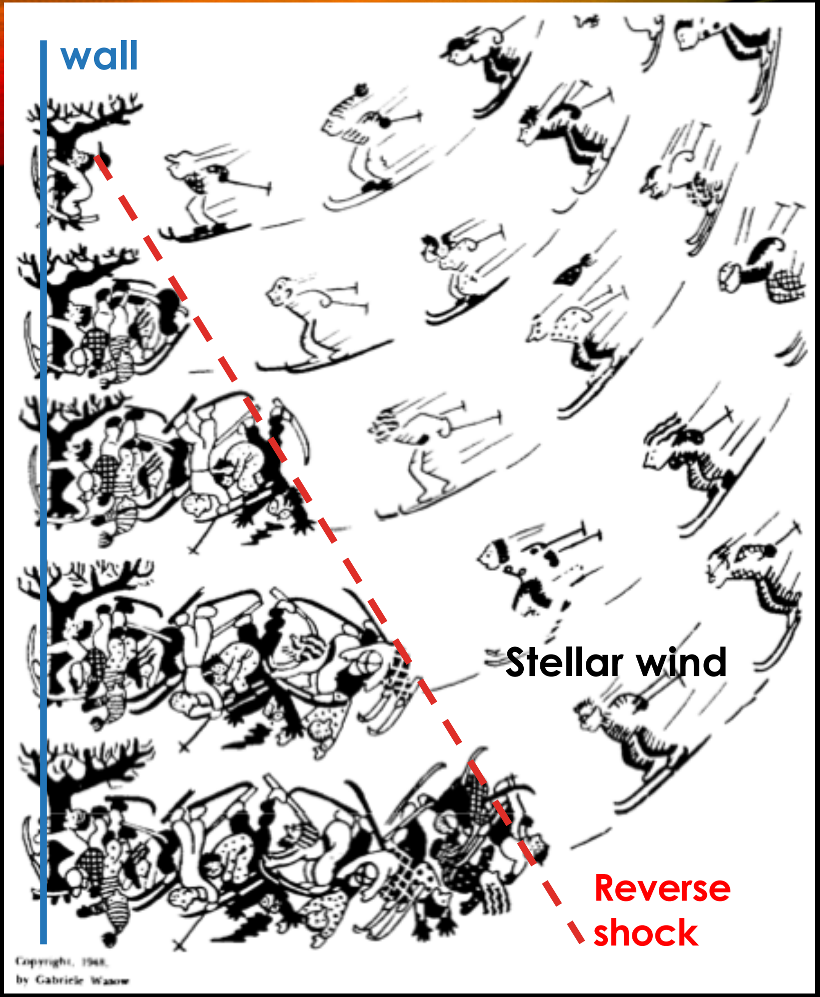
MODELING INTERSTELLAR SHOCKS

Sylvie CABRIT (Observatoire de Paris, LERMA)

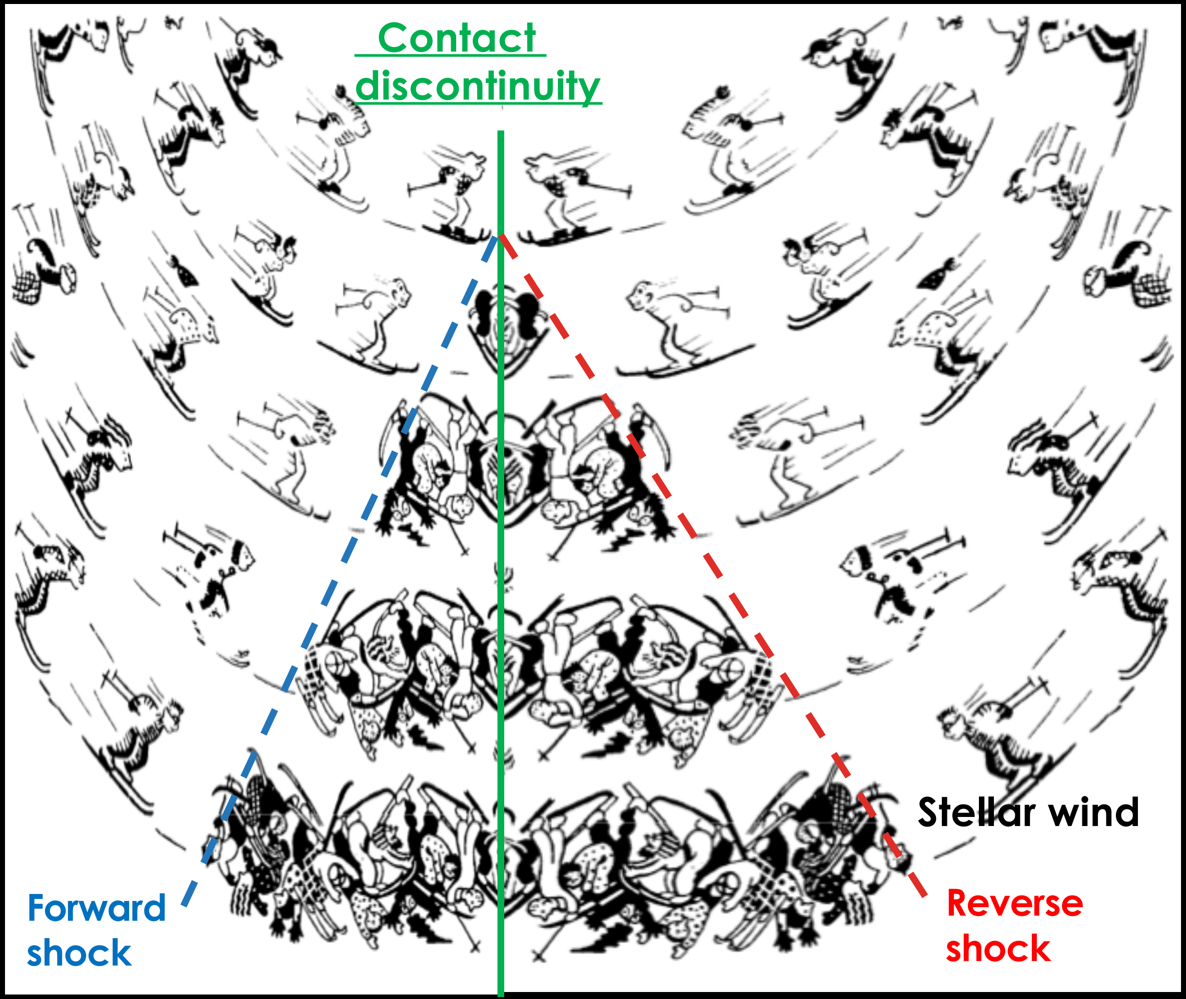


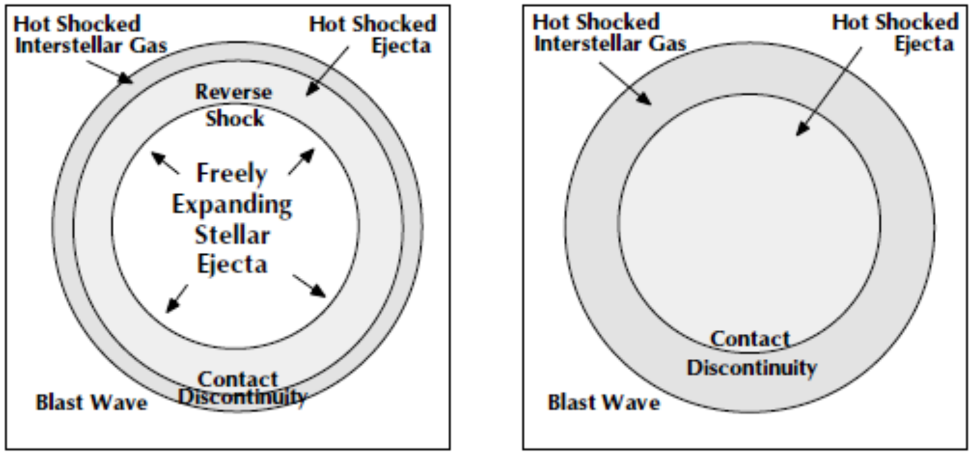
BASIC SHOCK THEORY

- Supersonic flow meets an obstacle at Vs > sound speed
- Sudden compression ➔ deceleration (mass conservation)
- Conversion of kinetic energy flux into
  - Thermal energy (heat)
  - Dissociation
  - Ionization
  - Magnetic energy (B compressed)
  - Internal energy ➔ Radiation signature

If compressible obstacle (ambient cloud, previous ejecta..)

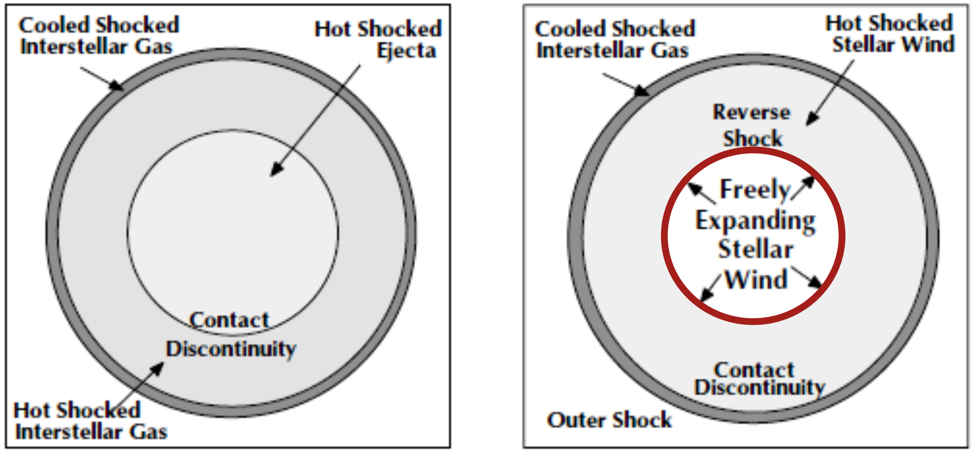
- « Forward shock » launched into the obstacle
- « Contact discontinuity » between the two shock fronts





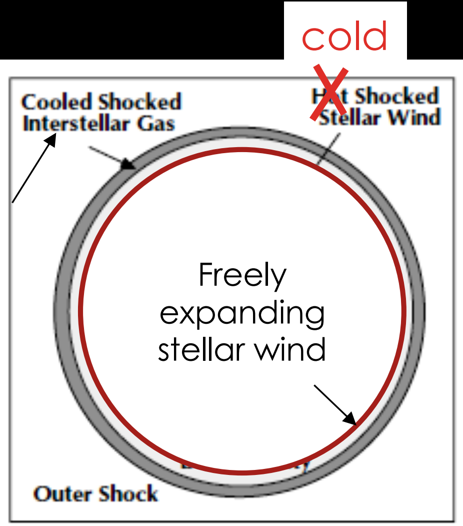
a. Supernova Remnant: pre Sedov-Taylor Phase

b. Supernova Remnant: Sedov-Taylor Phase



c. Supernova Remnant: post Sedov-Taylor Phase

d. Stellar Wind Bubble



e. Slow and/or dense winds (protostars, AGB stars..) : reverse shock cools rapidly ➔ thin shell driven by wind ram-pressure = « snowplow »

THIN SHELL SPEED (SNOW-PLOW)

- Shell mass increase (shocked ambient gas + shocked wind)
- Shell momentum increase (from shocked wind)

$$\frac{d\mathcal{M}}{dt} = r^2\rho_a v_s + r^2\rho_w(v_w - v_s)$$

$$\frac{d\mathcal{M}v_s}{dt} = r^2\rho_w(v_w - v_s)v_w$$

- dVs/dt = 0 ←→ ram pressure equilibrium between reverse and forward shock

$$\rightarrow \mathcal{M}\frac{dv_s}{dt} = \frac{d\mathcal{M}v_s}{dt} - v_s\frac{d\mathcal{M}}{dt}$$

$$= r^2\rho_w\left((v_w - v_s)^2 - \frac{\rho_a}{\rho_w}v_s^2\right)$$

- Solution:
- $V_s \ll V_w$ if $\rho_a \gg \rho_w$

$$\rightarrow V_s \sim \frac{v_w}{1 + \sqrt{\rho_a/\rho_w}}$$

SHOCK MODELING

« Forward modeling »

