Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

LE Ngoc Tram – LERMA/ENS - UMR 8112

le.ngoctram@lra.ens.fr

BOW-SHOCK CHEMISTRY IN THE INTERSTELLAR MEDIUM

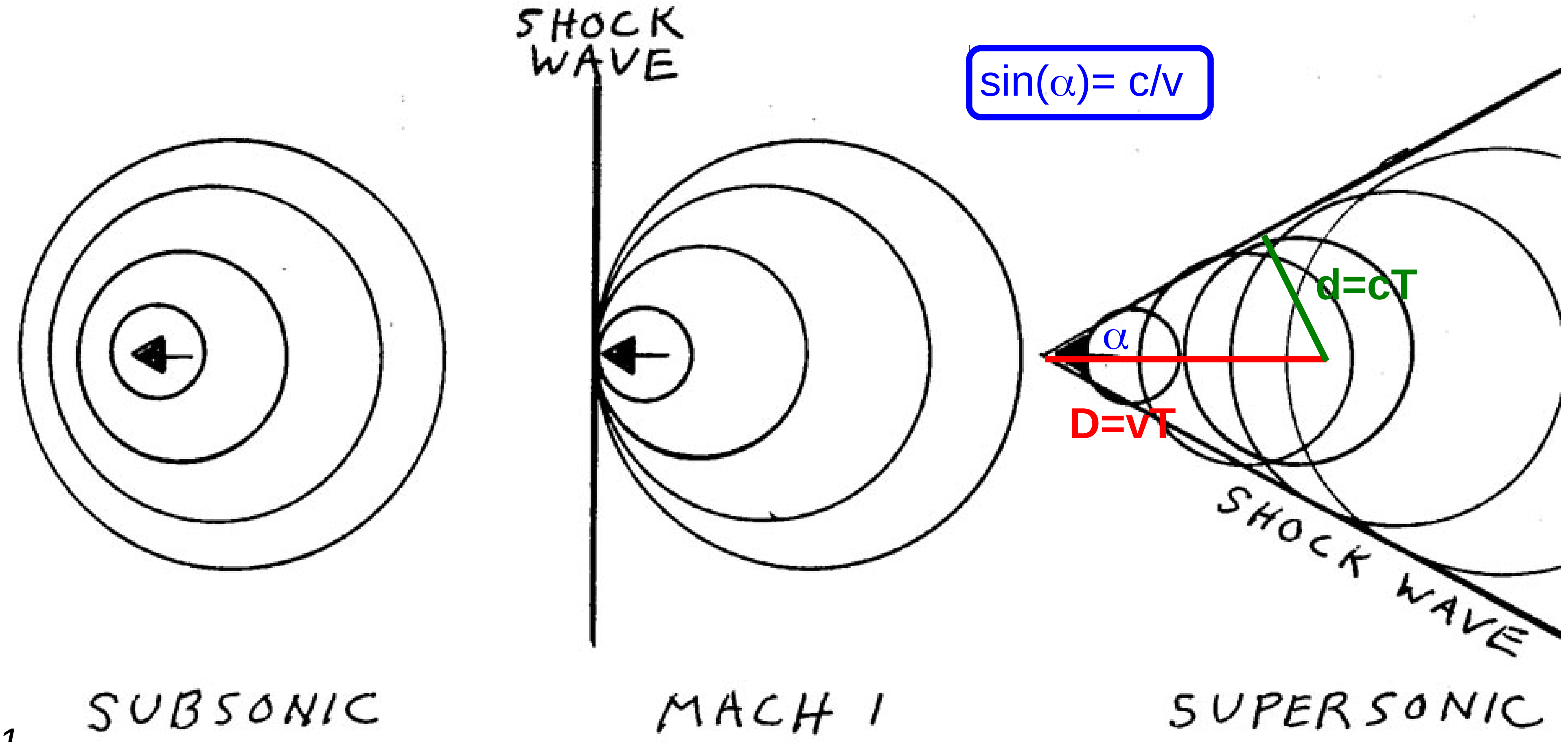
Sylvie CABRIT, Pierre LESAFFRE, PHAM T.T Nhung,
Antoine GUSDORF, Thibeau L. BERTRE and Benoit TABONE

Collaboration with DAP/VNSC-Vietnam

Blowing in the wind, Vietnam 09-08-2016

Overview

1. Shock wave definition



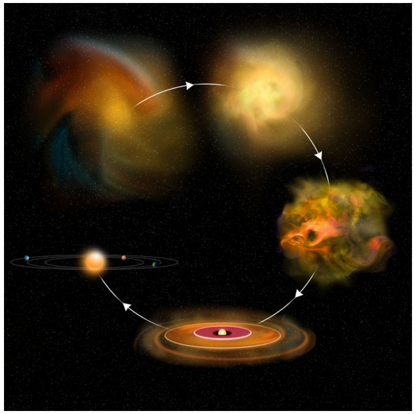
Overview:

3. Interstellar medium (ISM)

- ISM is the matter that exists in the space between the star systems.
- It includes gas, dust and cosmic rays, ...

2. The importance of shocks

- The shock-wave may not only lead to star formation.
- The shock-wave also quench star formation.
- Shocks have an important impact on the evolution of ISM, from a dynamic as well as from a chemical point of view.



