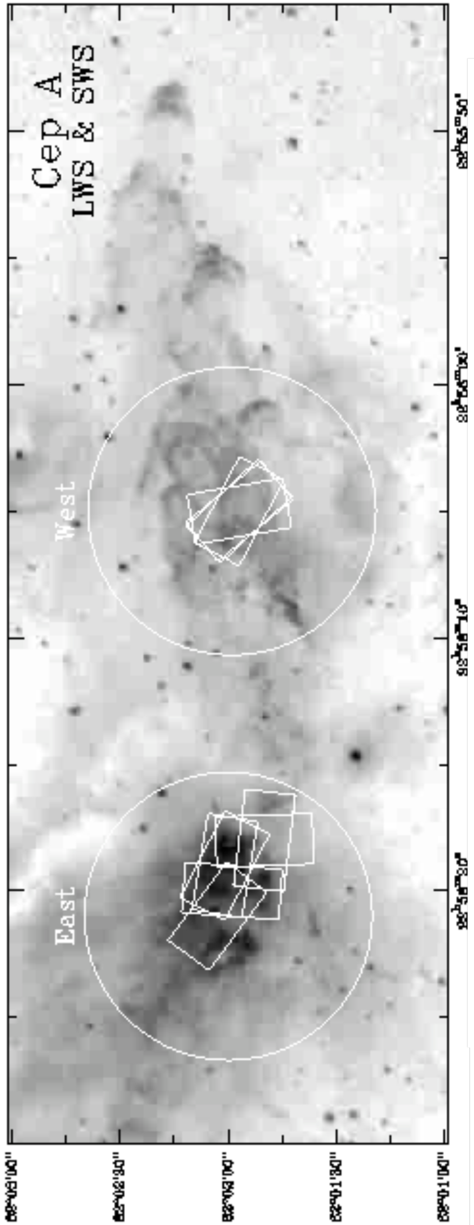


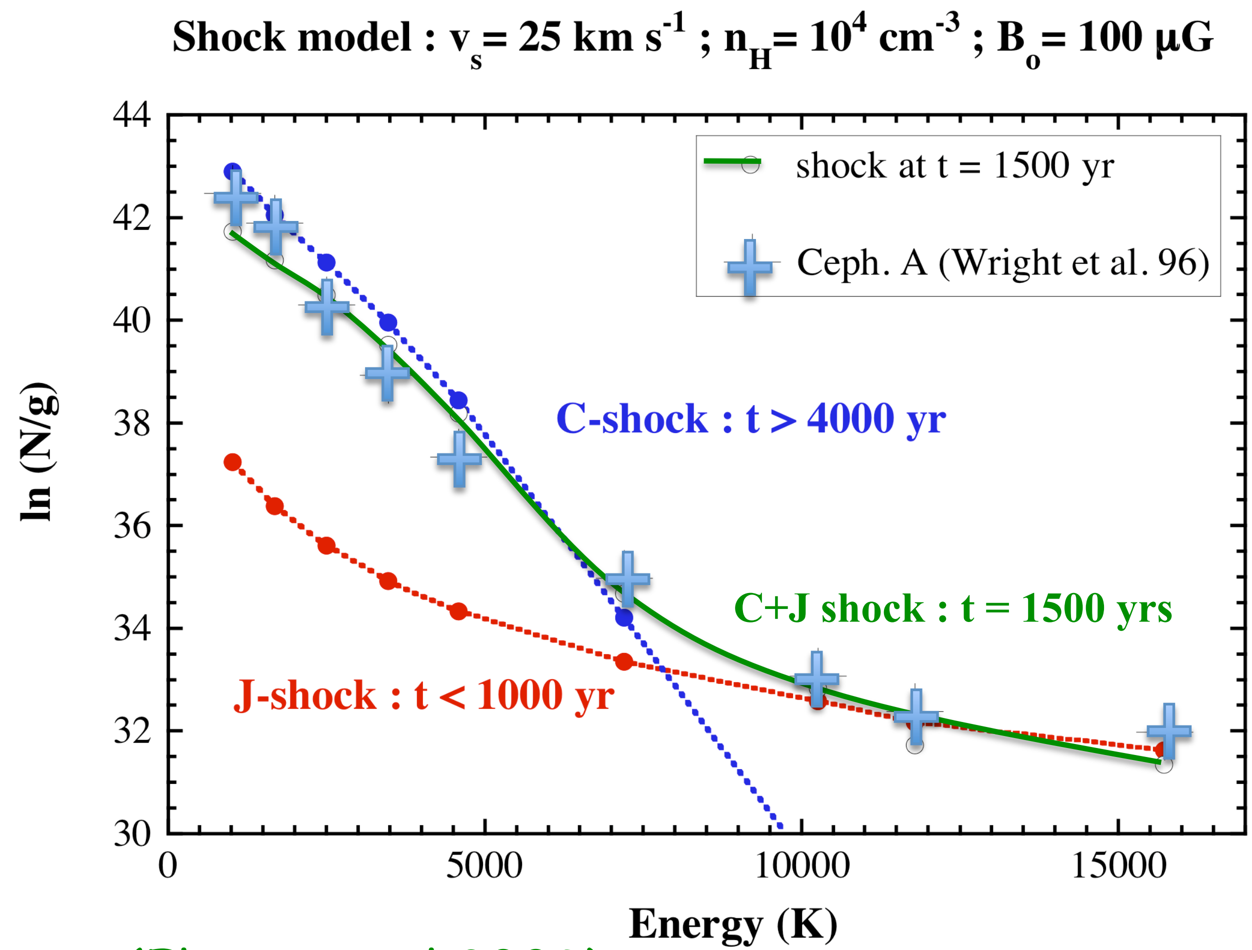
nH = 2 10^4 cm^{-3} Vs= 20 km/s

Evidence for C-type shocks in outflows

- H_2 pure rotational lines, and CO high-J excitation (ISO, Spitzer)
- Thickness of H_2 2.12mic bowshock in Orion
- Chemical richness
- H_2O abundance versus temperature

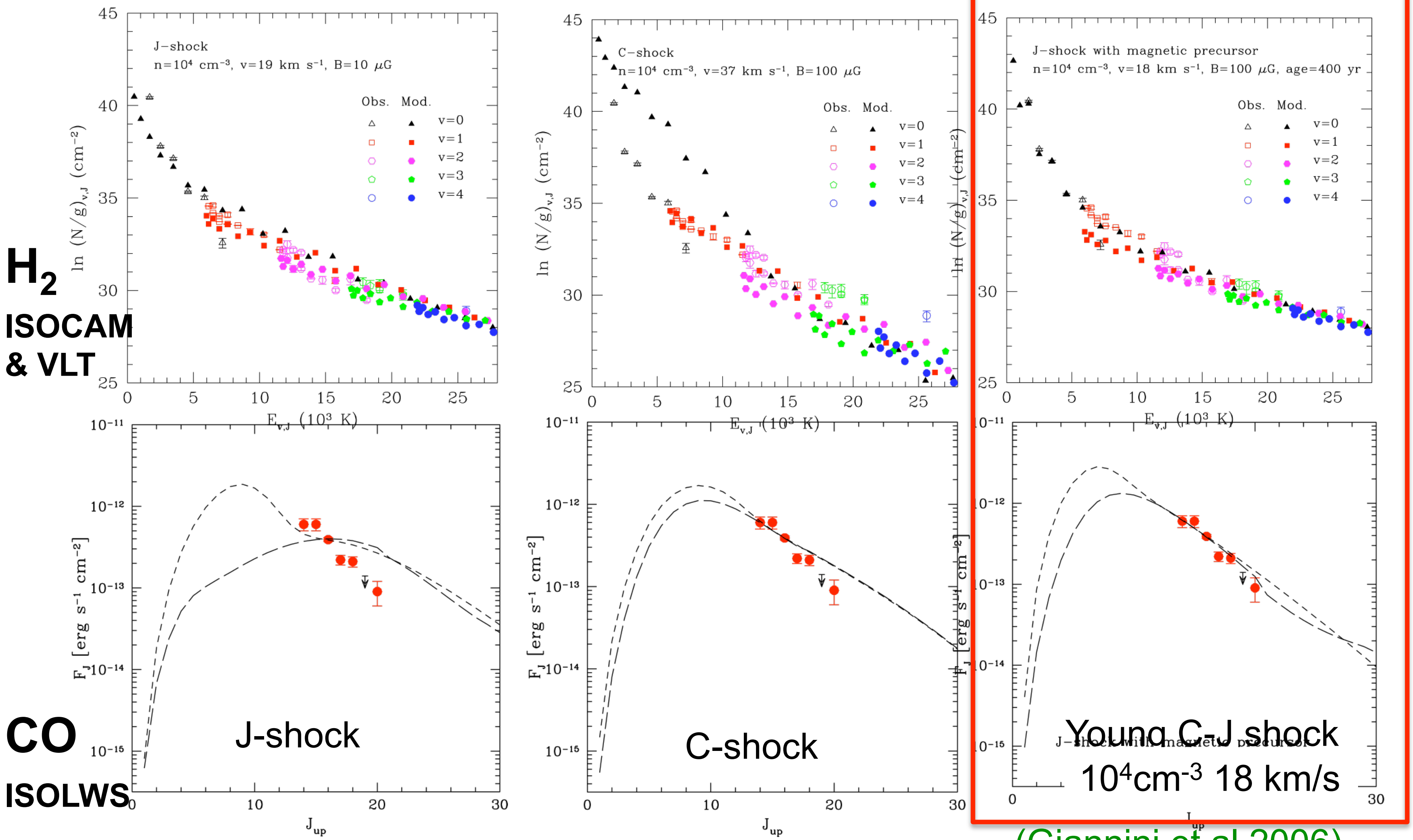
Evidence for C-precursors: H_2 pure rotational lines in molecular flows (ISO, Spitzer)