- Specify driving piston + ambient medium conditions
  - ➔ compute shock front(s) structure and propagation
  - ➔ compute emitted spectrum

« Backwards modeling » (= Inversion)

- Specify emission fluxes (observed)
  - ➔ fit shock parameters
  - ➔ constrain piston properties (eg. wind mass-flux, momentum flux, power, …)
  - ➔ constrain ambient medium properties (eg. B-field, density, ice composition,…)
  - ➔ Constrain global **shock feedback** on ISM (turbulent support, chemistry, SF regulation…)

FORWARD MODELING

Semi-Analytical

1D, steady-state

PRO:
- Very complete non-equilibrium micro-physics : ionization, chemistry, grains, ion-neutral drift…
- Fast: can compute large model grids
- Pseudo 2D = collection of 1D shocks

LIMITS:
- Ignore lateral loss of pressure in 2D
- Ignore time-dependence and instabilities

Numerical simulations

HD or MHD 1D/2D/3D

PRO:
- Exact time-dependence
- Study instabilities and turbulence
- Accurate effect of 2D curvature

LIMITS: CPU cost
- Simplified cooling and chemistry
- No large grids
- Challenging to resolve cooling length (J-shock) or treat Multi-fluid MHD (C-shock)

CONSERVATION LAWS

In the frame of shock wave

Single-fluid 1D steady-state with B // shock front

- **Mass conservation**

ρ V = cste

- **Magnetic Flux conservation**

B / ρ = cste

- **Momentum conservation** (ram, thermal and magnetic pressure)

ρ V^2 + P + B^2 / 8π = cste

- **Energy conservation**

V [½ ρ V^2 + P + u + B^2 / 4π] + F_{rad} = cste

u = internal energy

F_{rad} is radiative cooling flux

See eg. Hollenbach & McKee 1979 for oblique B case

Rankine-Hugoniot Jump conditions

set Frad = 0 (adiabatic front), case B=0

$$\rho_s = \rho_0 \frac{(\gamma+1)\mathcal{M}^2}{(\gamma-1)\mathcal{M}^2+2},$$

$$\rho_s \sim 4\rho_0 \text{ in the strong shock limit, } \gamma = 5/3,\ \mathcal{M} \gg 1$$

$$\frac{T_1}{T_0} = \frac{[(\gamma-1)\mathcal{M}_0^2+2][2\gamma\mathcal{M}_0^2-(\gamma-1)]}{(\gamma+1)2\mathcal{M}_0^2}.$$

$$T_s = \frac{2(\gamma-1)}{(\gamma+1)^2}\left[\frac{\mu m_u v_s^2}{k}\right],$$

~ 3000 K @ 10 km/s

~ 3 10^5 K @100 km/s

INTEGRATED EQUATIONS

Single-fluid 1D steady-state with B // shock front

In the frame of the shock wave:

- **Mass conservation**

ρ V = cste

- **Magnetic Flux conservation**

B / ρ = cste

- **Momentum conservation** (ram, thermal and magnetic pressure)

$\rho V^2 + P + B^2 / 8\pi$ = cste

- **Energy conservation**

$V [\frac{1}{2} \rho V^2 + P + u + B^2 / 4\pi] + F_{rad}$ = cste

u = internal energy

F_{rad} is radiative cooling flux

See eg. Hollenbach & McKee 1979 for oblique B case

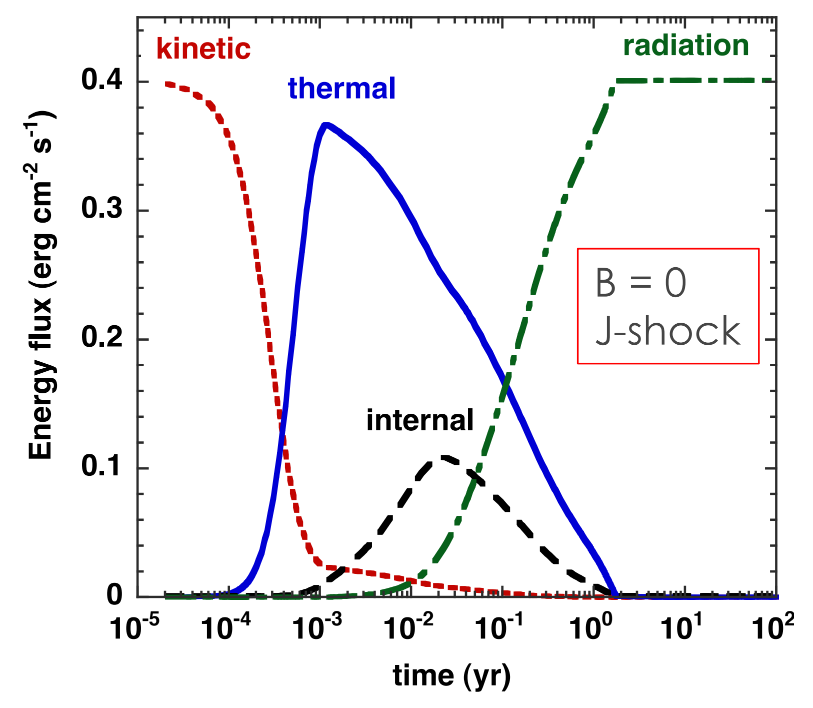
- Starting from initial conditions, solve differential equations for ρ, V, P (or T), u, F_{rad} along z
- $dF_{rad} / dz = \Lambda$ (erg/s/cm^3) = cooling rate
- $P = \rho kT / \mu m_H$

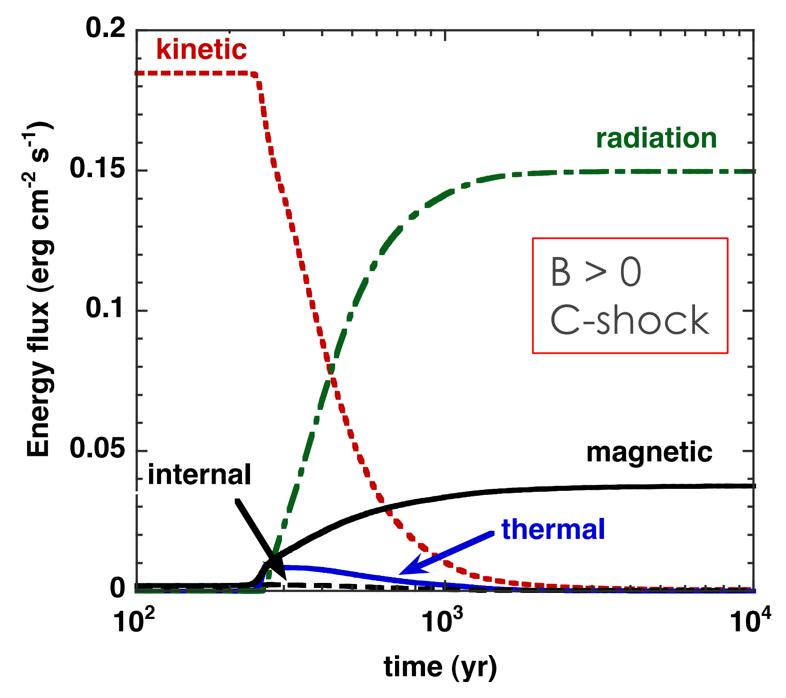
At equilibrium, Λ, u and μ depend only on ρ, T, elemental abundances: easy to integrate

BUT In shock cooling zone, ionization stages, molecular abundances, and internal excitation are **out of EQ** (no time to adjust)

➔ Also need to solve along z for each specie abundance, ionization stage,(level populations): « chemical » source terms

ENERGY CONVERSION IN SHOCKS



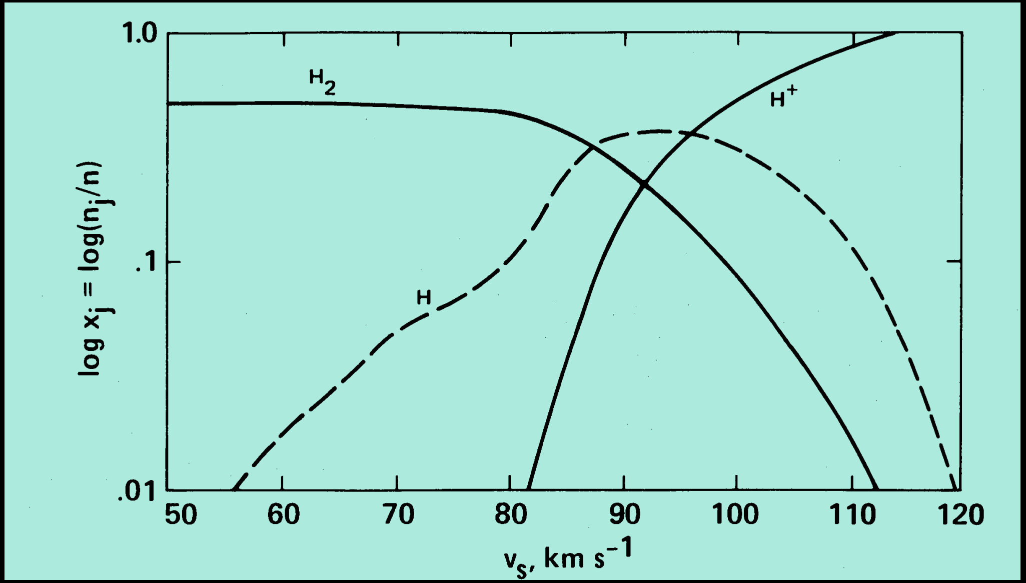


RADIATIVE PRECURSOR IN IONIZING SHOCKS

- UV photons emitted in shock front also propagate upstream in the preshock medium

  ➔« radiative precursor »
- Vs < 40 km/s: cold neutral
- 40 < Vs < 80 km/s: warm neutral, partly dissociated
- 80 < Vs < 120 km/s : partly ionized and fully dissociated
- 120 km/s < Vs : fully ionized at IEQ

Sutherland & Dopita (2017)



Hollenbach & Mc Kee (1989)

REFERENCE 1D-SHOCK MODELS

Atomic shocks, no molecules

30 < Vs < 2000 km/s

- MAPPINGS V (Sutherland & Dopita 2017)

Public code available at
https://mappings.anu.edu.au/code/

10 < Vs < 100 km/s

- Model grid in Hartigan et al. (1994, 1995)

Dissociative, with molecule reformation

30 < Vs < 120 km/s

- Hollenbach & McKee 1989 (infrared line predictions)