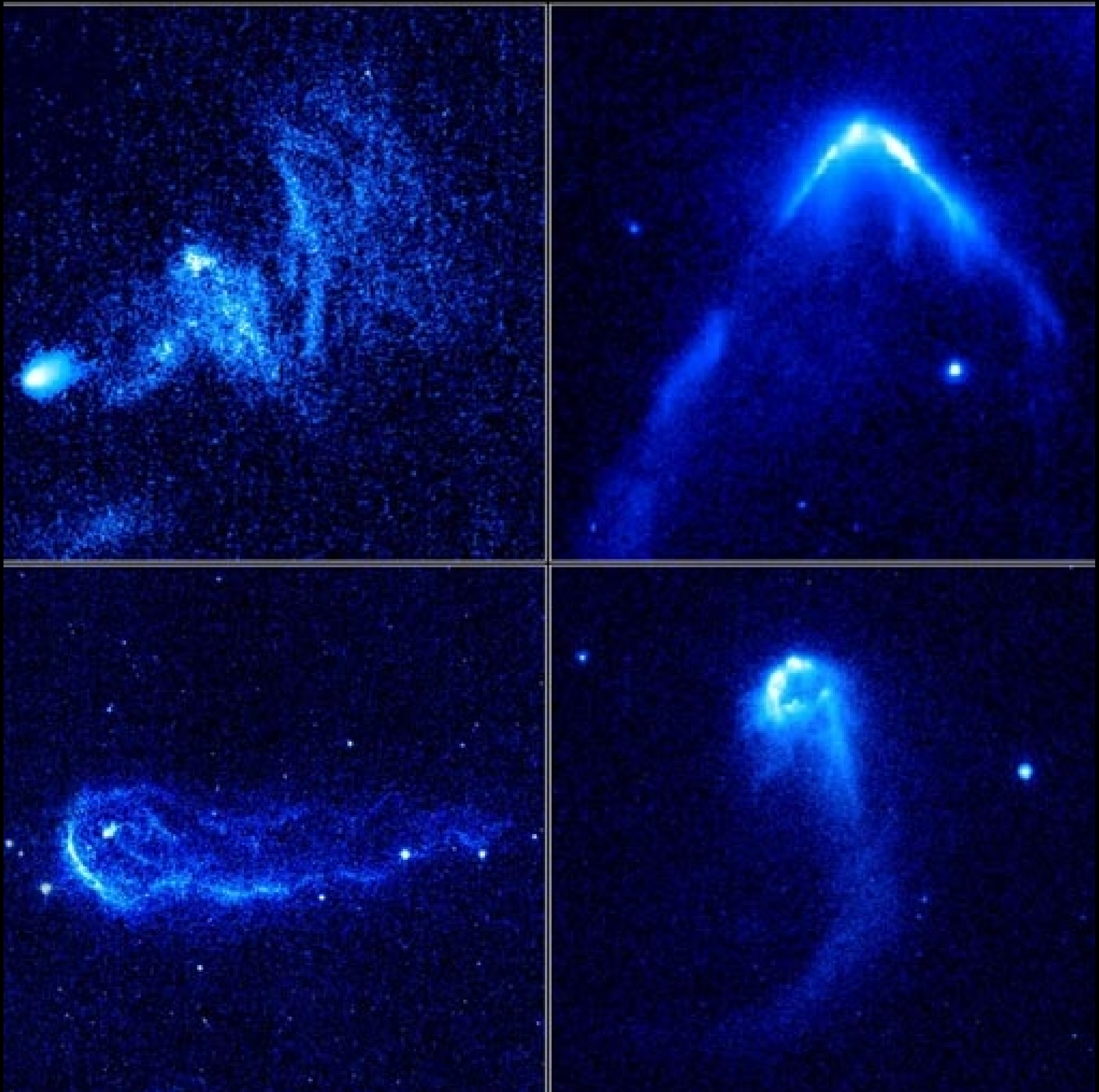
4. Objective of the thesis

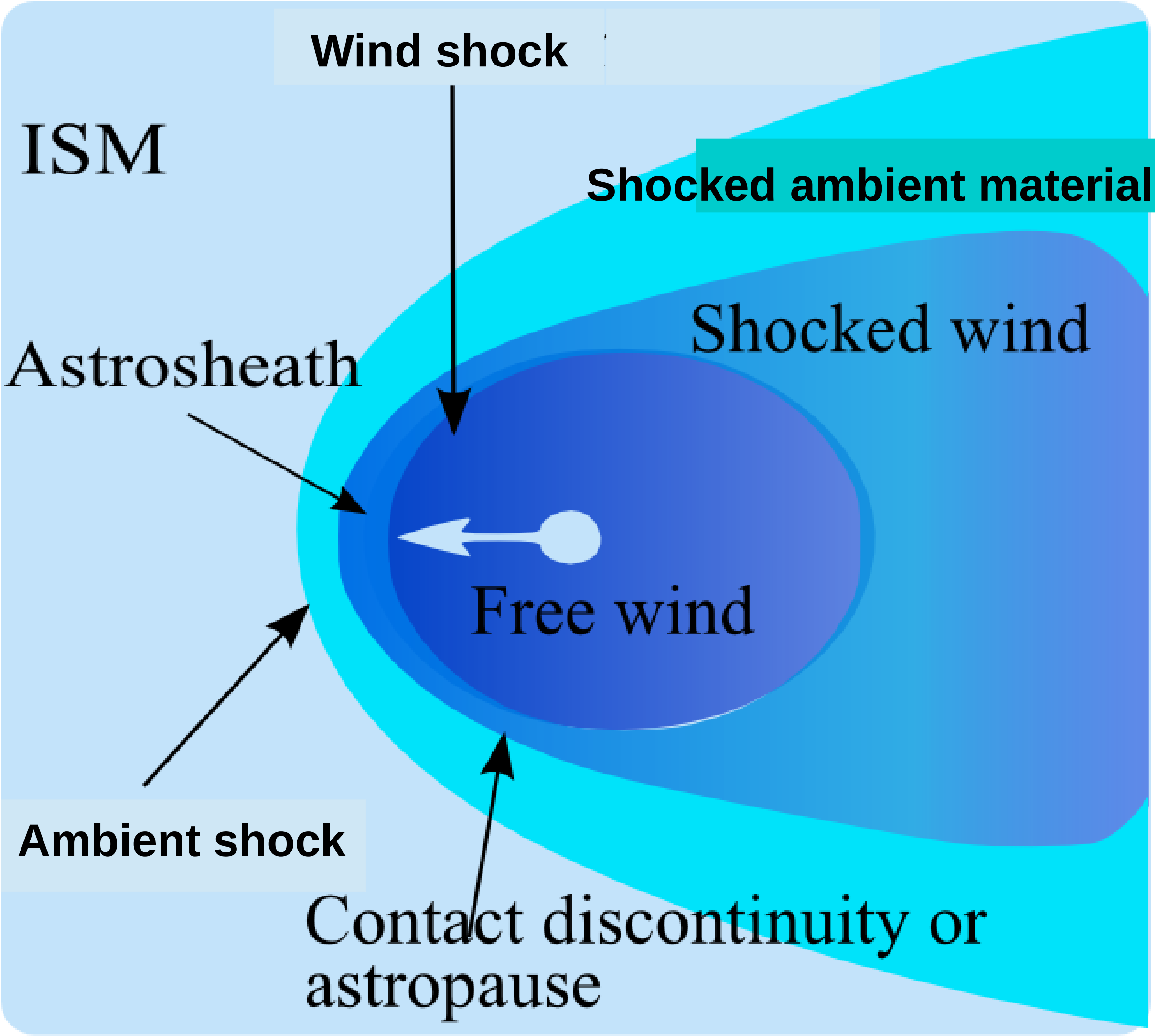
- Post-process chemistry in the shock model
- Build synthetic observations