(Flower et al 2003)

HH 54



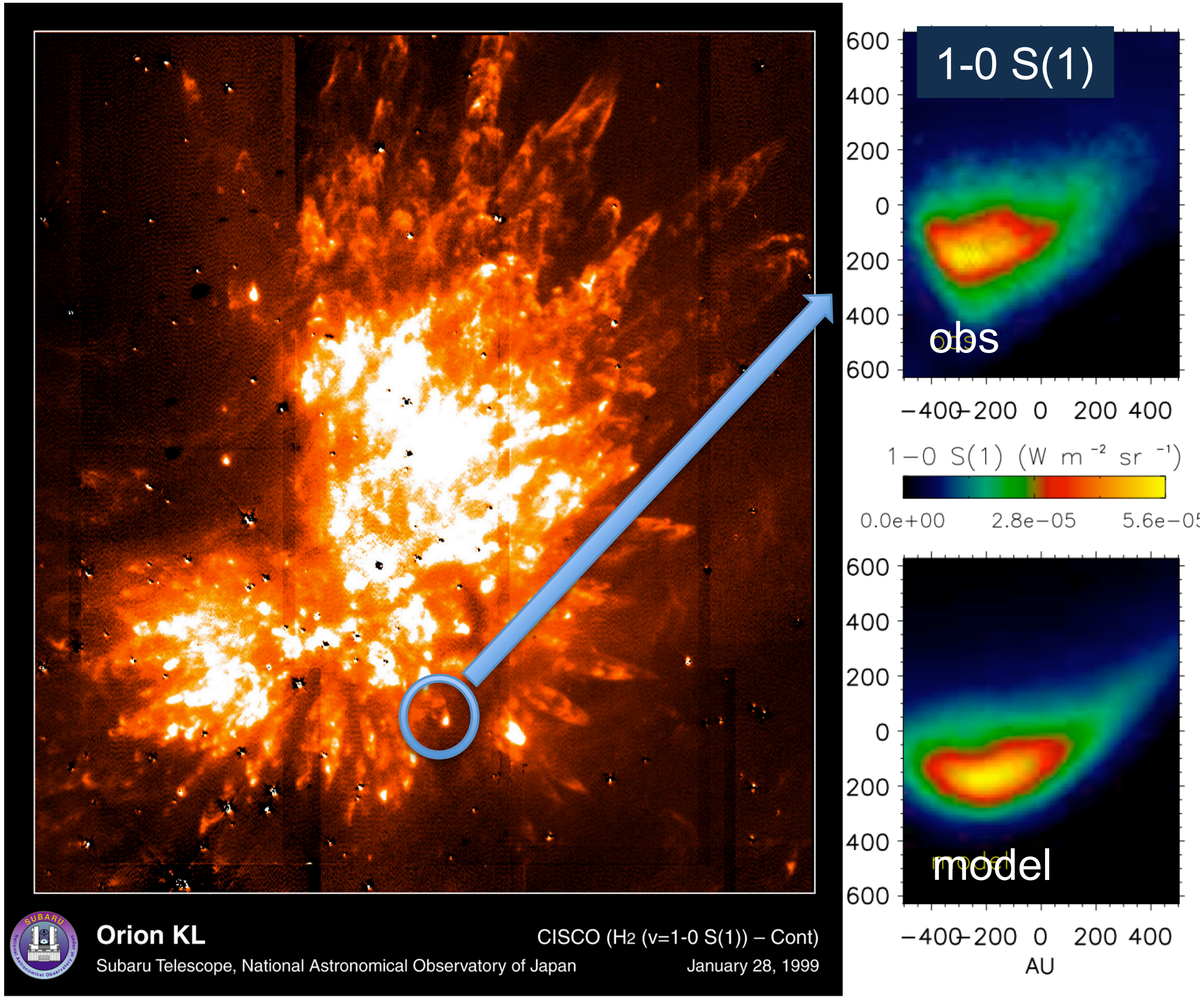
(Giannini et al 2006)

Resolved H_2 precursor in Orion

- Fit thickness and brightness in H2 v=1-0 along bow surface
- Kristensen et al. (2008): 2D model
- Gustafsson et al. (2010) Grid of 2.5D bow models with projection effects

➔ C-shocks needed

Strong B/sqrt(nH) ~ 3 agrees with polarization obs

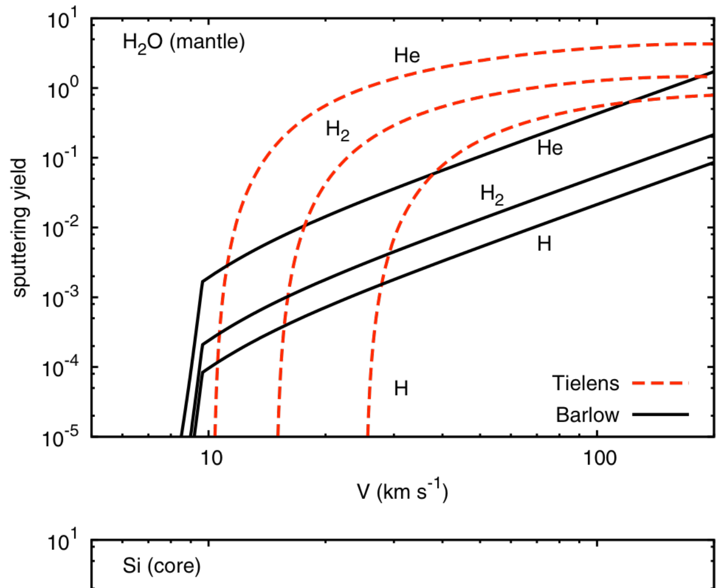


Water chemistry in C-shocks

- Gas-phase endothermic reactions *(cf. Kaufman & Neufeld 1996)*
  - O + H2 ➔ OH + H (Tc= 2980 K)
  - OH + H ➔H2O + H (Tc= 1490 K)
  - Complete for Vs > 15 km/s
  - Rapid: Timescale a few 100 yrs