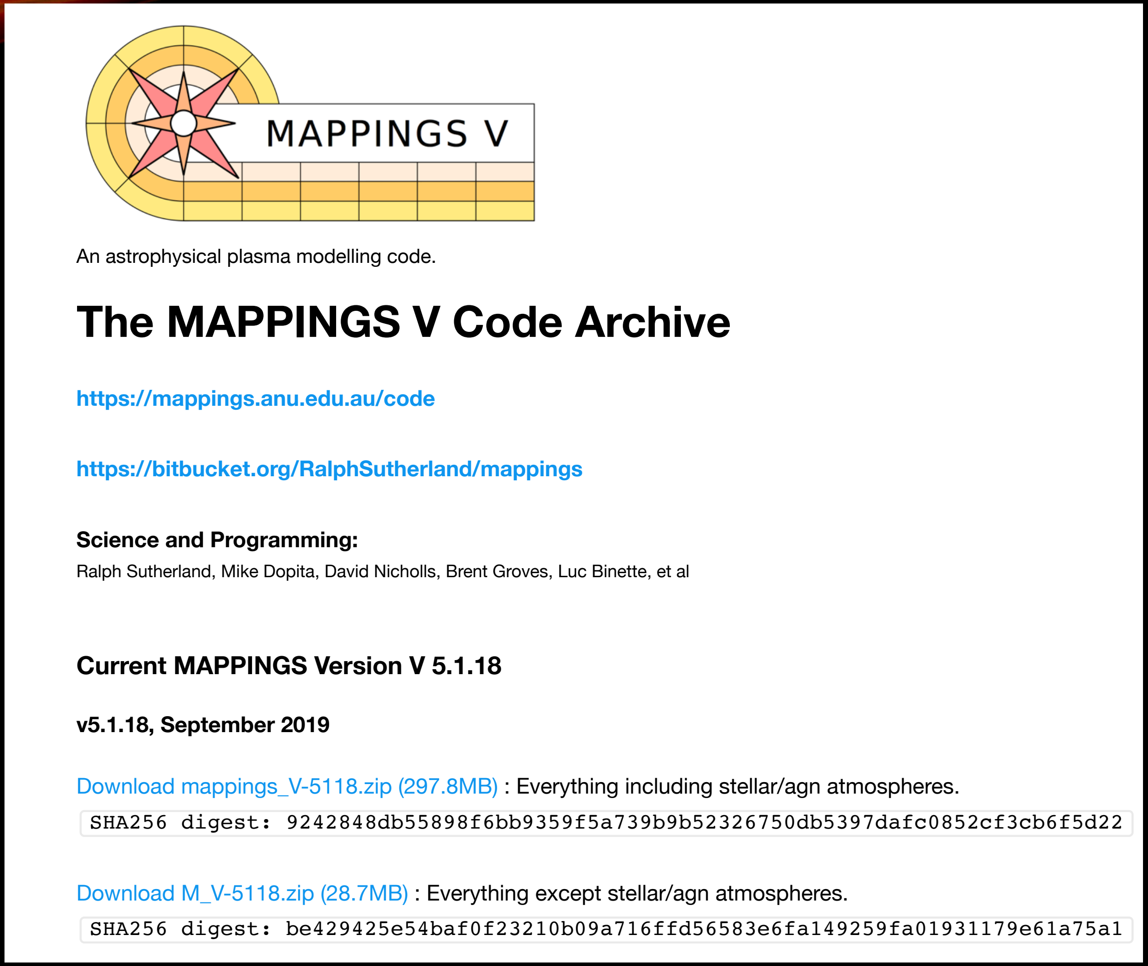
Non- (or weakly) dissociative

Vs < 40 km/s

- No radiative precursor
- Paris-Durham shock code (Flower & Pineau des Forêts 1985 ➔Godard 2019)

https://ism.obspm.fr/shock.html

https://mappings.anu.edu.au/code/



An astrophysical plasma modelling code.

The MAPPINGS V Code Archive

https://mappings.anu.edu.au/code

https://bitbucket.org/RalphSutherland/mappings

Science and Programming:

Ralph Sutherland, Mike Dopita, David Nicholls, Brent Groves, Luc Binette, et al

Current MAPPINGS Version V 5.1.18

v5.1.18, September 2019

Download mappings_V-5118.zip (297.8MB) : Everything including stellar/agn atmospheres.

`SHA256 digest: 9242848db55898f6bb9359f5a739b9b52326750db5397dafc0852cf3cb6f5d22`

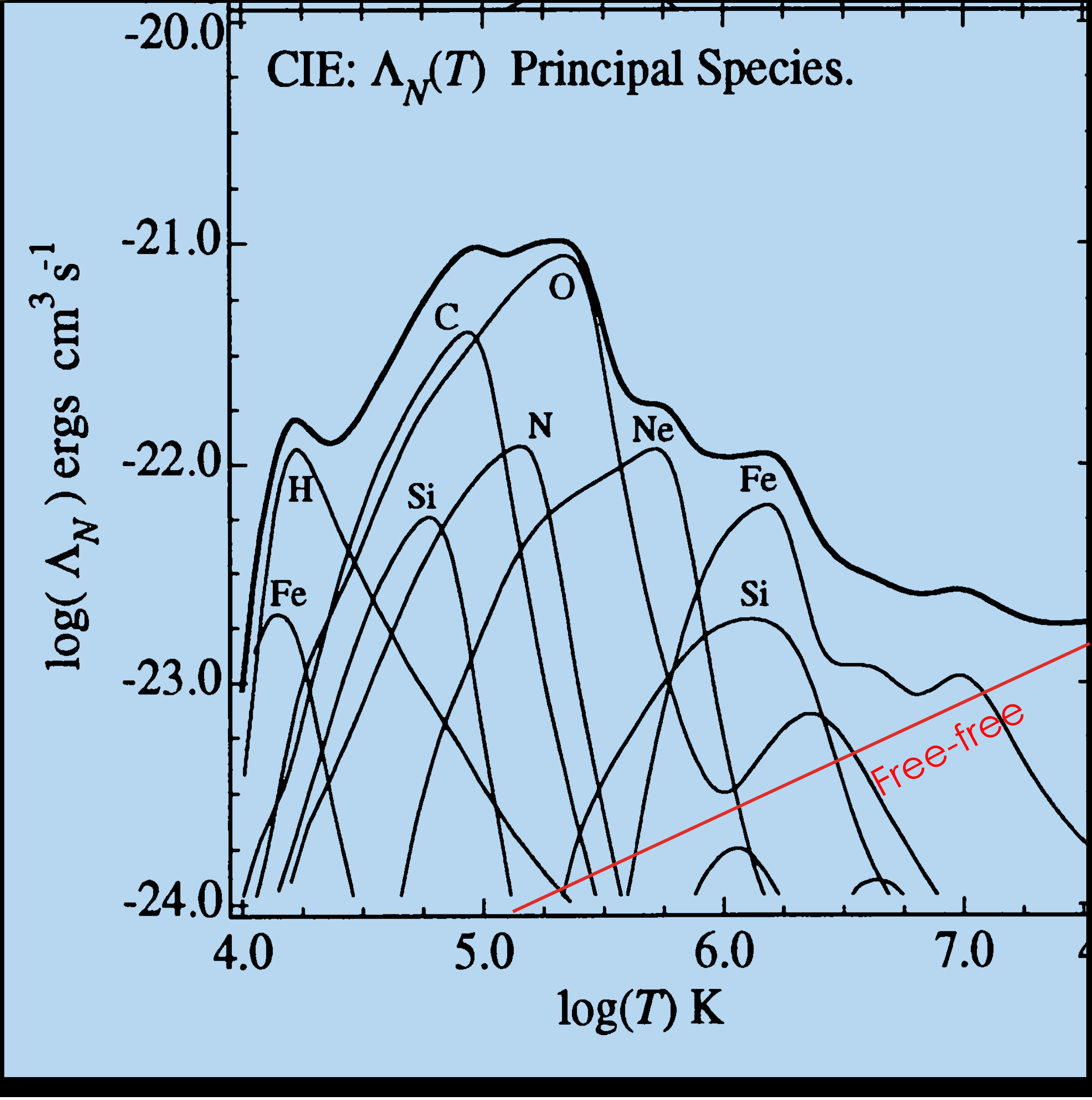
Download M_V-5118.zip (28.7MB) : Everything except stellar/agn atmospheres.

`SHA256 digest: be429425e54baf0f23210b09a716ffd56583e6fa149259fa01931179e61a75a1`

MAIN COOLANTS AT T > 10^4 K

Dopita+1993 cooling curve (MAPPINGS II)

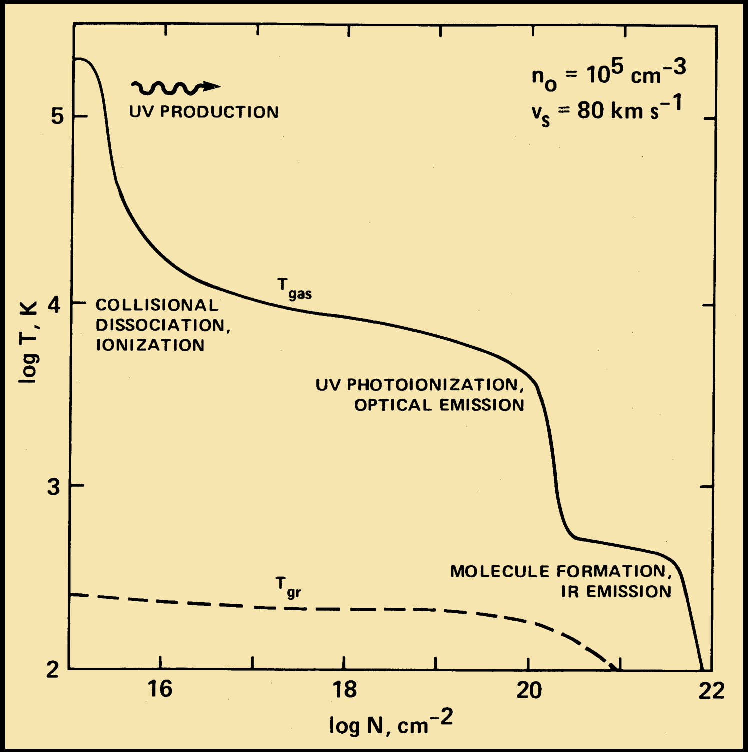
Updated with CHIANTI database In MAPPINGS V



DISSOCIATIVE SHOCK WITH MOLECULE REFORMATION

- UV photons emitted in shock front reabsorbed downstream
  - « Recombination plateau » @10^4 K (~ HII region)
  - Hydrogen lines and low-excitation ionic lines [O I], [Si II], [Fe II], etc..

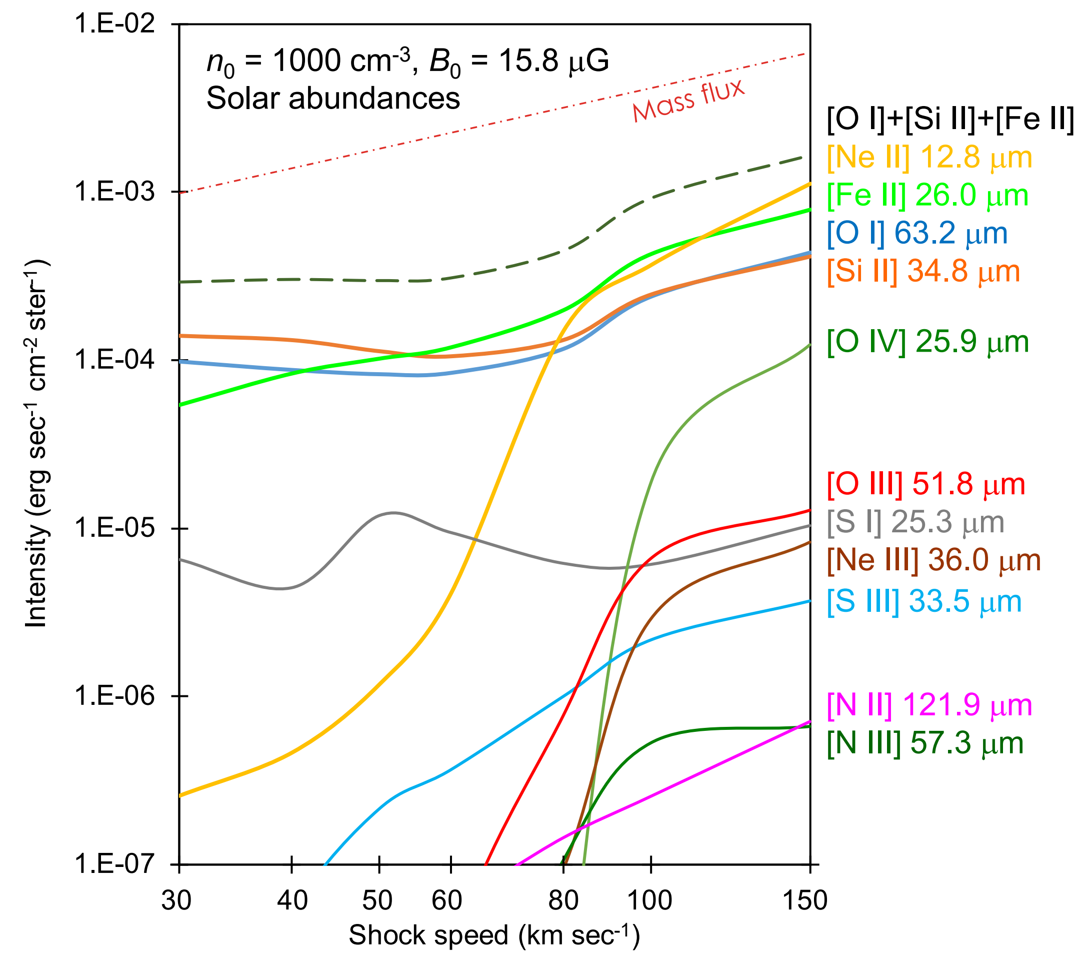
- Molecule reformation plateau
  - @500 K (each H_2 molecule releases 4.48eV)
  - H_2, CO, H_2O, (+SiO, ..)