Paris – Durham model

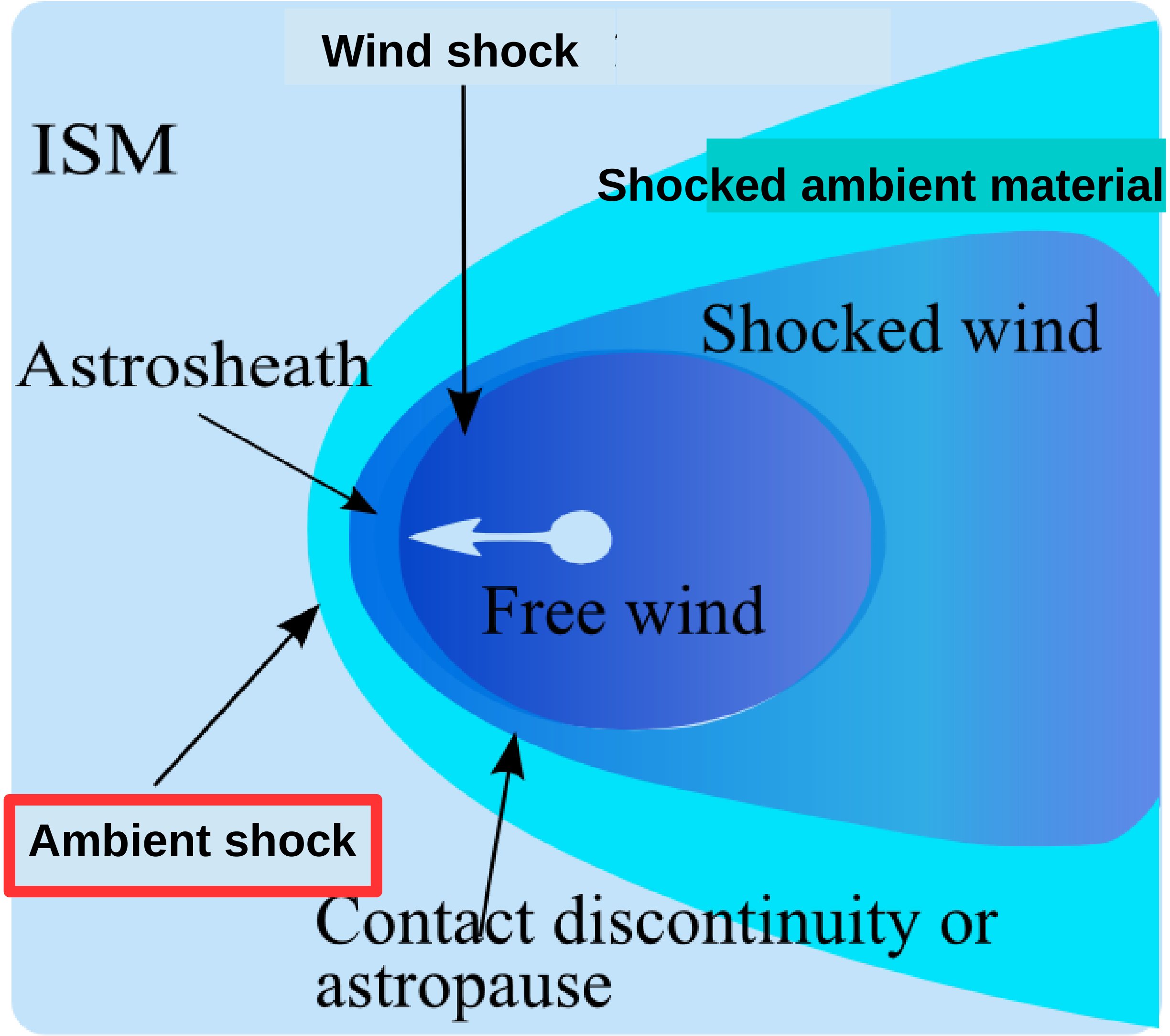
Flower & Pineau des Forêts 2015

“Mystic Mountain” A Pillar of Gas and Dust in the Carina Nebula



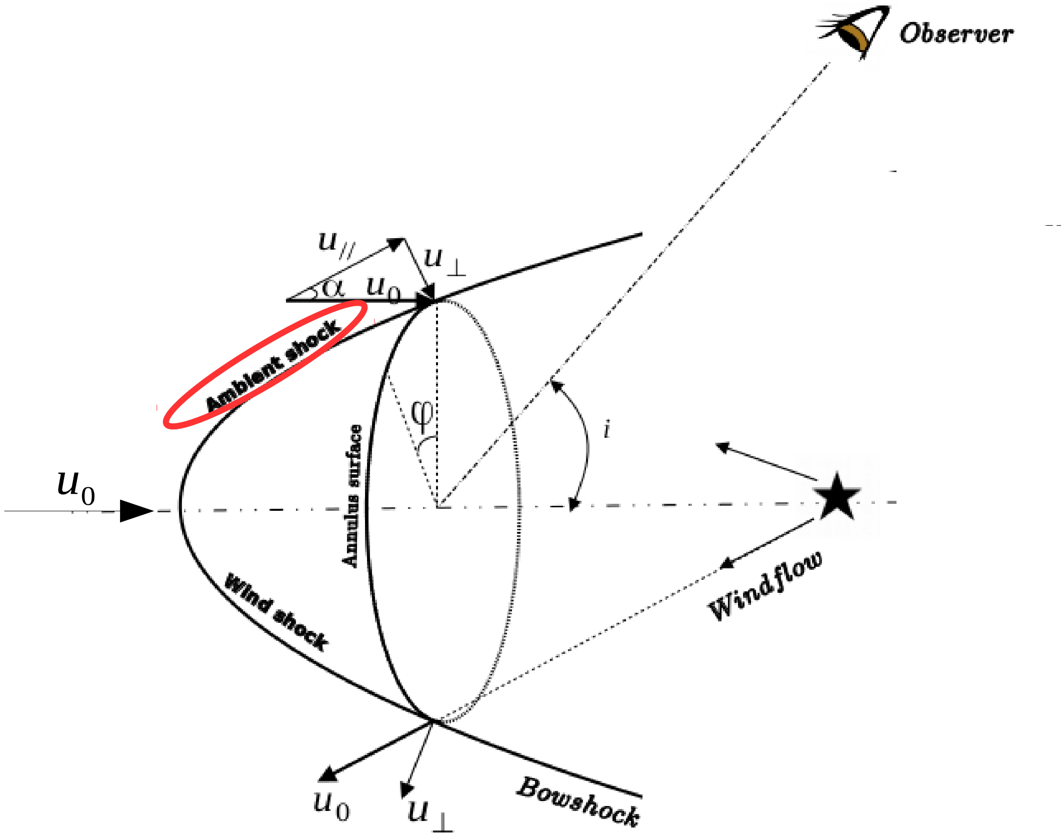


Sketching of bow-shock



Sketching of bow-shock

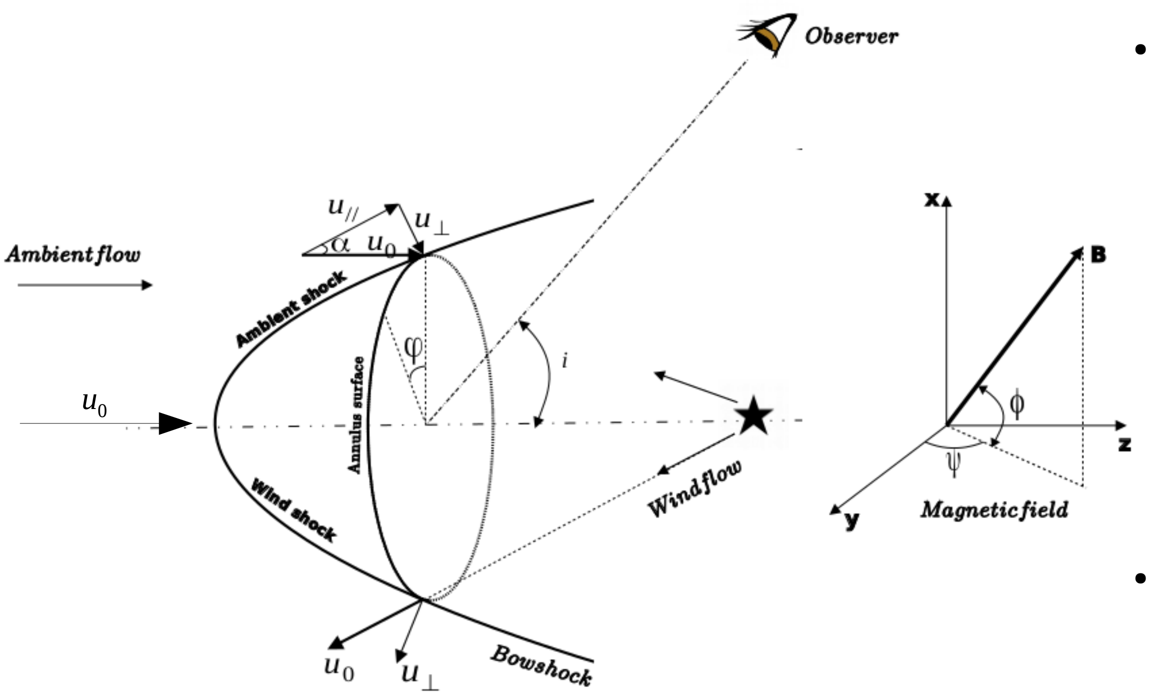
Ambient shock



Contents

- *1. Shock classifications*