- Dusty shocks: Sputtering of ice mantles by grain-neutral drift *(Caselli etal 1997, Flower & Pineau des Forêts 2010)*
  - Threshold at dV > 10 km/s

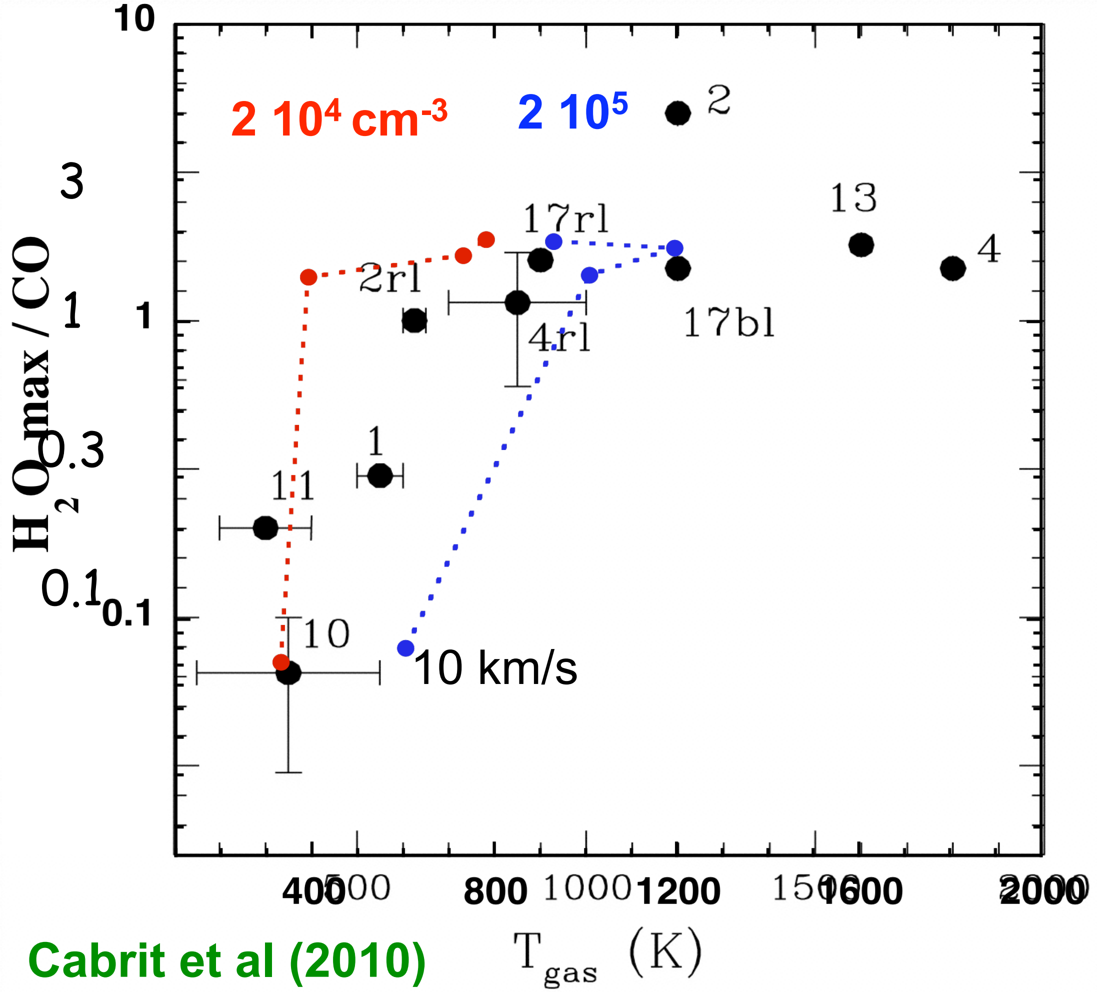
  ➔complete only for Vs > 20 km/s



H_2O abundance vs $T(H_2O)$

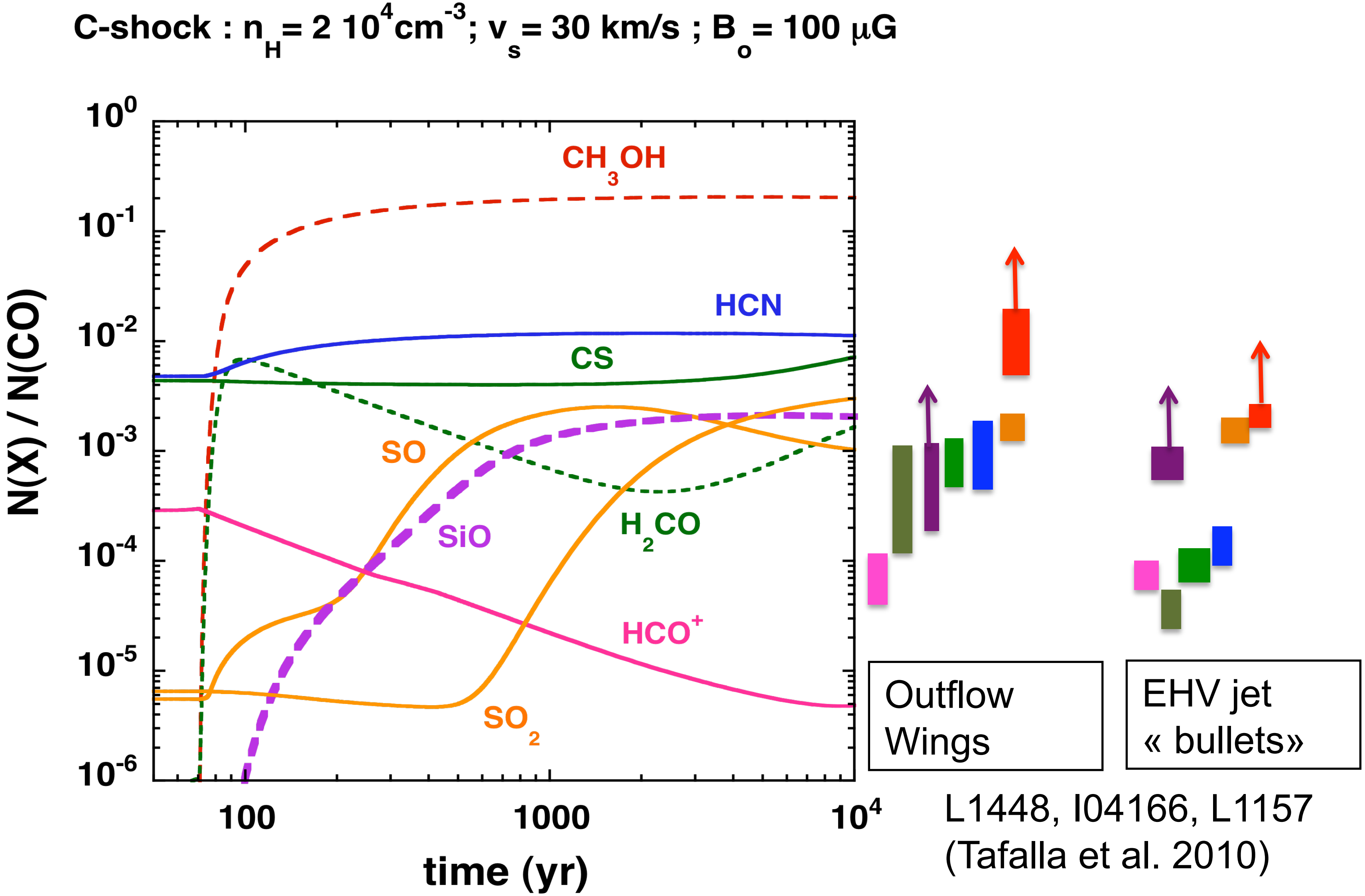
X(H2O)/X(CO)

- ISO results of Giannini etal (2001): T and N(H2O)/N(CO) from LVG fits
- Excellent agreement with C-shock models of Flower & Pineau des Forêts 2010



Cabrit et al (2010)