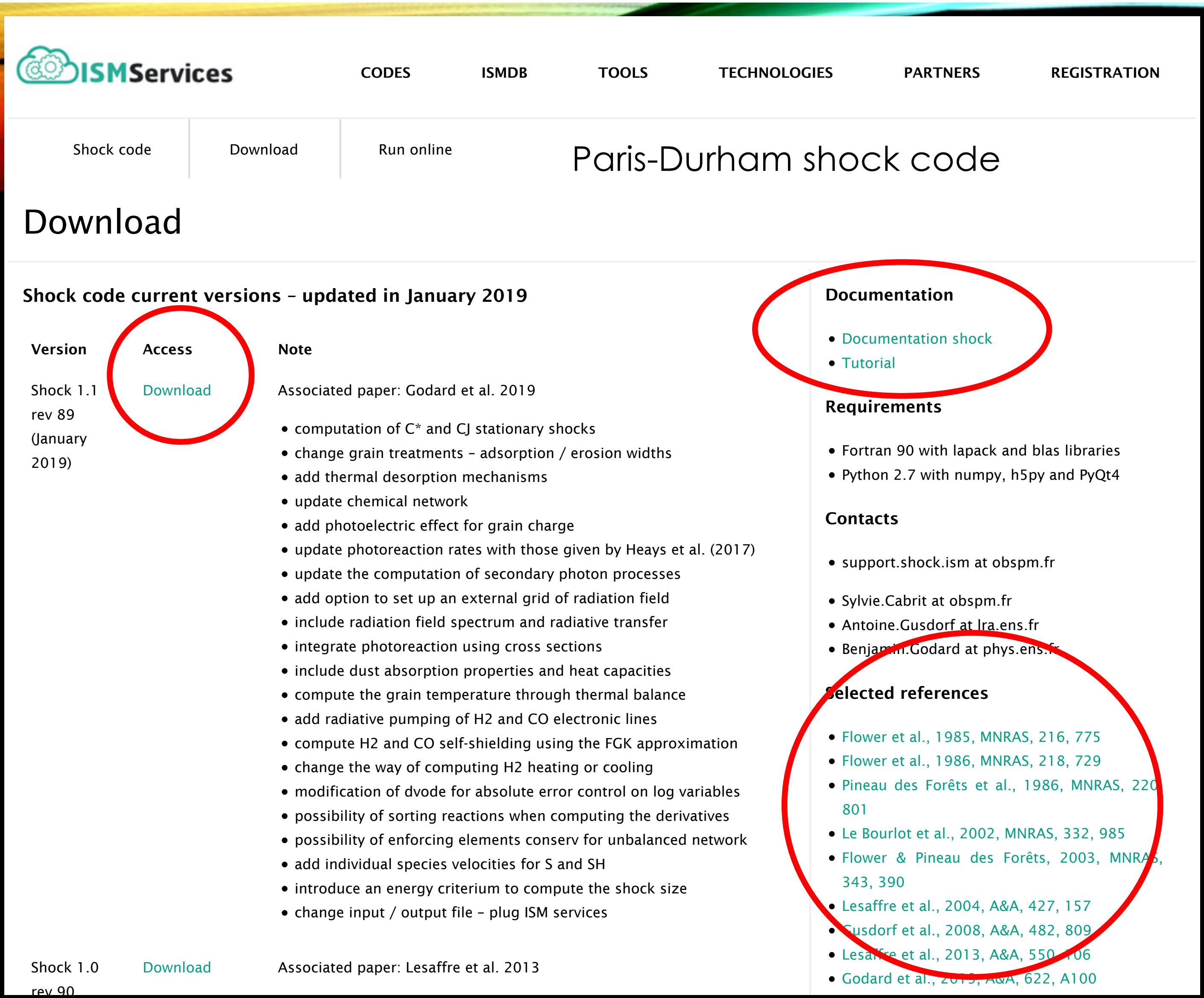


Hollenbach & Mc Kee (1989)

SHOCK SPEED DIAGNOSTICS

MAPPINGS V calculations





ISMServices

CODES ISMDB TOOLS TECHNOLOGIES PARTNERS REGISTRATION

Shock code | Download | Run online

Paris-Durham shock code

Download

Shock code current versions – updated in January 2019

Version	Access	Note
Shock 1.1 rev 89 (January 2019)	Download	Associated paper: Godard et al. 2019 • computation of C* and CJ stationary shocks • change grain treatments – adsorption / erosion widths • add thermal desorption mechanisms • update chemical network • add photoelectric effect for grain charge • update photoreaction rates with those given by Heays et al. (2017) • update the computation of secondary photon processes • add option to set up an external grid of radiation field • include radiation field spectrum and radiative transfer • integrate photoreaction using cross sections • include dust absorption properties and heat capacities • compute the grain temperature through thermal balance • add radiative pumping of H2 and CO electronic lines • compute H2 and CO self-shielding using the FGK approximation • change the way of computing H2 heating or cooling • modification of dvode for absolute error control on log variables • possibility of sorting reactions when computing the derivatives • possibility of enforcing elements conserv for unbalanced network • add individual species velocities for S and SH • introduce an energy criterium to compute the shock size • change input / output file – plug ISM services
Shock 1.0 rev 90	Download	Associated paper: Lesaffre et al. 2013

Documentation

- Documentation shock
- Tutorial

Requirements

- Fortran 90 with lapack and blas libraries
- Python 2.7 with numpy, h5py and PyQt4

Contacts

- support.shock.ism at obspm.fr

- Sylvie.Cabrit at obspm.fr
- Antoine.Gusdorf at lra.ens.fr
- Benjamin.Godard at phys.ens.fr

Selected references

- Flower et al., 1985, MNRAS, 216, 775
- Flower et al., 1986, MNRAS, 218, 729
- Pineau des Forêts et al., 1986, MNRAS, 220, 801
- Le Bourlot et al., 2002, MNRAS, 332, 985
- Flower & Pineau des Forêts, 2003, MNRAS, 343, 390
- Lesaffre et al., 2004, A&A, 427, 157
- Gusdorf et al., 2008, A&A, 482, 809
- Lesaffre et al., 2013, A&A, 550, A106
- Godard et al., 2019, A&A, 622, A100

SPEED LIMITS IN MAGNETIZED SHOCKS

Alfven speed in neutrals

- $V_{Alfven} = B / \mathrm{sqrt}(4\,\pi\,\rho) = 1.8\ \boldsymbol{b}$ km/s
- $M_A = Vs / V_{Alfven}$

- Maximum compression in postshock gas ($M >> 1$)

$C = 4 M_A^2 / (1 + \mathrm{sqrt}(1+8M_A^2))$

➔ Shock compression only if $M_A > 1$

Magnetosonic speed in charged fluid

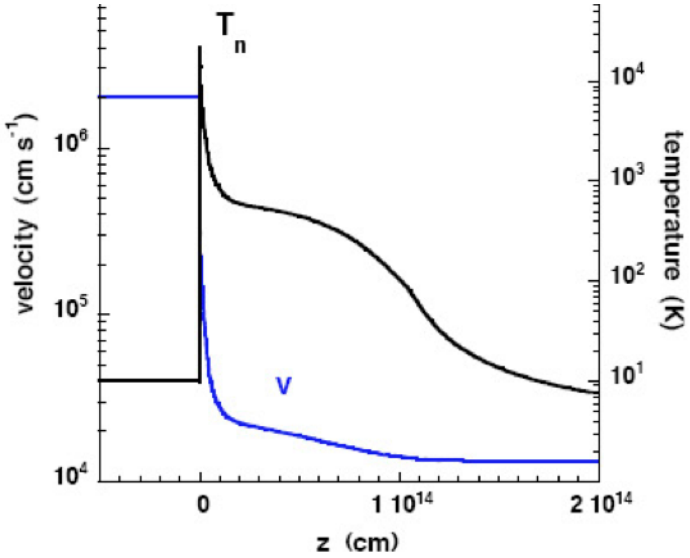
- $V_{magnet} = \mathrm{sqrt}(\, C_i^2 + B^2 / 4\,\pi\,\rho_i)$
- If $V_A < Vs < V_{magnet}$, magnetic compression wave propagates ahead of shock in charged fluid ➔ **« magnetic precursor »**
- Ions slow down by mag. pressure
- Neutrals slow down by collisions with ions ➔ jump can disappear

J-TYPE VS C-TYPE SHOCKS

Draine (1980), Flower et al. (1985), Smith (1991), Kaufman & Neufeld (1996), Caselli et al (1997)

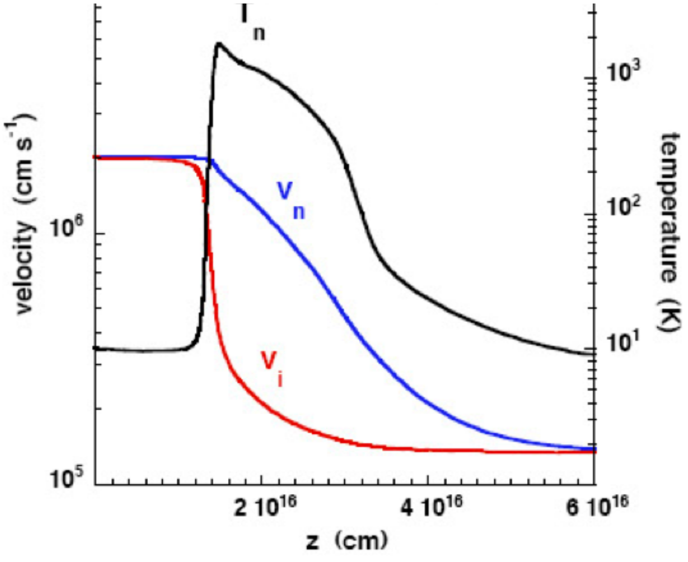
- **V > Vmagnet (B)**

J (Jump)-shock = monofluid
Fast dissipation by n-n collisions
High Tmax ~ V^2



- **V < Vcrit(B)**

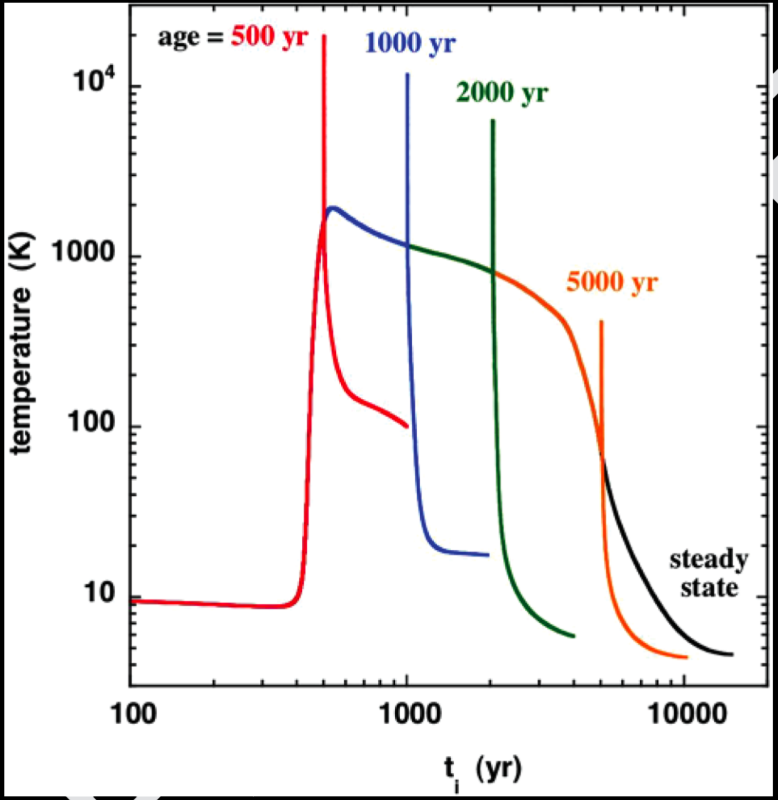
C (Continuous)-shock = **multifluid**
Slow dissipation by n-i collisions
Wider = Lower Tmax (H_2 cooling)