- *2. Distribution of shock velocity*
- *3. Column density of H2*
- *4. H2 emission lines of H2*
- *5. Excitation diagram of H2*

Ambient shock



- The morphology of bow-shock is parameterize by:
  - Terminal shock velocity: u_0
  - Single shock position: α
  - Annulus angle: φ
  - Inclination angle: i
- The morphology of magnetic field:
  - Obliqueness angle: Φ
  - Rotation angle: ψ

Ambient shock

1. Shock classifications

- For 1D-shock: Just $u_\perp$ and B_{para} play a role

$u_\perp$ Planar (1D) shock velocity

B_{para} Effective magnetic field

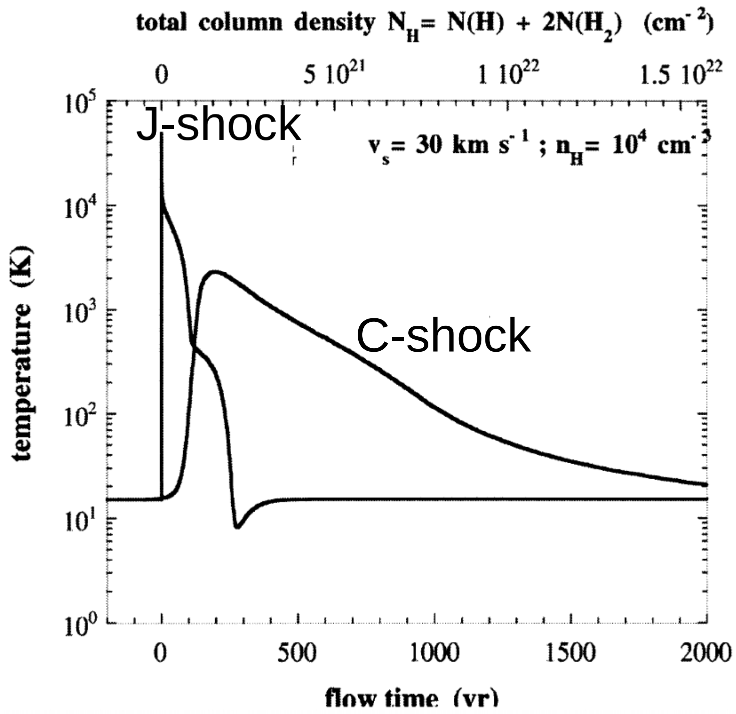
- Magnetosonic speed: $\boxed{v_{mag}=\sqrt{c_s^2+v_{AC}^2}}$

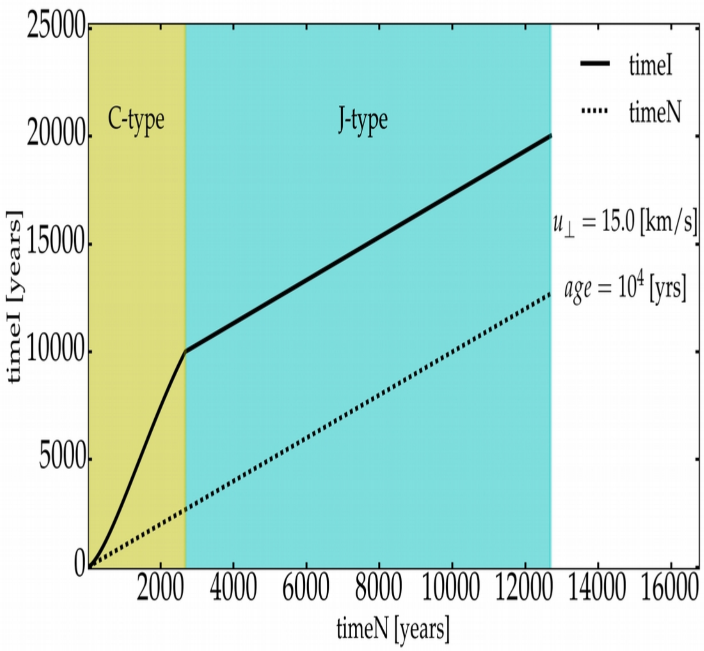
Where:

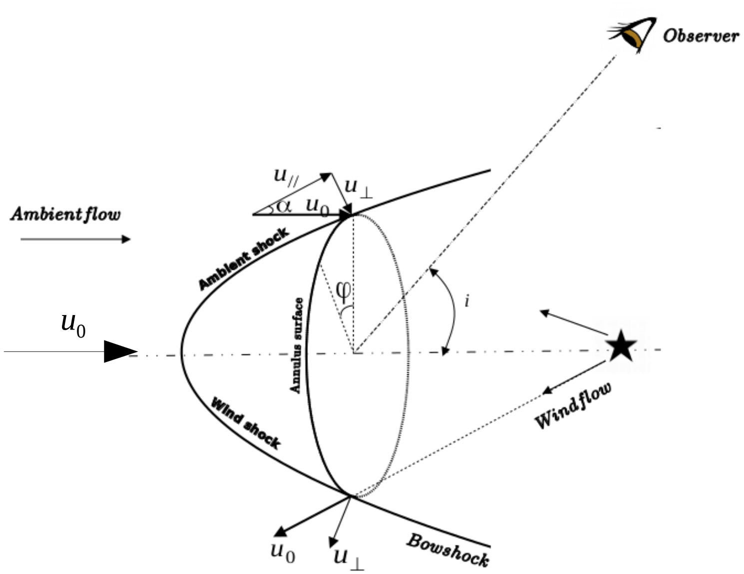
- Sound speed $c_s^2=\gamma k_B \frac{T}{\mu}$
- Alfven speed $v_{AC}^2=\frac{B^2}{4\pi\rho_c}$

- ***If $u_\perp$ > vmag : "Jump"-shock type***
- ***If $u_\perp$ < vmag : "Continuous"-shock type***
- ***Young age : CJ-shock type***

Paris-Durham code.
Flower & Pineau des Forêts 2015





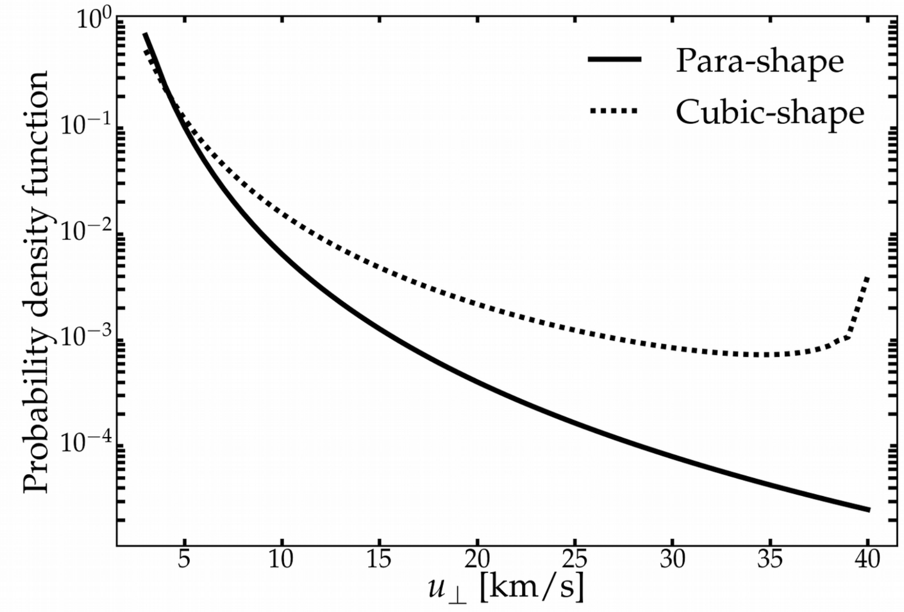


Ambient shock

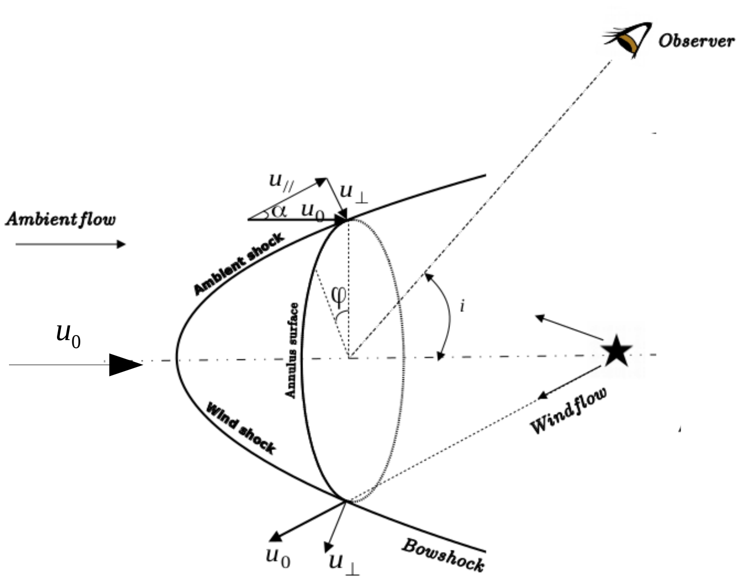
2. Distribution of shock velocity

- The surface fraction dS/dvs covered by each shock velocity can be seen as a distribution (PDF)

- We are able to analytically and numerically calculate the PDF with bow-shock shapes given as a parameter


Ambient shock

- In Para case, the PDF decreases respect to the local velocity $u_\perp$
- In Cubic case, the PDF also decreases respect to the local velocity $u_\perp$ increases, but when it approximates to u_0, the PDF likely becomes the delta function