Overall comparison with observed abundances



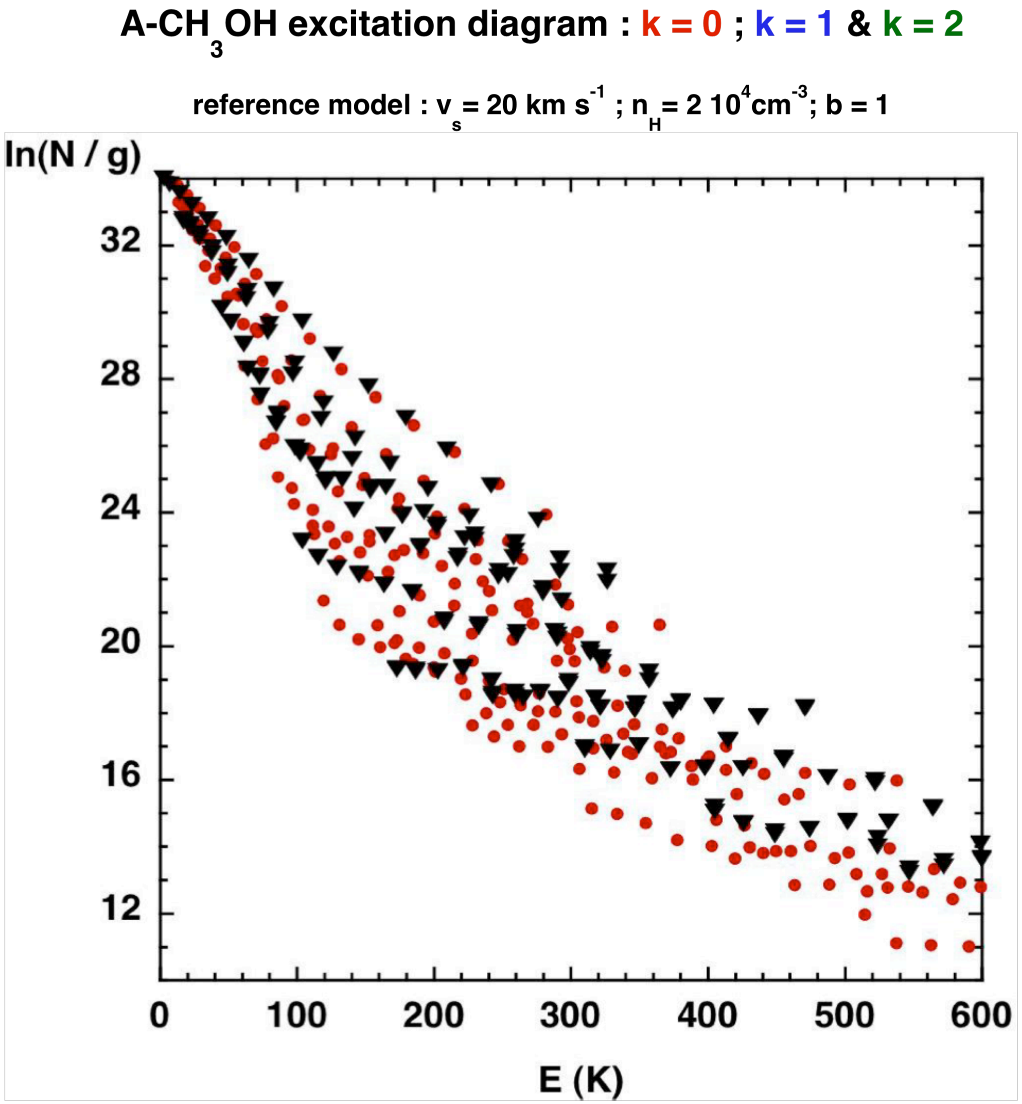
L1448, I04166, L1157
(Tafalla et al. 2010)

CH3OH in C-shocks

- Pure « mantle » species (no gas-phase route)
  - Model with LVG populations solved along flow *(Flower et al. MNRAS 2010, in press)*
    - X(CH3OH*) = 1.86 x 10^{-5} (W33A by Gibb et al. 2000, if CO*/CO = 10%)
    - Assume same sputtering yield as for H_2O ice
  - Extreme sensitivity of X(CH3OH) to Vs < 20 km/s:
    - 10^{-9} (10 km/s) ➔ 6x10^{-7} (15 km/s) ➔ 2x10^{-5} (20 km/s)
    - fit to L1157: low ff, or reduced ice abun ?
  - Strongly subthermal excitation and $\tau > 1$

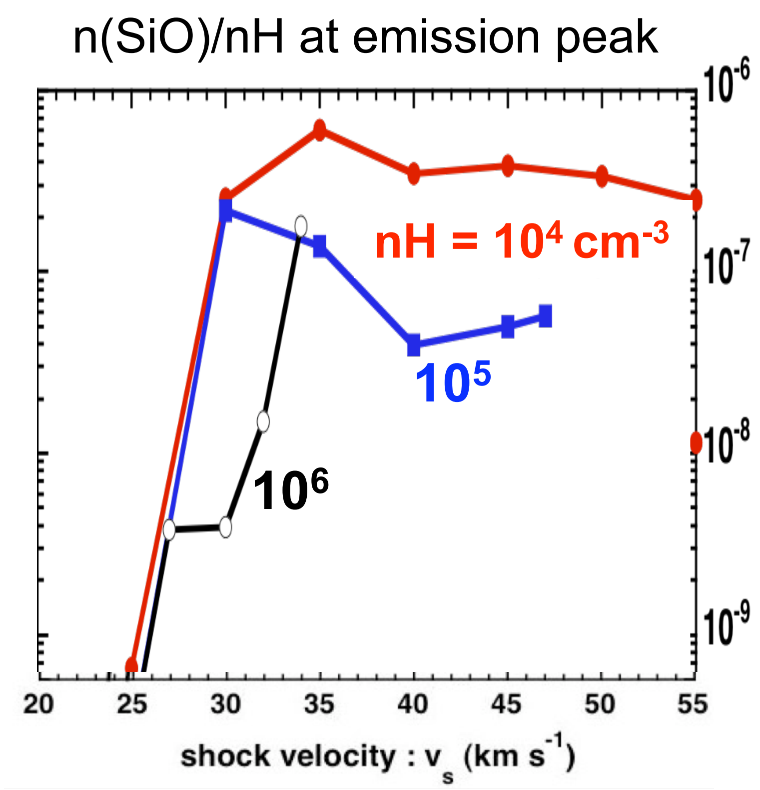
CH3OH excitation diagrams

- Strongly subthermal excitation
  - Different Trot on each K-ladder
  - Strong curvature at high Eup
  - Spread between A-type and E-type
  - Herschel will be a powerful test !
- NB: τ > 10 in some lines underestimate Nup



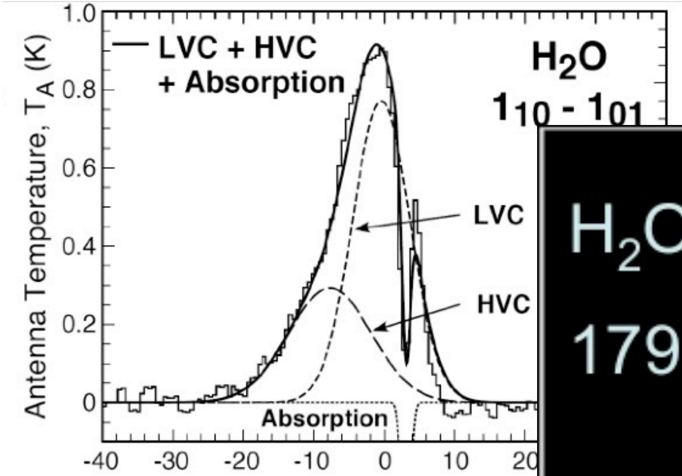
SiO in C-shocks

- Silicate erosion by heavy neutral impact, followed by oxydation of Si into SiO *(Schilke et al. 1998)*
- Erosion for Vs >25 km/s
  - NB: % sensitive to yield (amorphous vs. olivine) and grain-neutral coupling (timescale)
- Oxydation
  - More complete a low nH
  - $X(O_2) < 10^{-5}$ ➔ slow, peaks in postshock *(Gusdorf et al. 1998a)*
    - Optically thick SiO (50 K)