YOUNG AGE

- When age < tcool:
  - C-type magnetic « precursor » truncated at t_ion = age
  - followed by a J-type front truncated at t = age *(Chièze et al. 98, Smith 98)*
  - Well described by truncated steady C + J models **if nH, Vs constant** *(Lesaffre et al. 2004)*

➔ *Age is free parameter in the Paris-Durham model*



GRAINS

- **Grains** dominate inertia of charged fluid (Guillet 2007)
- For gas/dust ratio ~ 100

$V_{magnet} \sim 10\ V_{Alfven} \sim 20$ km/s **x b**

➔ Maximum speed for C-shocks

- Ion-neutral drift in C-shocks

➔ Sputtering of ice mantles

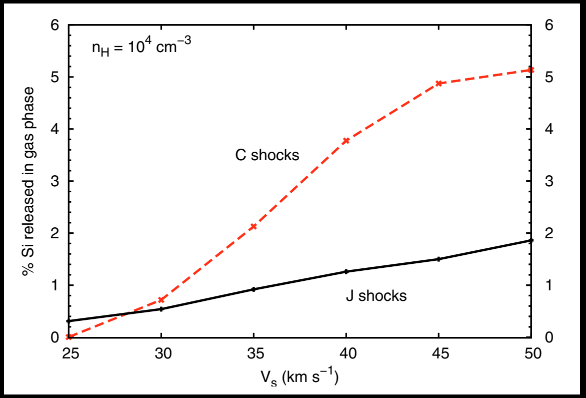
- Releases ice species: H_2O, CH_3OH, NH_3, H_2CO…

➔Erosion of grain cores

Release Si ➔ SiO (Gusdorf+2008ab)

SiO also released in J-shocks by grain-grain shattering and vaporization (Guillet 2009, 2011)

Not included in public code version



EXTERNAL FUV IRRADIATION

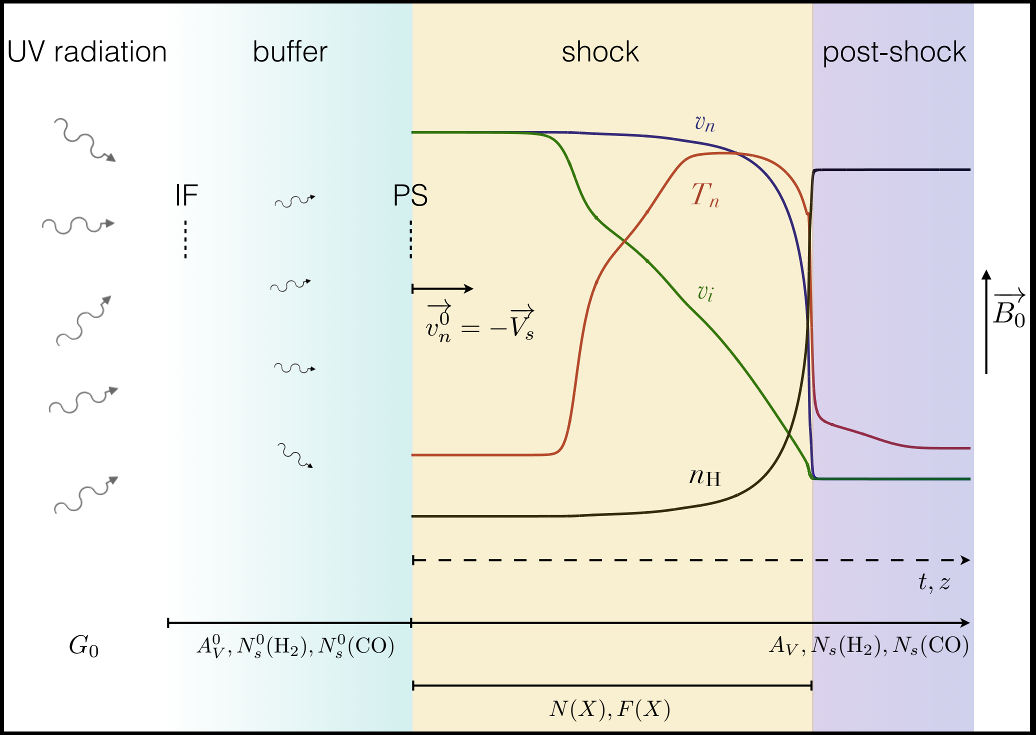
See Godard+2019

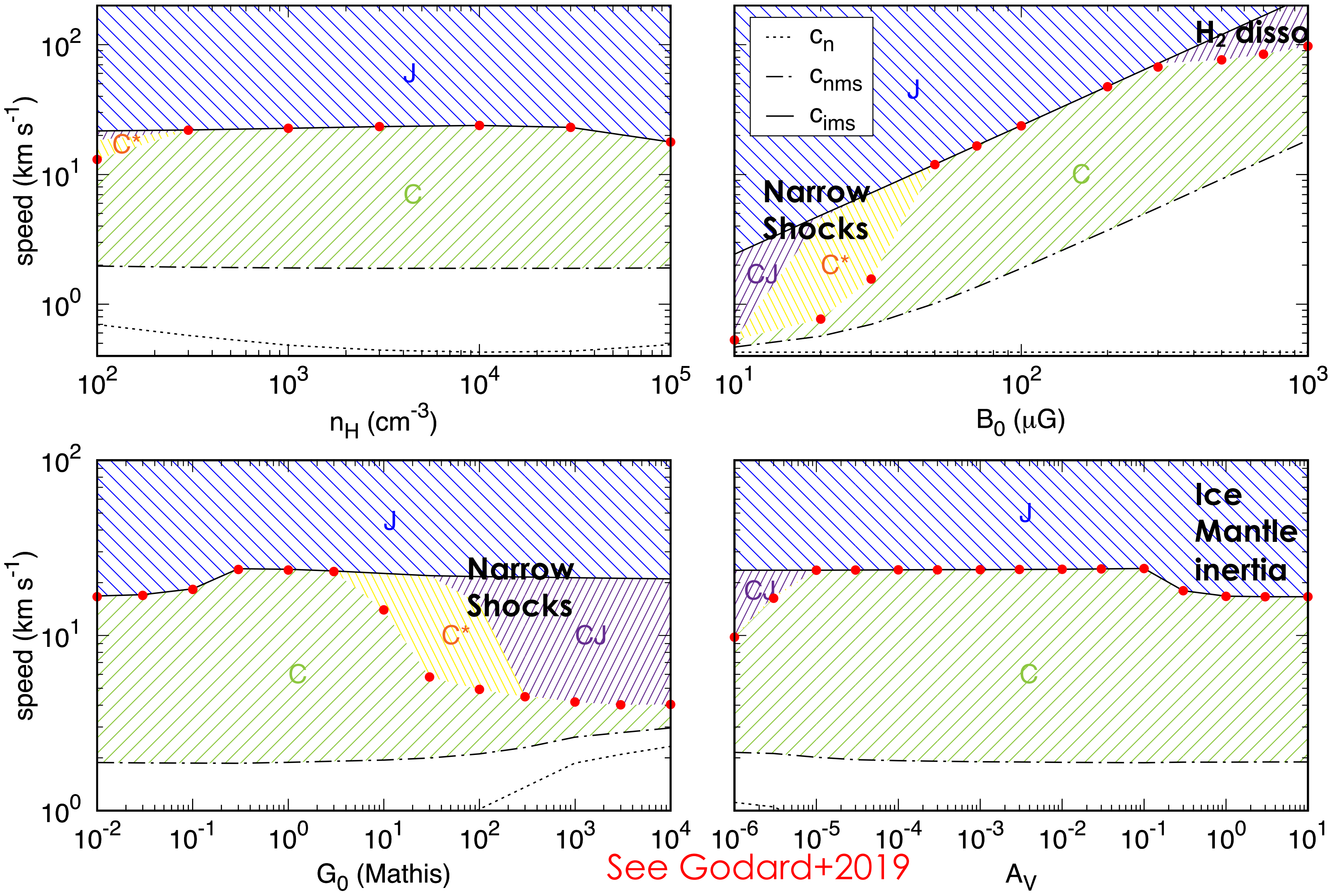
- Extra-Free parameters: G_0 , Av_0
- Lowers H2 cooling + Increases ionization and ion-neutral coupling : narrower hotter C-shock
- ➔ C-shocks disappear for

$$\boxed{G_0 > 0.2\ (n_\mathrm{H}/\mathrm{cm}^{-3})^{1/2}}$$

and become C* (subsonic) or C-J (jump)

- Specific diagnostics: CH^+ rotational lines, H_2 rovib (FUV pumping)





See Godard+2019

BACKWARD MODELING (INVERSION PROBLEM)

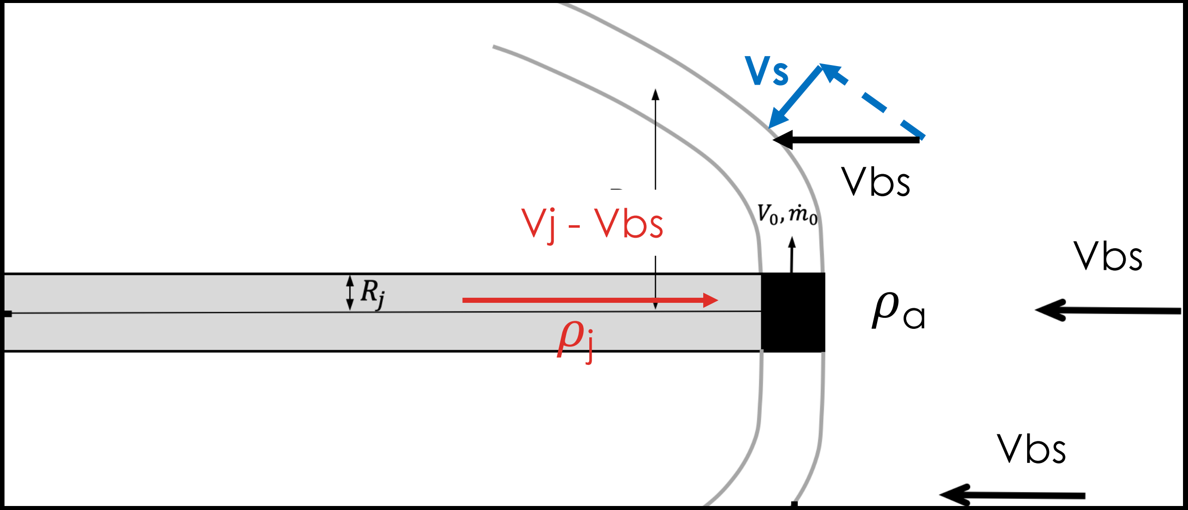
Many free parameters ➔ degeneracy

Ideally combine as many constraints as possible:

- Line fluxes PB: filling factor, depletion in grain+ ice ➔ H2, CO, O
- Line ratios PB: relative depletion ➔ single specie, or undepleted
- Shock thickness PB: spatial resolution ➔Hubble, JWST, ALMA
- Line profile width PB: inclination ➔ 2D bowshocks
- Ortho/para of H2 (if < 3)
- Ambient conditions (nH, G0, Av, zeta_CR, zeta_X) from ancillary data
- Shock Age: from speed + size

JET BOWSHOCK

- Lateral escape of shocked jet material
- Swept back by ambient gas
- Oblique shocks : Vs changes along bow surface
- Largest area at low shock speeds