Ambient shock

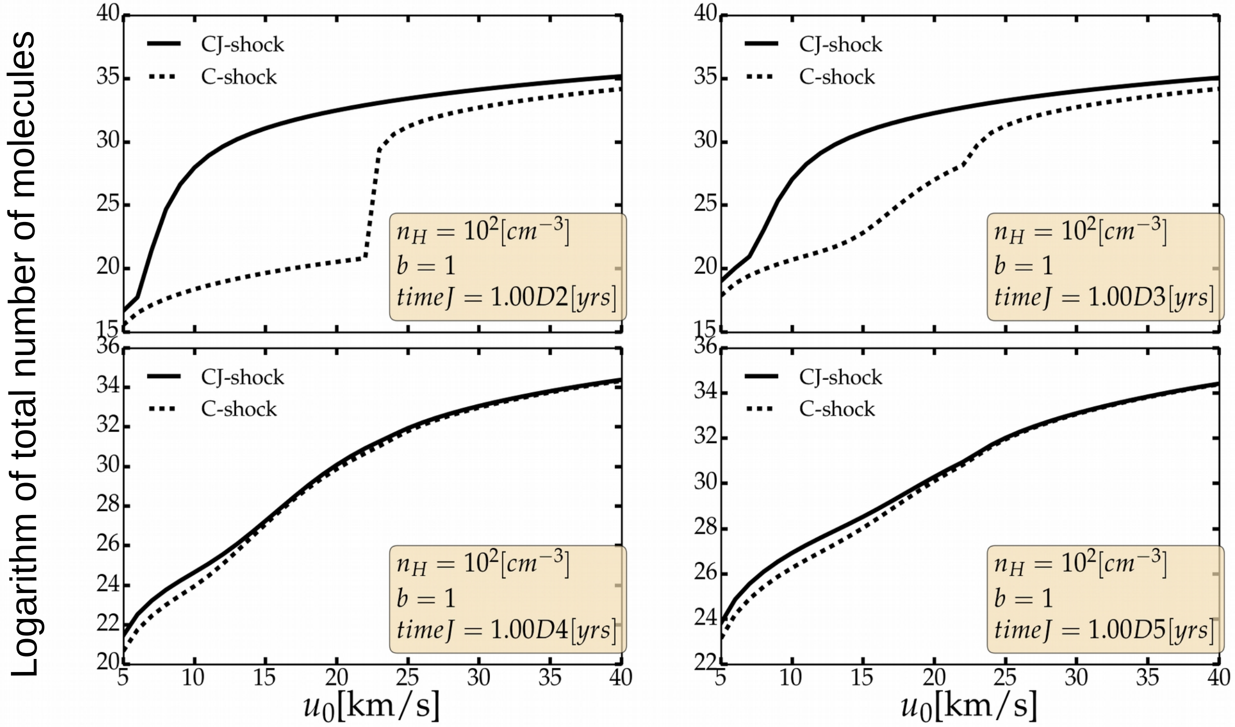
3. H2 Density number

- Distribution of number molecules

$$dN^i(u_\perp) = N^i(u_\perp).PDF(u_\perp, u_0).S_{\text{shock}}.du_\perp = N^i(u_\perp)\ ds(u_\perp)$$

- Total number molecules

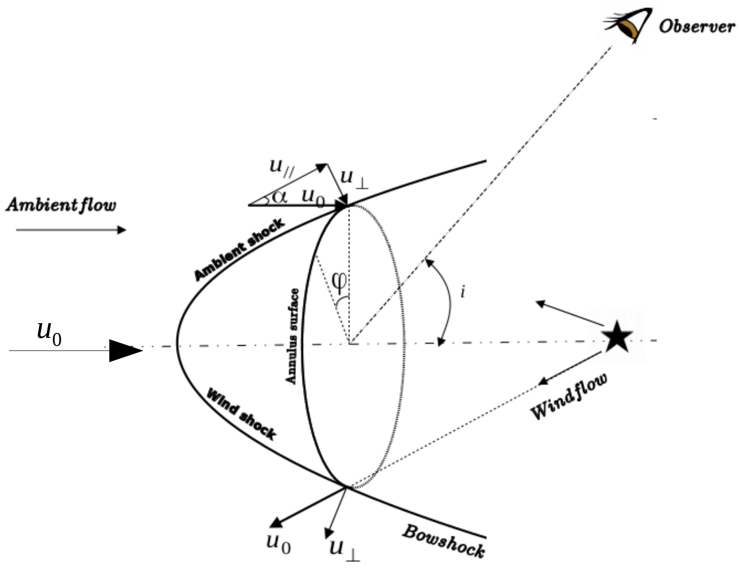
$$\boxed{N^i_{tot}(u_0) = \int_{c_s}^{u_0} dN^i(u_\perp)du_\perp}$$



Total number of molecules H2 - 1-0S(1)