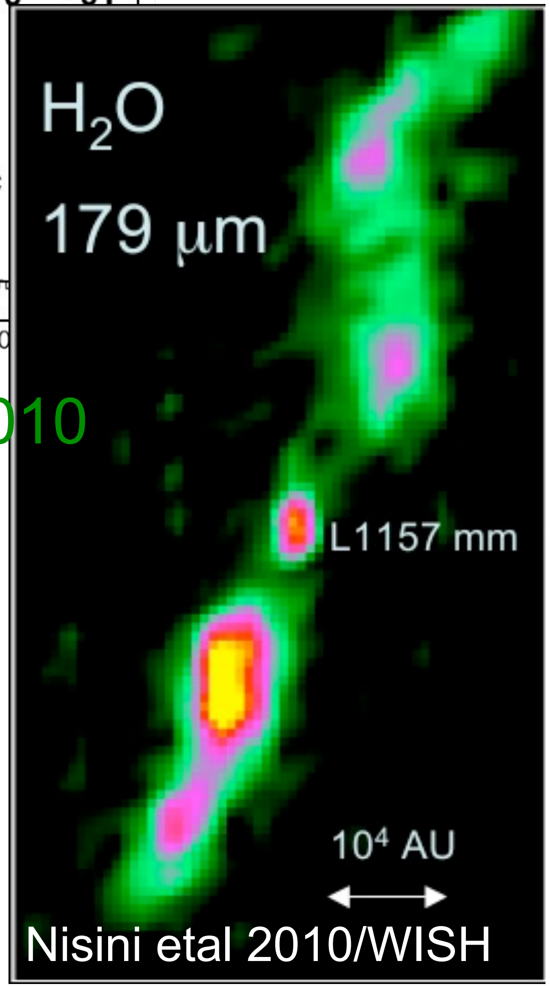


Herschel: a major step

- After SWAS and ODIN, Herschel is revealing the full H_2O (and CO) line profiles
- And the full spatial distribution of H2O and high J CO (PACS/SPIRE maps)
- A challenge for modelers !



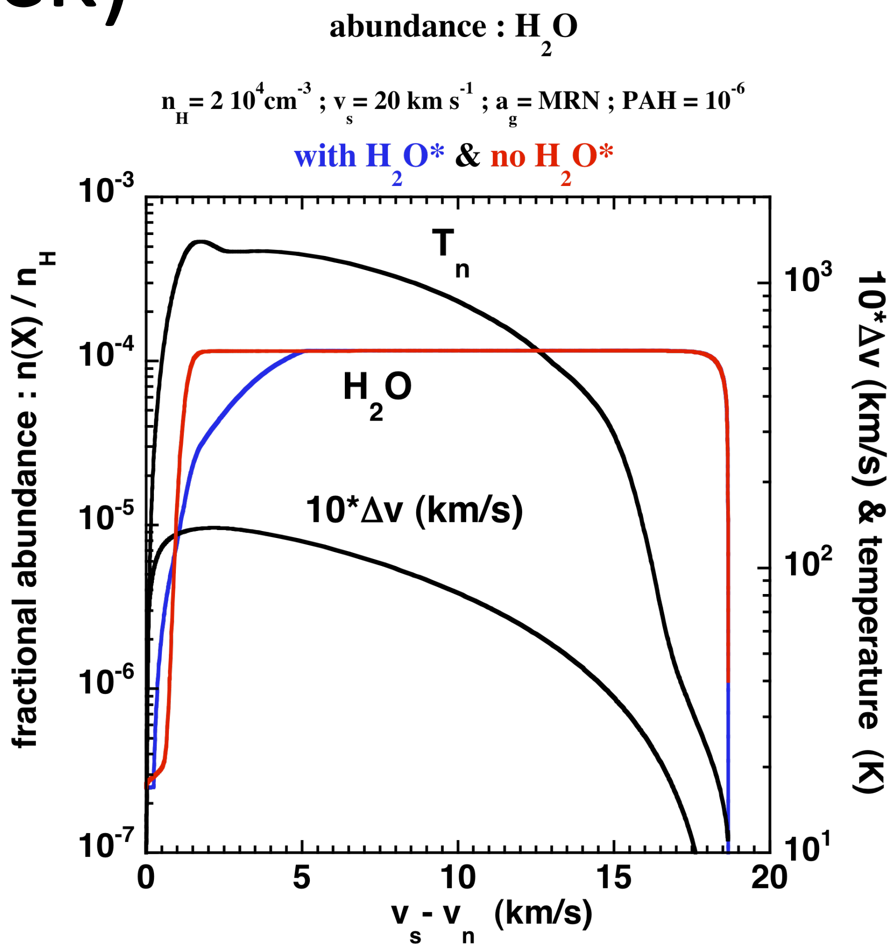
Lefloch etal. 2010



Nisini etal 2010/WISH

Predicted H_2O line profile (planar shock)

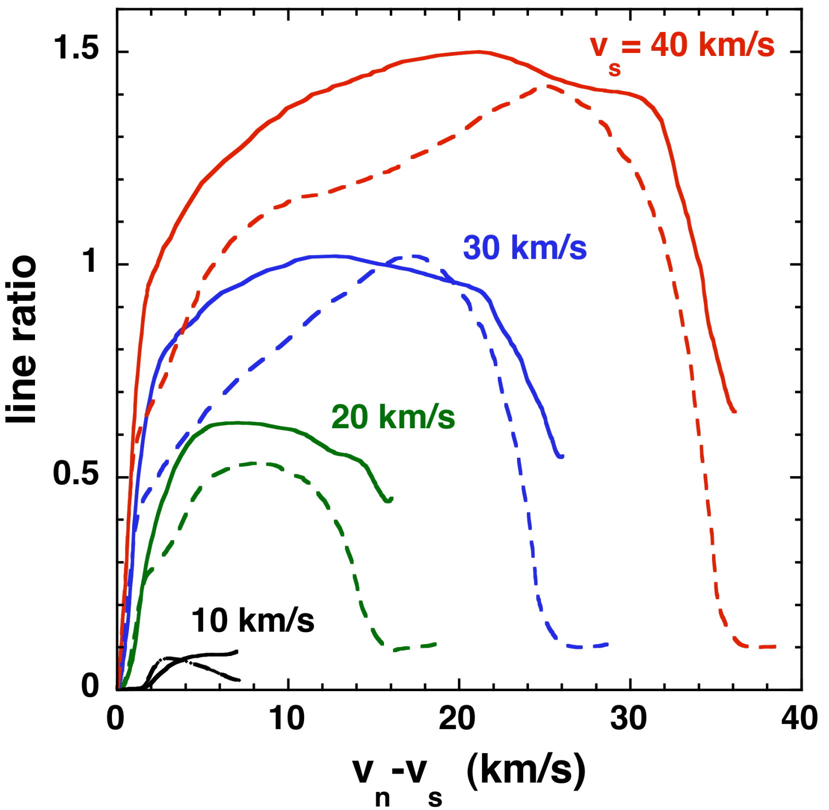
- Gas-phase formation and sputtering both occur at V-Vprechock < 5 km/s (maximum ion-neutral drift)
- Consistent with enhanced CH3OH already at low V in outflows (Tafalla et al. 2010, Codella et al. 2010)