UNRESOLVED 3D BOWSHOCK MODELS

Tram L.N. 2018, MNRAS

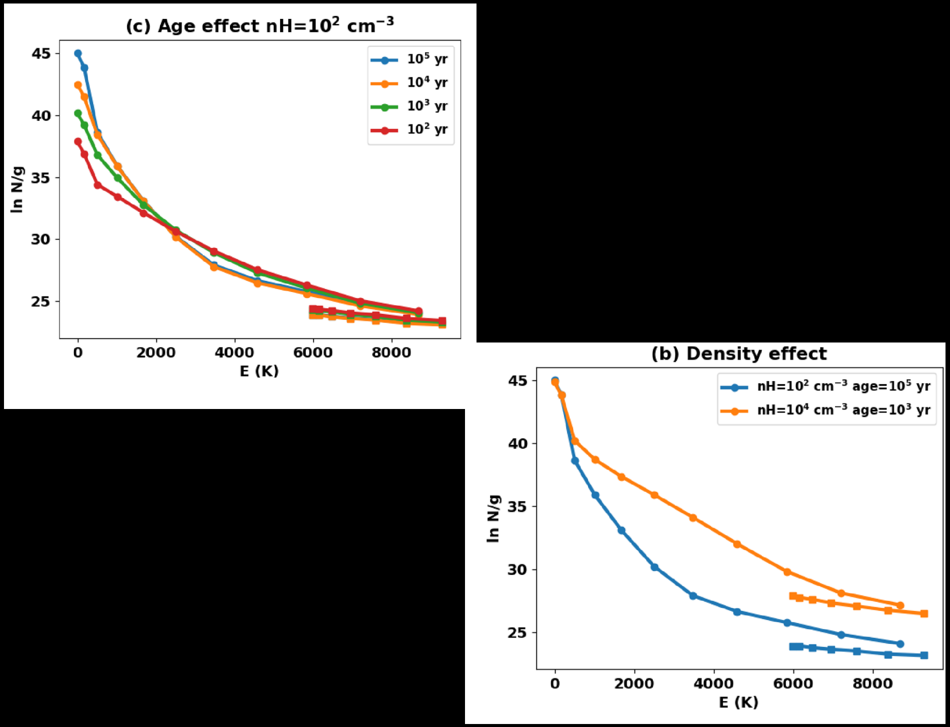
- Stitch 1D models along bow surface

+ Compute total H_2 excitation diagram

- resembles slower 1D shock ~ 10 km/s with ~ **same B**

➔Fitting with Vs = Vbow would strongly overestimate B-field !

- Distinctive effects of density, age, bow shape, B-field strength and angle ➔ good diagnostic potential

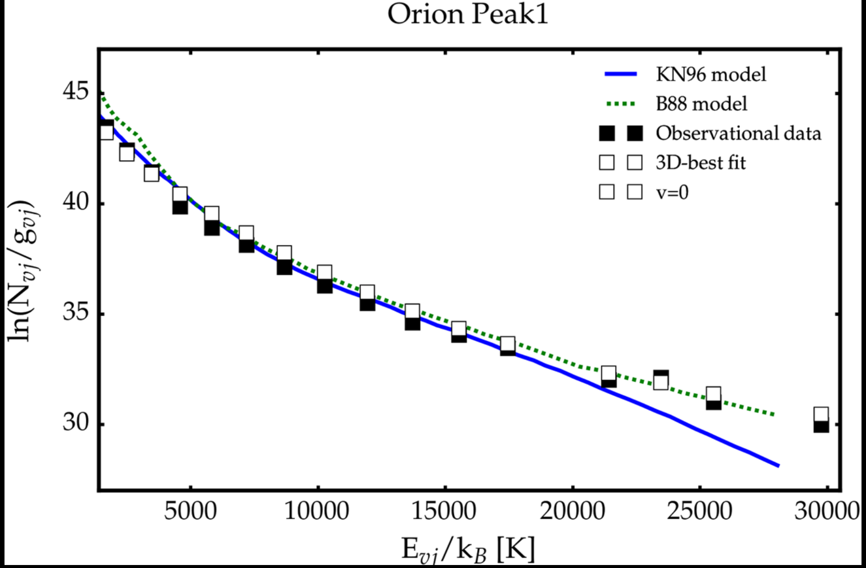


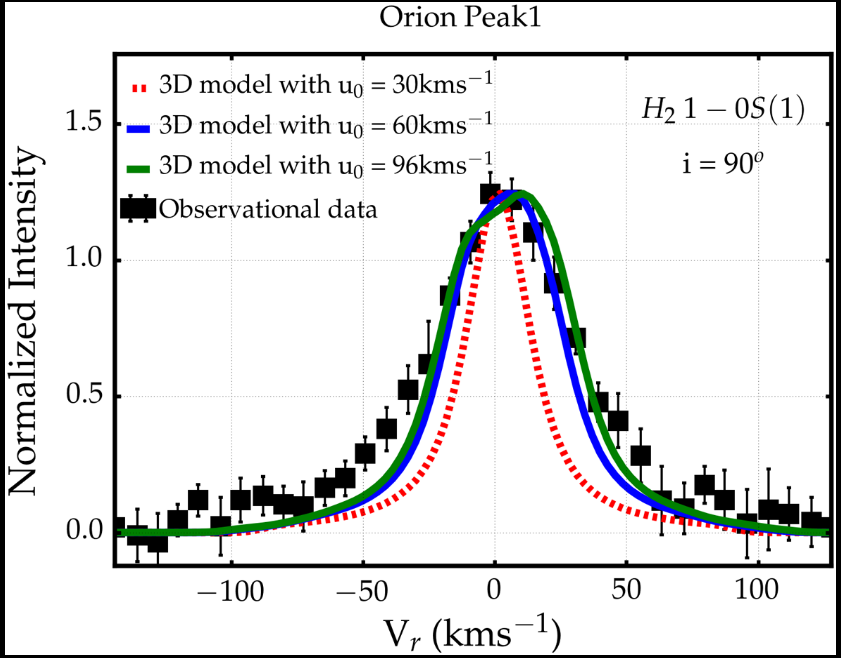
Tram L.N. 2018, MNRAS

FITTING H_2 IN ORION PEAK-1

Line profile lifts degeneracy on bow speed U_0
Agrees with proper motion info

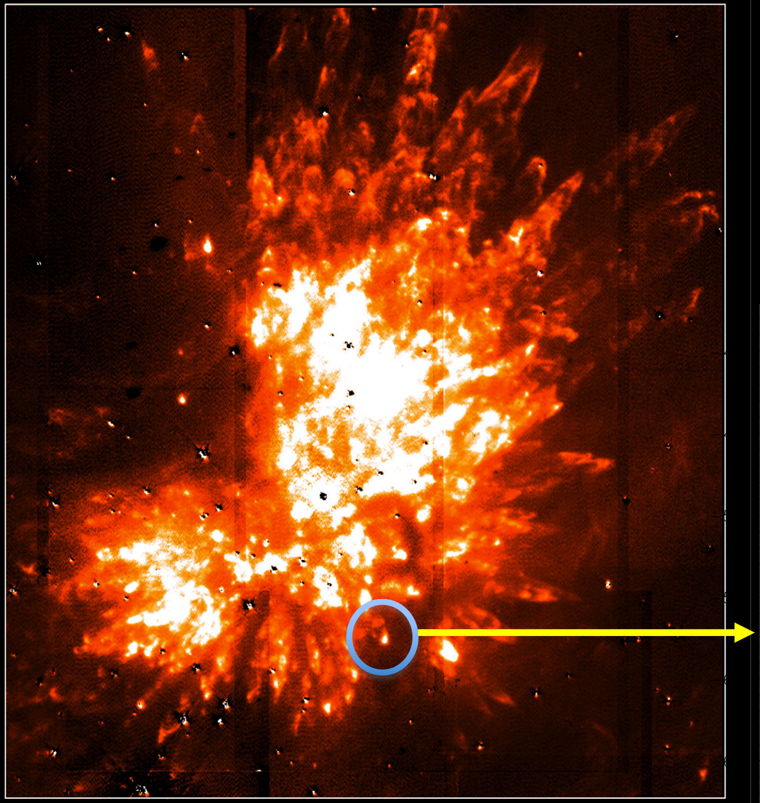
- nH = 10^6 cm^{-3}, age = 1000 yrs, b = 4.5
- U_0 ≥ 30 km/s





Tram L.N 2018, MNRAS

RESOLVED H_2 BOWSHOCK MODELS

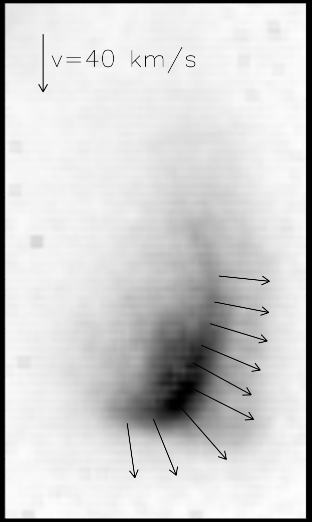


Orion KL
Subaru Telescope, National Astronomical Observatory of Japan

CISCO (H_2 (v=1-0 S(1)) – Cont)
January 28, 1999

0.15'' resolution (adaptive optics)

3 Flux-calibrated H_2 lines (v= 1-0)



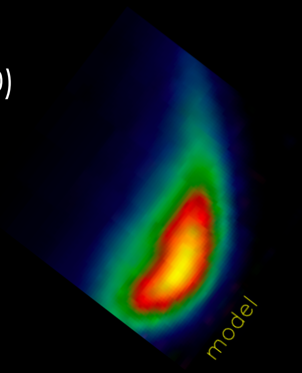
- Resolved emission thickness across bow surface
- Fit cuts by 1D shocks (Kristensen et al. 2008)
- Fit image by 3D bowshock model with projection effects (Gustafsson et al. 2010)

➔ C-shocks with

b = B/sqrt(nH) ~ 3-5

agrees with unresolved bow model in Peak 1

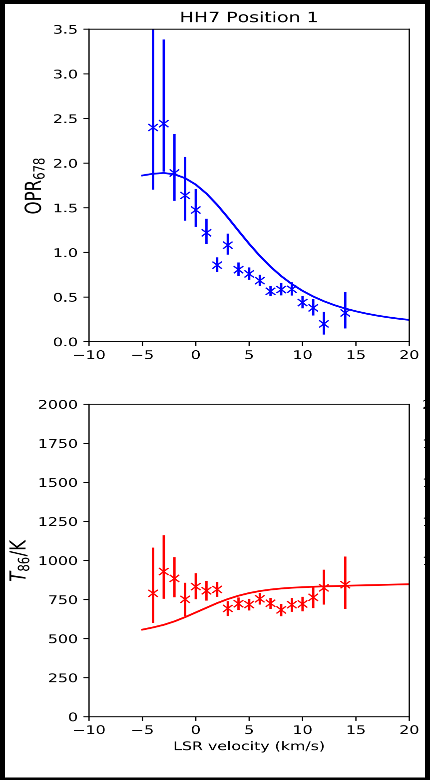
(and polarization data)