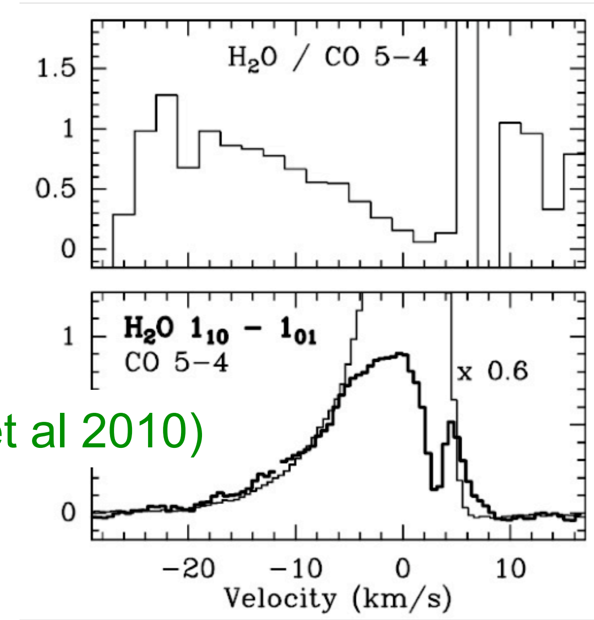


H_2O/CO line profile ratios

C-shocks : line ratio H_2O (557 GHz) / CO (5-4)

$n_H = 2\ 10^4 cm^{-3}$ (full line) & $n_H = 2\ 10^5 cm^{-3}$ (*0.1, dashed line)



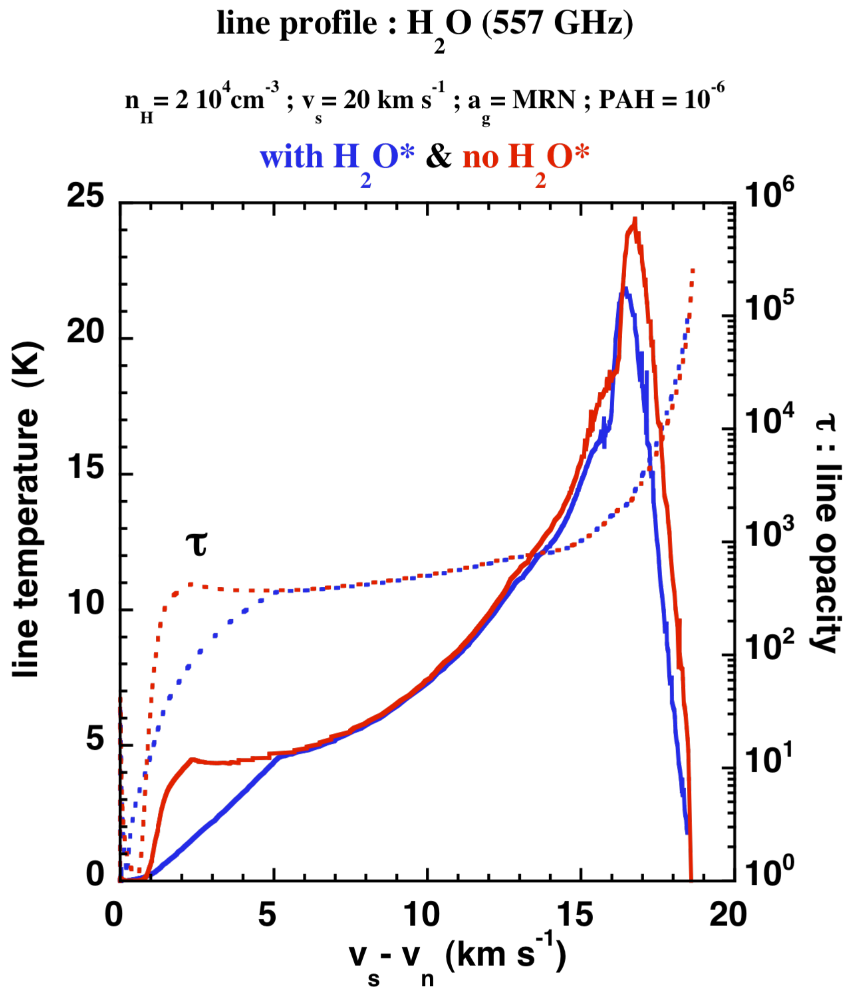


(Lefloch et al 2010)

- Ratio flat or rising towards postshock (high V)
- OK with observed trend (SWAS, ODIN, Herschel) but not as steep: low velocity shocks in same beam ?
- NB: Ratio propto nH ➔ **key parameter to derive water abundance**

Predicted H_2O line profile (planar shock)

- intensity peaks in postshock (denser & more column density per km/s)
- All observations peak at low V
- 2D flow (cf. poster P. Bjerkeli) + range of shock speeds and filling factors (cf. C. Codella) + postshock mixing ?

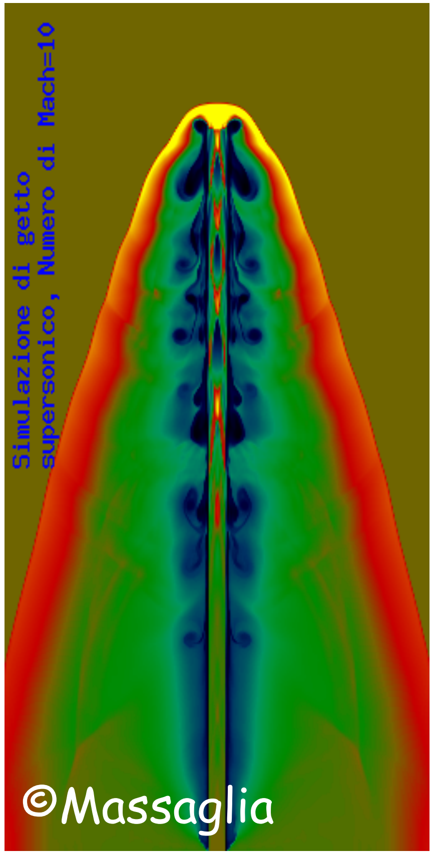


nH = 2 10^4 cm^-3 ; vs = 20 km s^-1 ; ag = MRN ; PAH = 10^-6

Origin of molecules in EHV jets ?

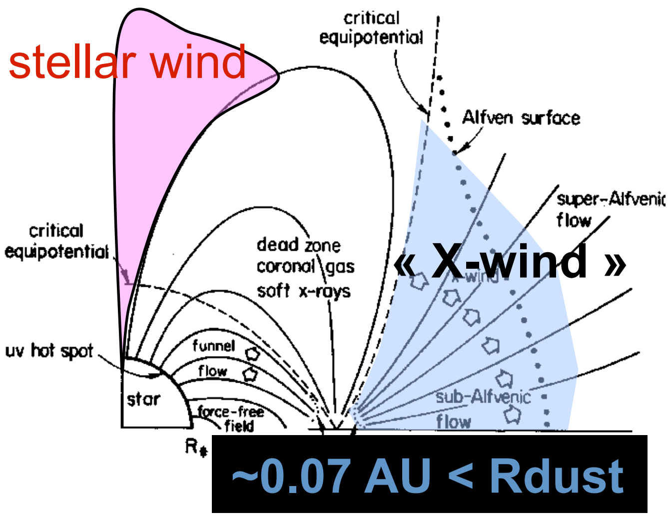
1) Entrainment of ambient gas by shocks/ turbulence

Raga et al. (1995)
Micono et al. (2001)



2) (re)Formation in dense dust-free wind

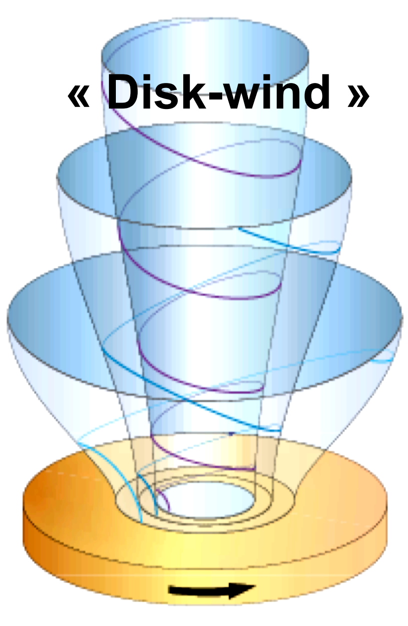
Glassgold et al (1991)
Raga et al. (2005)



Shu et al. (1995)

3) Ejection from molecular disk

Pudritz (1986)
Safier (1993)
Panoglou (2010)



©Ferreira (1997)

Entrained molecules in jet?

- Problems with entrainment of ambient matter :
  - Turbulent entrainment inefficient in a highly supersonic jet; low columns (Taylor & Raga 2005)
  - Not enough material along jet path to explain mass in EHV bullets (eg. HH111, Hatchell et al. 1999)
  - Fast shocks (V > 50 km/s) reform HCN >> SO while opposite is observed in EHV jets (Neufeld & Dalgarno 1989, Tafalla et al 2010)

- EHV components trace the primary wind itself !

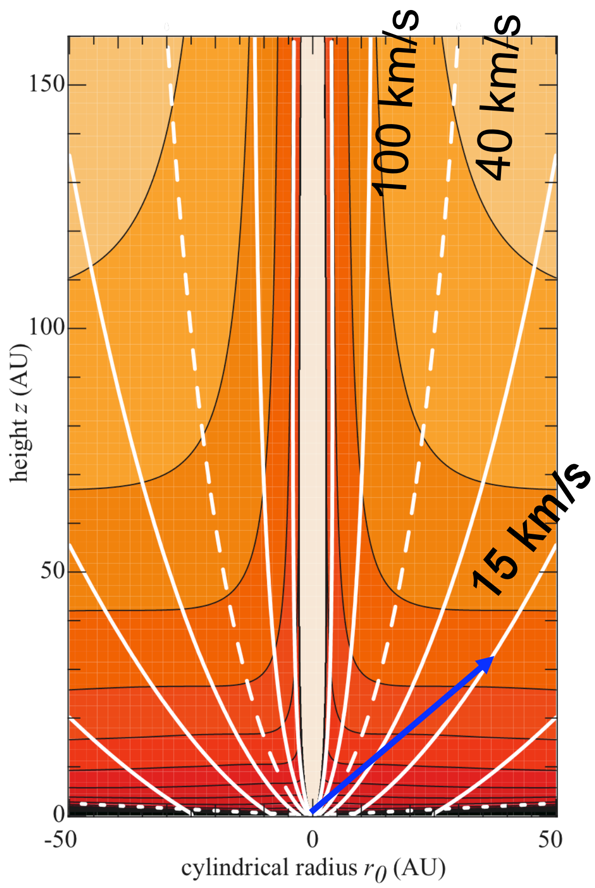
A dust-free protostellar wind?

- Chemistry + Heating by ambipolar diffusion (Ruden et al. 90, Glassgold et al. 91)
  - CO and SiO abundant for Mdot(wind) > 10^{-6} $M_{\odot}$/yr
  - Expect SO and little CS,HCN (Tafalla et al. 2010)
- Shortcomings:
  - Overpredict SiO
  - No dust to form CH3OH
  - H_2 abundant only if Mdot(wind) > 3×10^{-5} $M_{\odot}$/yr >> L1448,HH211 where H_2 is seen in jet (Dionatos et al. 2009, 2010)
  - Evidence for dust in molecular jets, from Spitzer [FeII]/[SI] (Dionatos et al. 2009,2010), or near-IR (Podio etal. 2006)

A dusty molecular disk wind ?

- Time dependent chemistry along MHD disk wind streamlines outside Rsub
-
  - nH, V, J, B, div(V) from MHD disk wind solution consistent with rotation in DG Tau jet (Casse & Ferreira 00):
    - Vp ~ 4 Vkep(r0)
  - Non-equ. chemistry/ ionisation/ heating/ cooling using C-shock code of Flower & Pineau des Forets (03)
  - Vdrift from accelerating JxB force (cf. Safier 93, Garcia etal. 01)
  - Ionisation by (attenuated) stellar X-rays and FUV from accretion shock

(Panoglou et al. 2009; 2010)



Slow wide-angle flow around fast inner jet (cf. Cabrit et al. 1999)

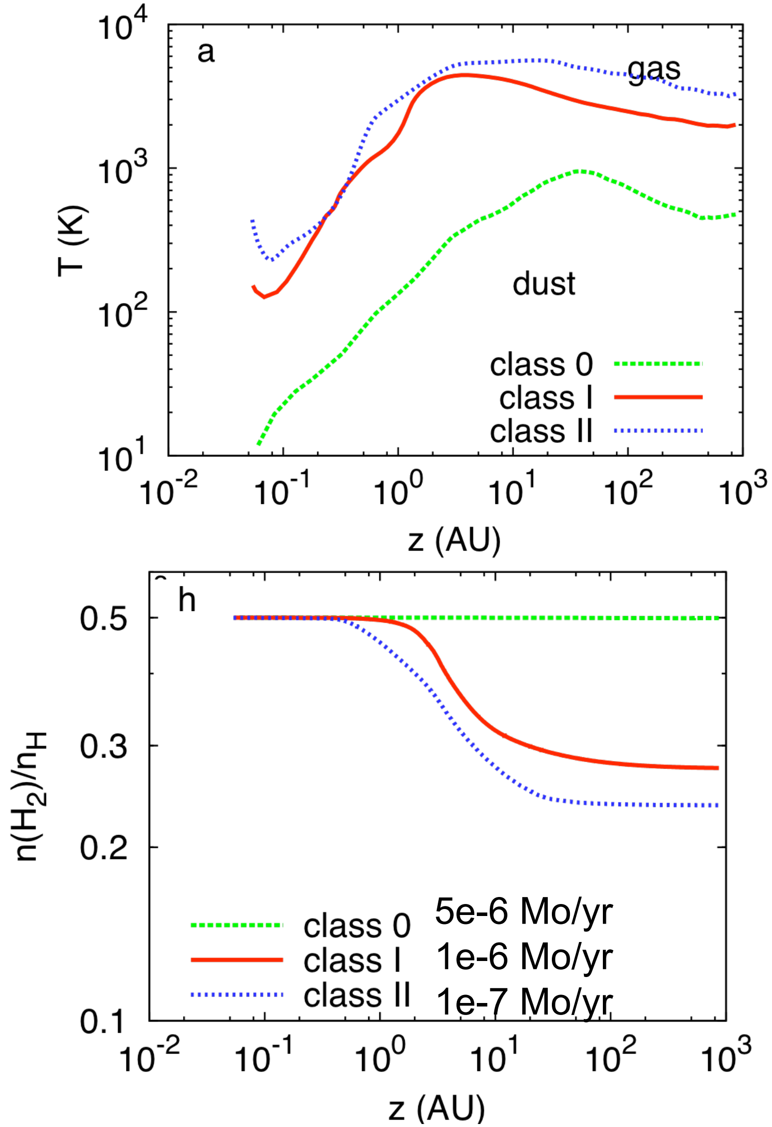
Molecule survival in MHD disk winds

- Enough ionisation to lift neutrals out to r ~ 9 AU (Vdrift << Vp)
- Strong heating by ion-neutral drift (like in C-shock!) but H2 survives thanks to short wind crossing time, sharp density fall-off
- Good self-screening by inner streamlines

○ Conditions favorable to H_2O formation: broad H_2O component seen by Herschel ?

○ NB: Vdrift too small for grain sputtering: no SiO or CH3OH: could form in internal C-shocks ?