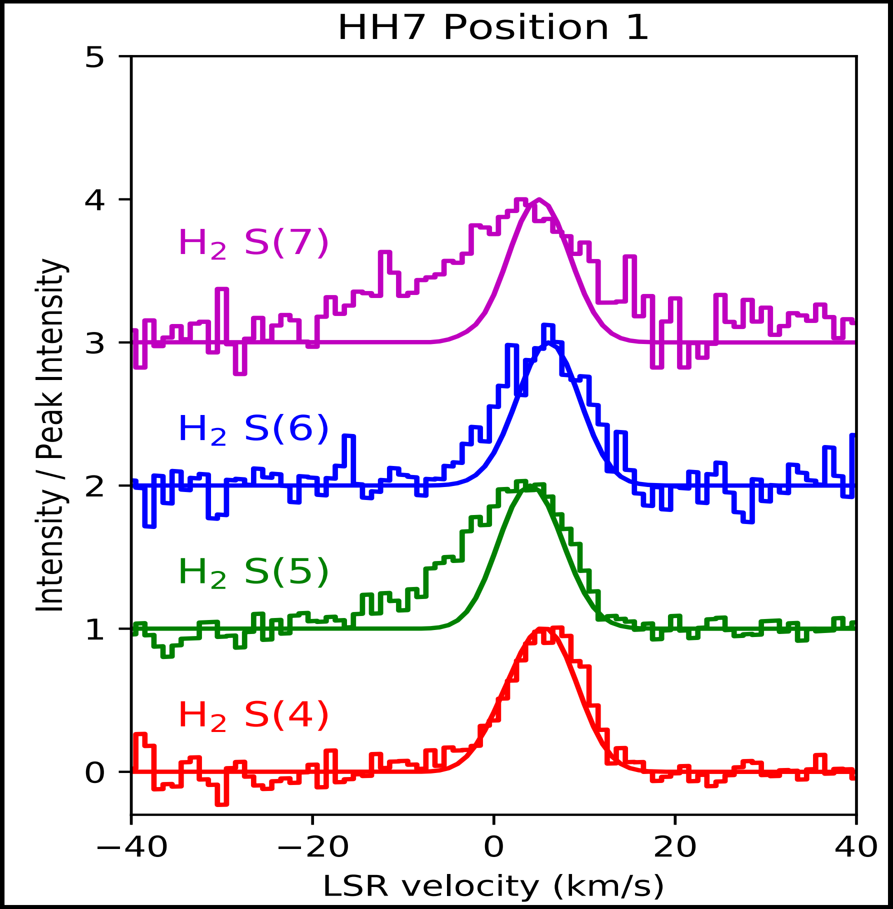


ORTHO/PARA RATIO OF H_2

- Spectrally resolved observations in HH7 (EXES/SOFIA)
- Velocity shift between ortho and para H2 lines ➔ large OPR variation
- only explained with C-shock model (10^4 cm^{-3}, 20 km/s, 130microG)

- (Neufeld+2018)



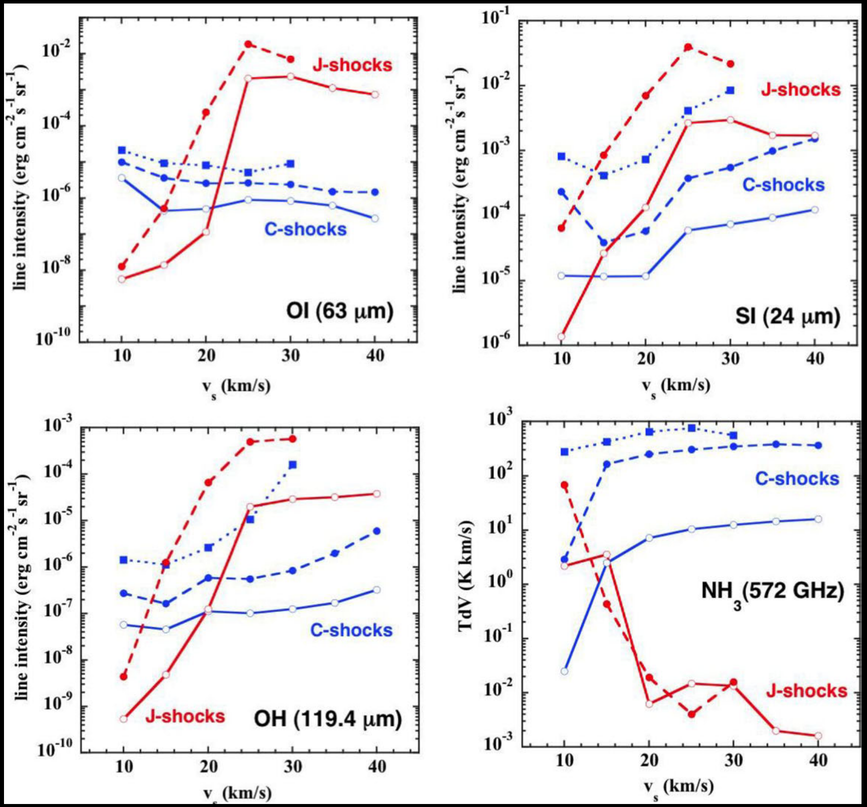


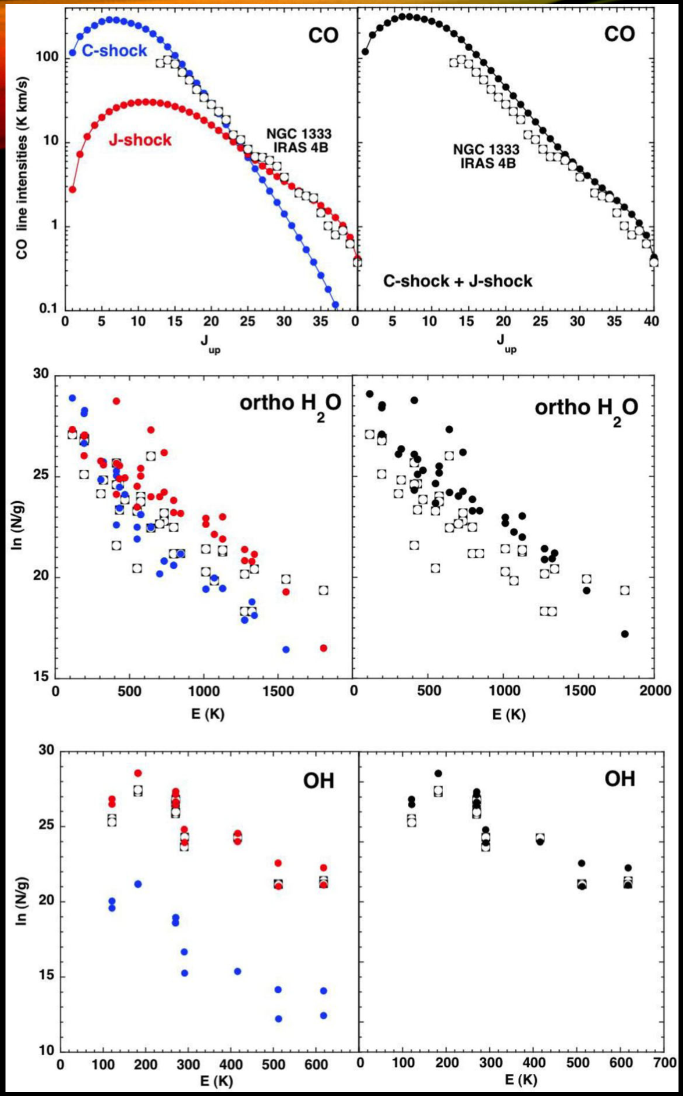
OTHER MOLECULES

- Flower & Pineau des Forêts 2010: CO and H_2O in C and J shocks
- Flower et al. 2010: Methanol in C-shocks
- Flower & Pineau des Forêts 2012: NH_3 emission in C-shocks, **Effect of age**, **revised methanol and ammonia ice abundances**
- Pineau des Forêts et al. 2013 : OH emission as diagnostic of C vs. J shocks
- Flower et al. 2015 : detailed code description and updated atomic + molecular line predictions using LVG escape formalism

C VS J DIAGNOSTICS

- NB: NH3 in C-shocks depends on assumed initial ice abundance (ill-known)
- NB2: absolute fluxes depend on « filling-factor » ➔ look at relative line fluxes (excitation diagrams)



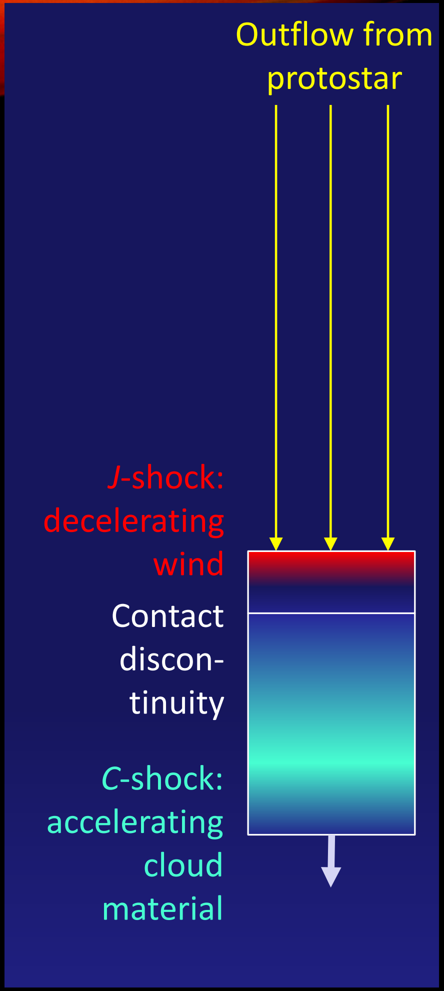


EXAMPLE: IRAS4A

- Herschel PACS data

Flower & Pineau des Forêts 2013

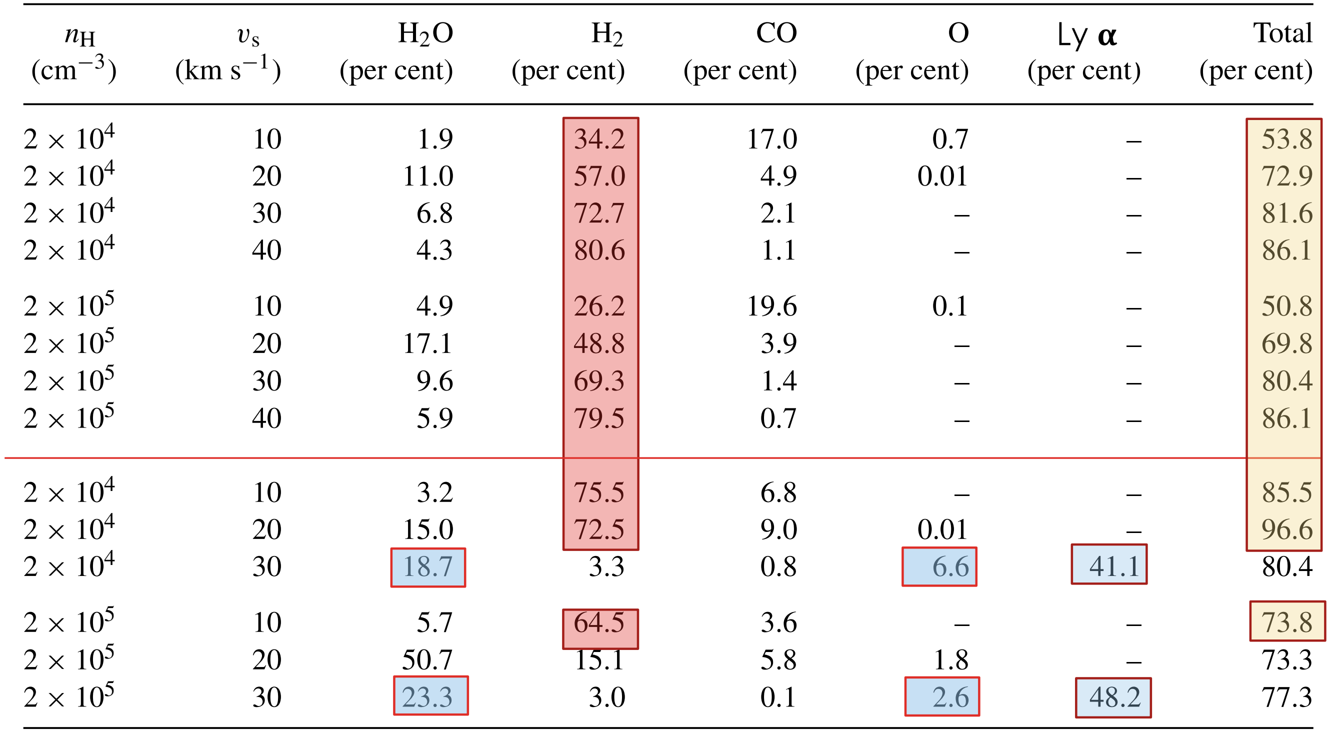
DOUBLE SHOCK STRUCTURE



« BOLOMETRIC METHOD »

- **H_2 main coolant in non-dissociative shocks** (25%-80%): **useful « bolometric » tool at Vs < 30 km/s**
- CO % and H_2O % depend too strongly on (nH,Vs) (but improve total % if added to H_2)
- **O and H lines ➔ dissociative J-shocks**

% of kinetic energy flux ½ ρV_s^3 radiated by shock tracers:



C-type

J-type

n_H (cm^{-3})	v_s ($km\ s^{-1}$)	H_2O (per cent)	H_2 (per cent)	CO (per cent)	O (per cent)	Ly α (per cent)	Total (per cent)
2×10^4	10	1.9	34.2	17.0	0.7	–	53.8
2×10^4	20	11.0	57.0	4.9	0.01	–	72.9
2×10^4	30	6.8	72.7	2.1	–	–	81.6
2×10^4	40	4.3	80.6	1.1	–	–	86.1
2×10^5	10	4.9	26.2	19.6	0.1	–	50.8
2×10^5	20	17.1	48.8	3.9	–	–	69.8
2×10^5	30	9.6	69.3	1.4	–	–	80.4
2×10^5	40	5.9	79.5	0.7	–	–	86.1
2×10^4	10	3.2	75.5	6.8	–	–	85.5
2×10^4	20	15.0	72.5	9.0	0.01	–	96.6
2×10^4	30	18.7	3.3	0.8	6.6	41.1	80.4
2×10^5	10	5.7	64.5	3.6	–	–	73.8
2×10^5	20	50.7	15.1	5.8	1.8	–	73.3
2×10^5	30	23.3	3.0	0.1	2.6	48.2	77.3

H_2 BOLOMETRIC METHOD APPLIED

Maret et al. 2009

- *Spitzer:* H_2 pure rotational lines from outflows in NGC1333 (green in image)

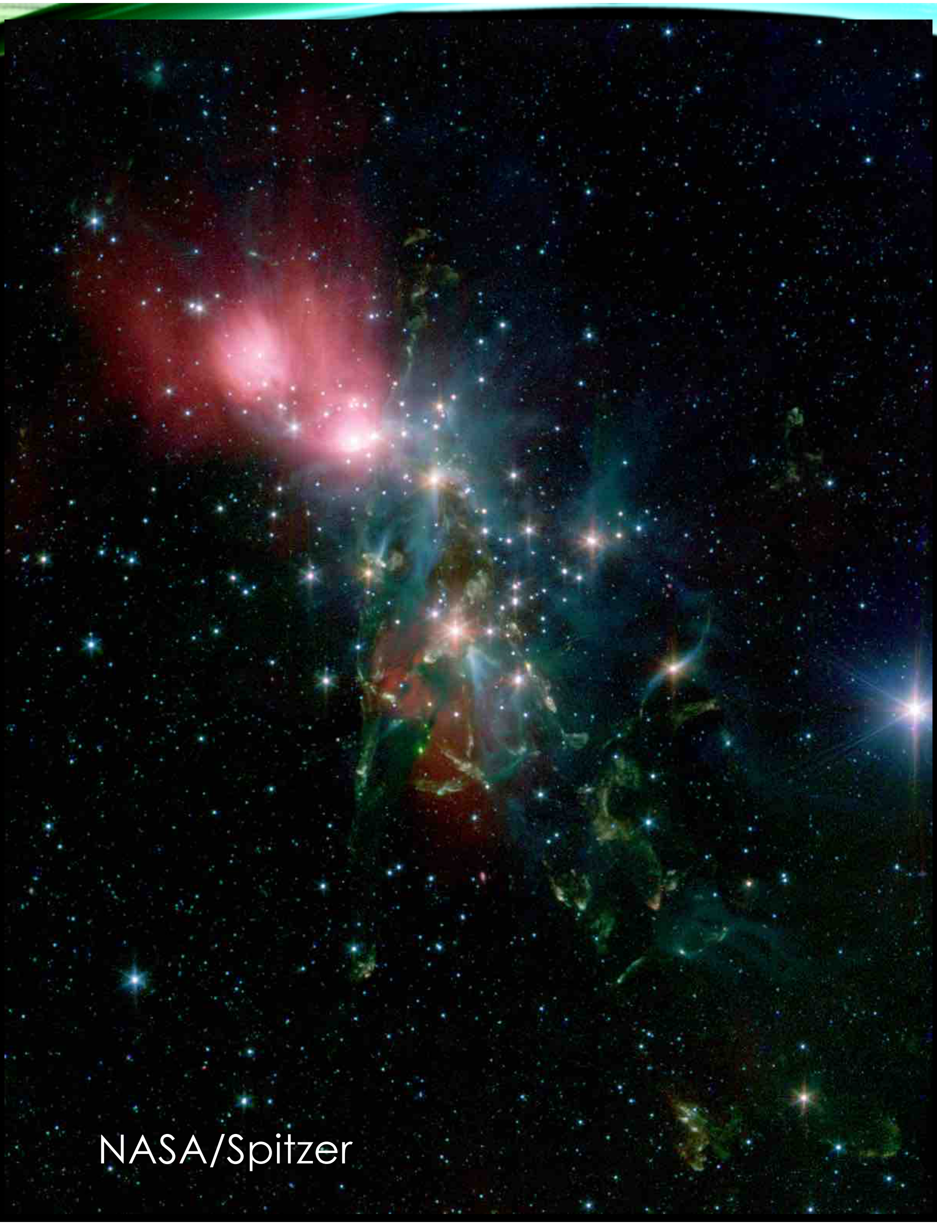
  C-shocks at Vs ~ 20-30 km/s
- L(H2) ➔ KE flux in shock = Lmech

  ➔ **Momentum injection rate** :

  P_s = 2 Lmech / Vs

  = 2-5 10^{-5} M⊙ km/s /yr   per flow
- **After $2x10^5$ yr, each flow imparts 1 km/s turbulence in 5M⊙**

  20 flows: 100 M⊙= 30% of cloud mass



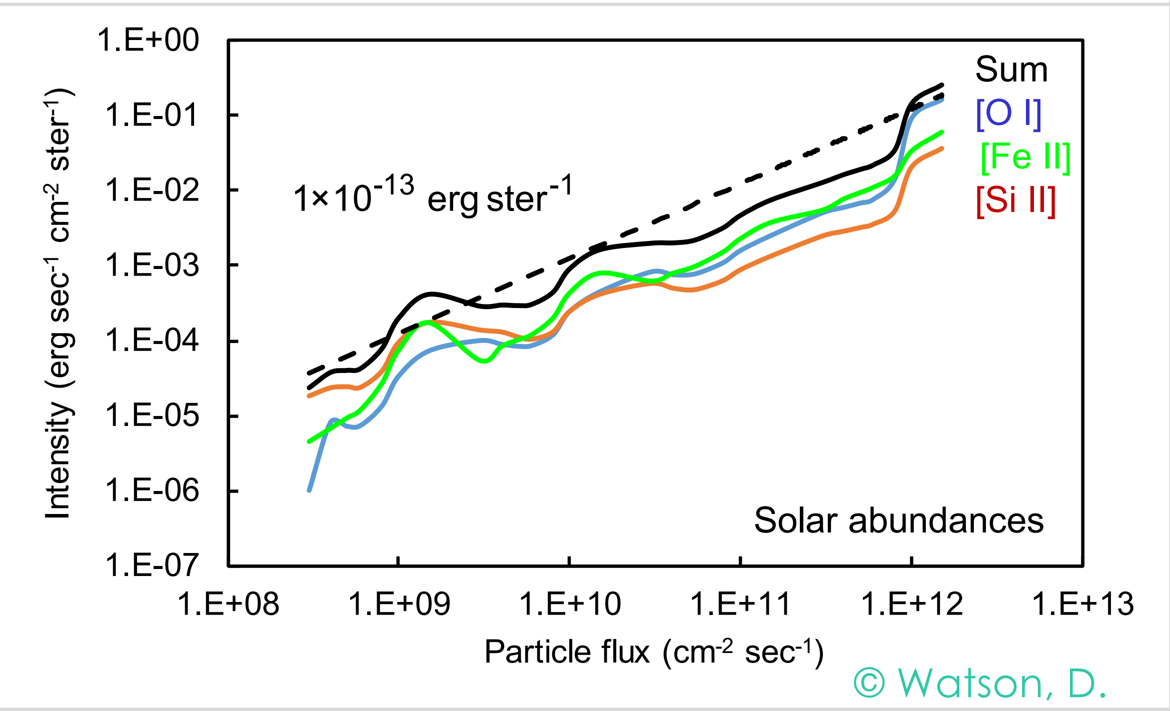
NASA/Spitzer

« BOLOMETRIC METHOD » FOR DISSOCIATIVE SHOCKS

- [O I] 63mic flux is (roughly) proportional to mass-flux into shock (Hollenbach 1985)
- Same for [Fe II]26mic and [Si II]35mic

$$
\begin{aligned}
\dot{M}_w &= 8.1 \times 10^{-5} L([\mathrm{O\ I}]\ 63.2\ \mu\mathrm{m}) \frac{M_\odot\ \mathrm{year}^{-1}}{L_\odot} \\
&= 9.8 \times 10^{-4} L([\mathrm{Si\ II}]\, 34.8\ \mu\mathrm{m}) \frac{M_\odot\ \mathrm{year}^{-1}}{L_\odot} \\
&= 1.4 \times 10^{-3} L([\mathrm{Fe\ II}]\, 26.0\ \mu\mathrm{m}) \frac{M_\odot\ \mathrm{year}^{-1}}{L_\odot}.
\end{aligned}
$$

Watson+2016



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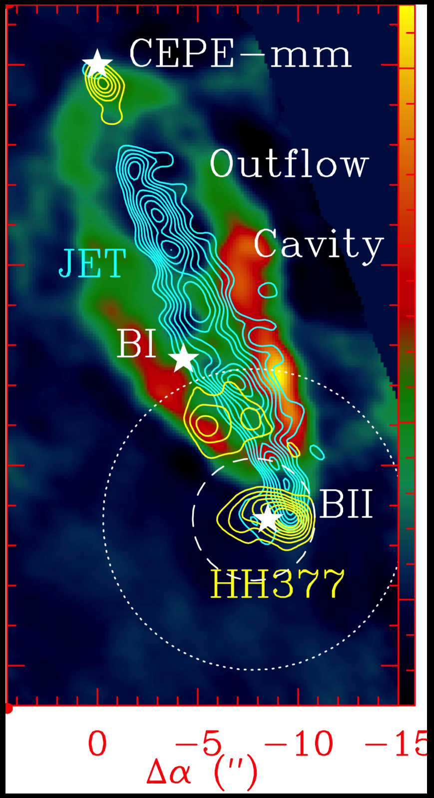
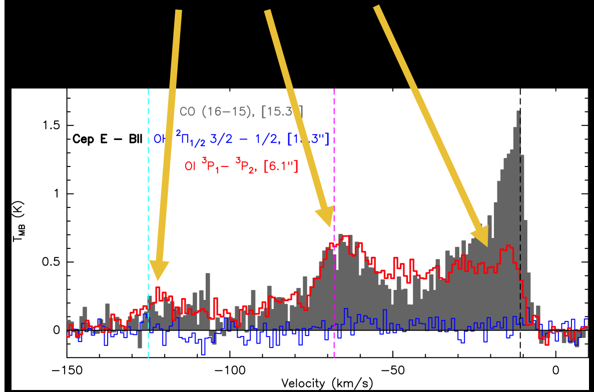
LIMITATIONS OF « BOLOMETRIC » METHODS

- Several shock fronts contribute to [O I] not just the final terminal shock
  - Overestimate mass-flux in jet/wind
- Need spectrally (SOFIA-GREAT, EXES) and spatially (JWST, ALMA, NOEMA) resolved observations of shocks to separate components



- 3 components in [OI] profile (SOFIA) Gusdorf+2017



CONCLUSIONS

- Interstellar shock waves are complex systems to model, but very detailed public 1D models exist for different shock regimes
- Backward inversion is difficult exercice
  - Many free parameters: beware of degeneracies, combine constraints !
  - Several key atomic coolants (Fe+, S, Si+) may have grain depletion
  - When non-dissociative: Output radiation depends on preshock chemical conditions (ice mantles + ambient G0 and zeta): necessary to use self-consistent preshock before running models
  - May have several shock fronts in beam (reverse J + forward C): favor high angular resolution and spectral resolution: JWST, SOFIA and ALMA
- Fast progress in 2D/3D simulations including NEQ chemistry: new tool