Launch radius = 1 AU

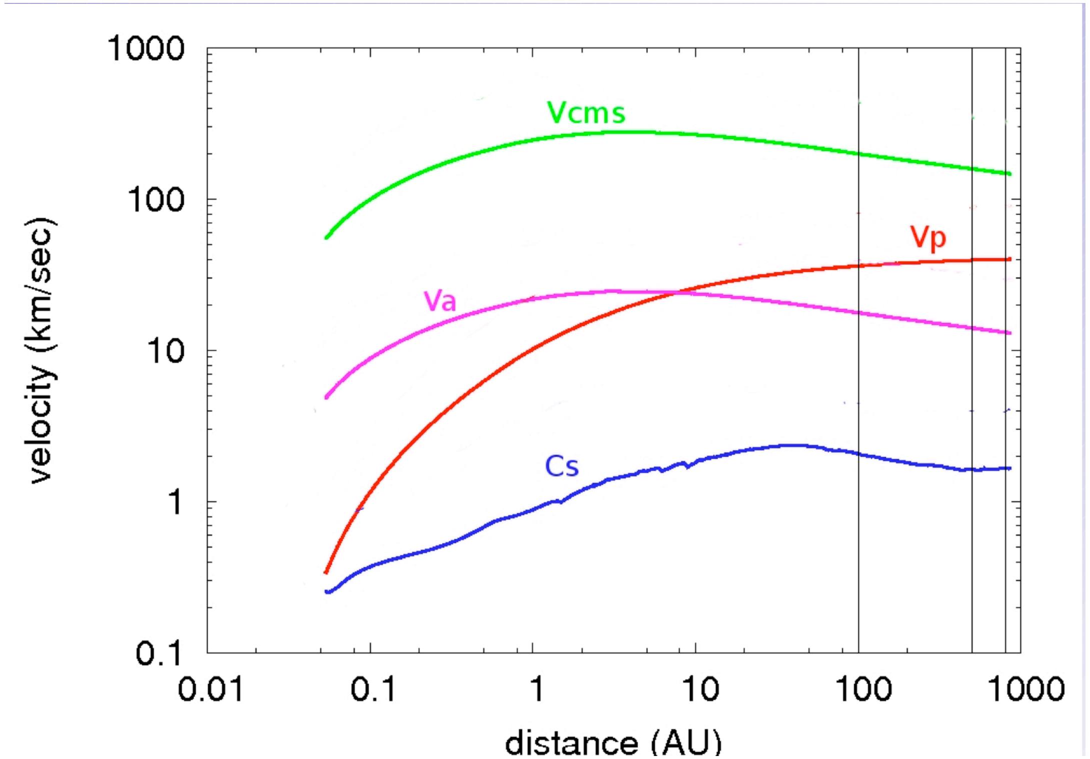


Internal shocks in MHD disk winds

- Strong magnetic field:
  - B/sqrt(nH) ~10-20
  - V_{cms} > Vp > V_A

  ➔ C-type magnetic precursor
- Short timescales
  - Tdyn = 100 yrs at 800 AU ➔ young C-J shock
- High pre-shock ionisation:
  - Xion ~10^{-5}-10^{-6} at density 10^5 - 10^6 cm^{-3}

➔ New shock parameter range

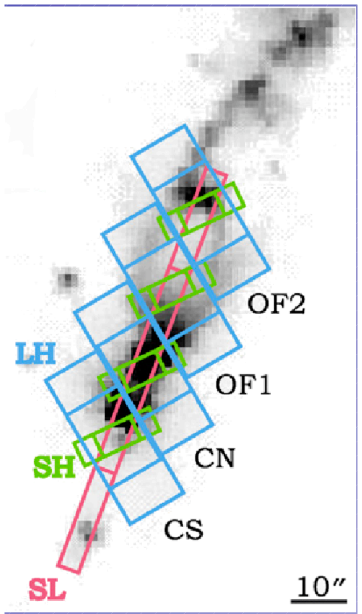


Disk wind streamline launched from 1 AU
Around a class 0 with M* = 0.1 Msun

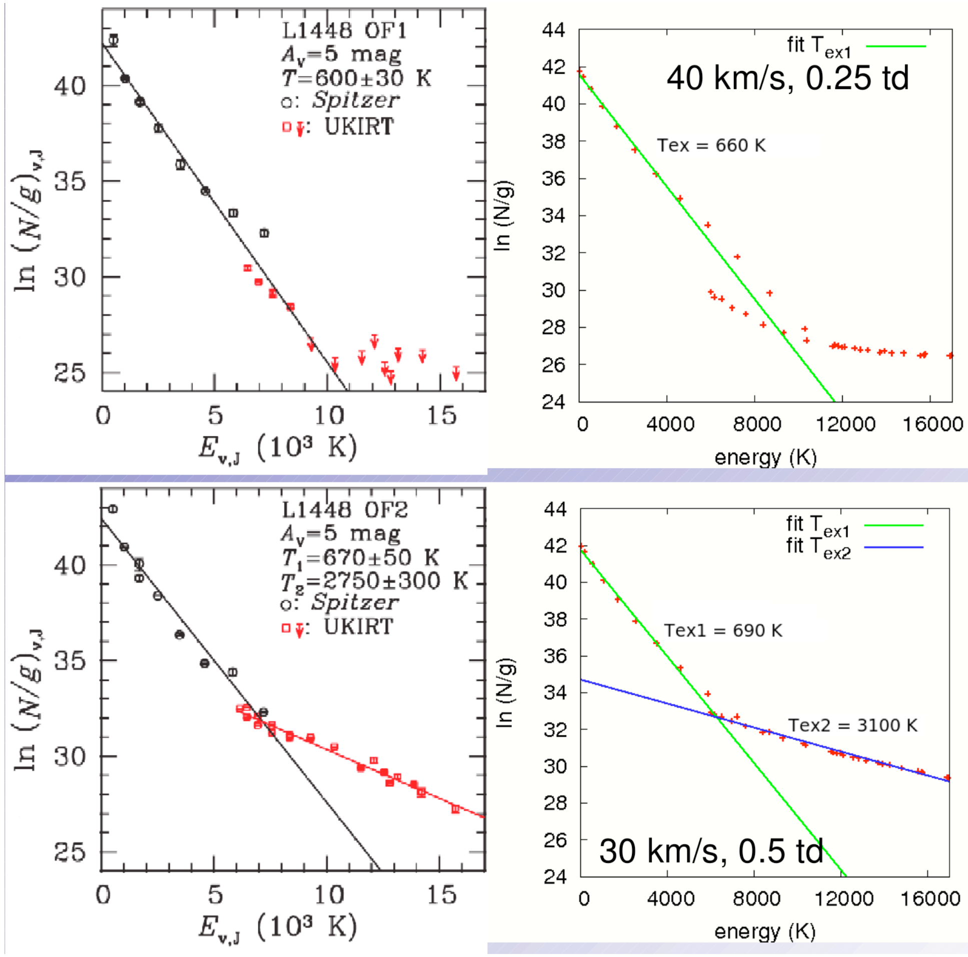
(Taquet et al. 2010)

Comparison with H_2 in L1448 (Spitzer)

- Good fits for Vshock 30-40 km/s along 1 AU streamline
  - Similar to V jumps in IRAS04166 jet
- To do:
  - Several streamlines
  - Other species (HCN, SO, SiO..)



(Dionatos et al. 2009)



(Taquet et al. 2010)

Summary

Huge progress in the last 10 years thanks to submm interferometry, ISO, Spitzer, SWAS, ODIN, and now of course Herschel !

- Swept-up cavities:
  - Cooling budget : Primary wind taps a large fraction of accretion power: could play key role in angular momentum extraction
  - C-shocks are prevalent up to 20-30 km/s at least (> 60 km/s in Orion KL); non-dissociative J-shocks not seen. Dissociative J-shocks only close to axis.
  - C-shocks may explain global chemical richness including H2O abundance vs T
  - Line profiles and abundance vs V not yet fully understood: 2D + mixing ?
  - Preshock abundances to be better constrained
  - ➔ work for Herschel and ALMA

- Molecular Jets :
  - Tight density and velocity collimation within Z = 50 AU: magnetic process
  - Dusty,partly atomic/molecular, specific chemistry (eg. SiO, SO, but no HCN)
  - enough average momentum to drive the CO flow, but cavity opening ?
  - protostellar wind or disk wind ? Herschel / ALMA studies of jet shocks
  - implications for inner disk and envelope clearing ? MHD disk wind speeds up accretion..