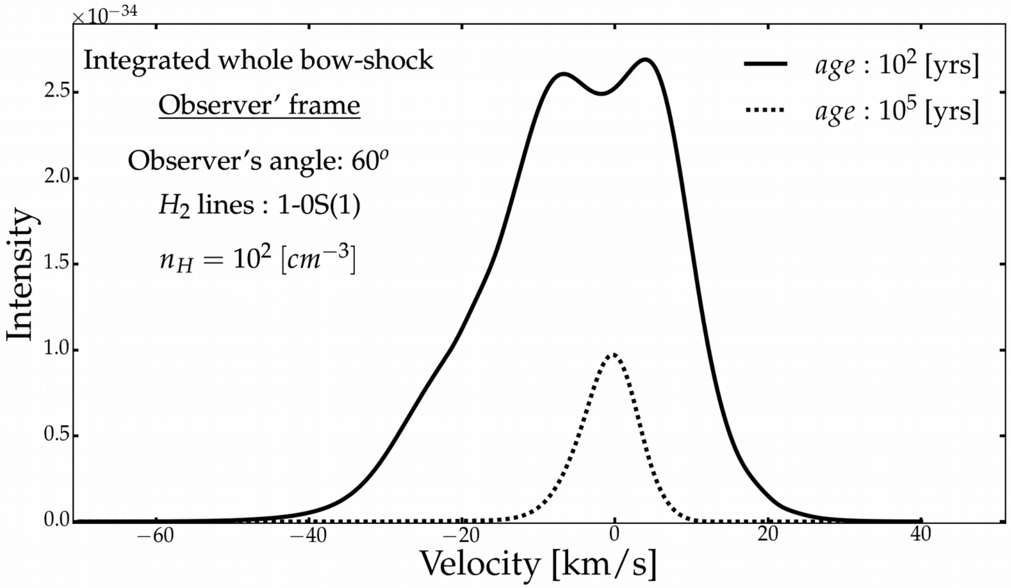
Ambient shock

4. H2 emission lines

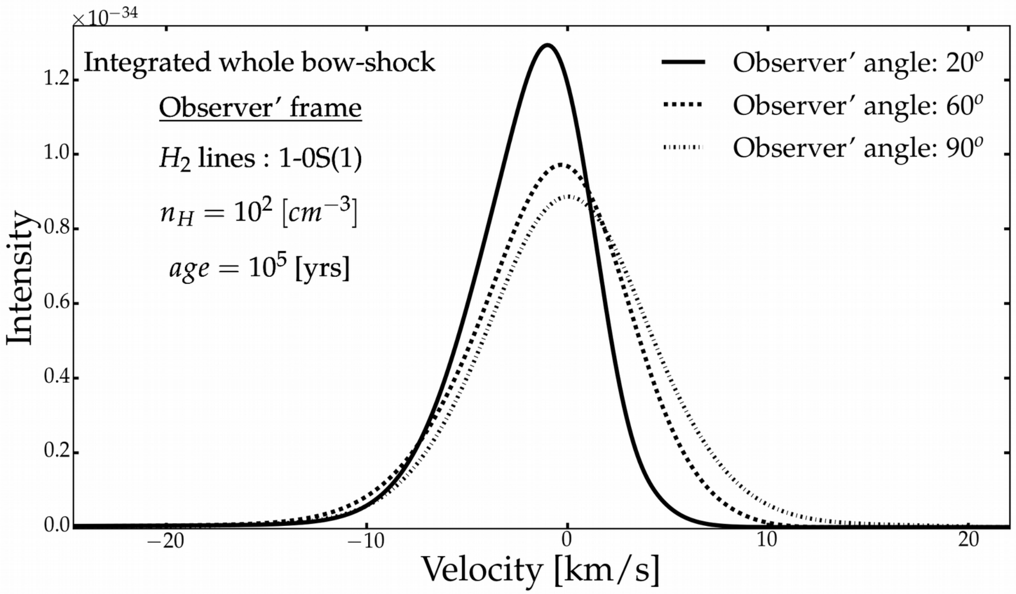


$$f(V,i) = \int_r \int_\alpha \int_\varphi \frac{R_0^2}{\sqrt{32\pi}\sigma_T(r,\alpha)}\epsilon(r,\alpha)e^{-\frac{[v(r,\alpha,\varphi)-V]^2}{2\sigma_T^2(r,\alpha)}} \frac{dr\ d\alpha\ d\varphi}{\tan\alpha\ \sin^3\alpha}$$

- Observer's frame: $v(r,\alpha,\varphi) = -\hat{\mathbf{n}}\ u_\perp\ (\zeta - 1)\ \hat{\mathbf{l}}$



H2 emission of bow-shock in different ages

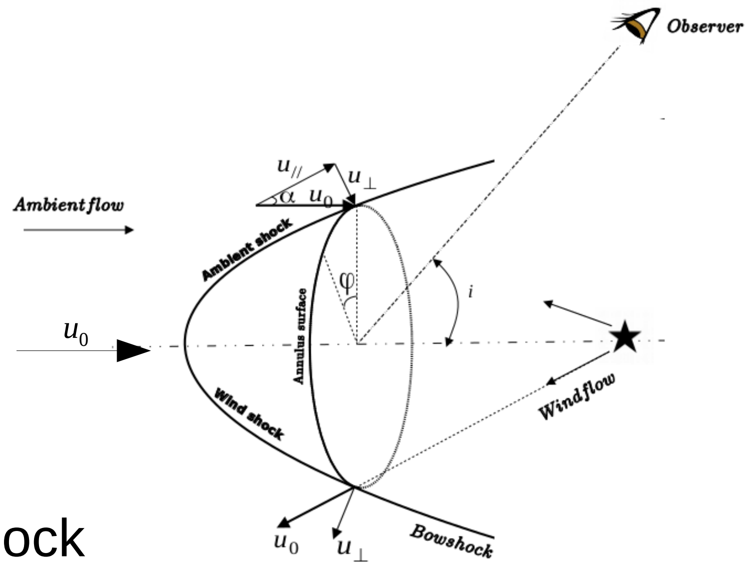


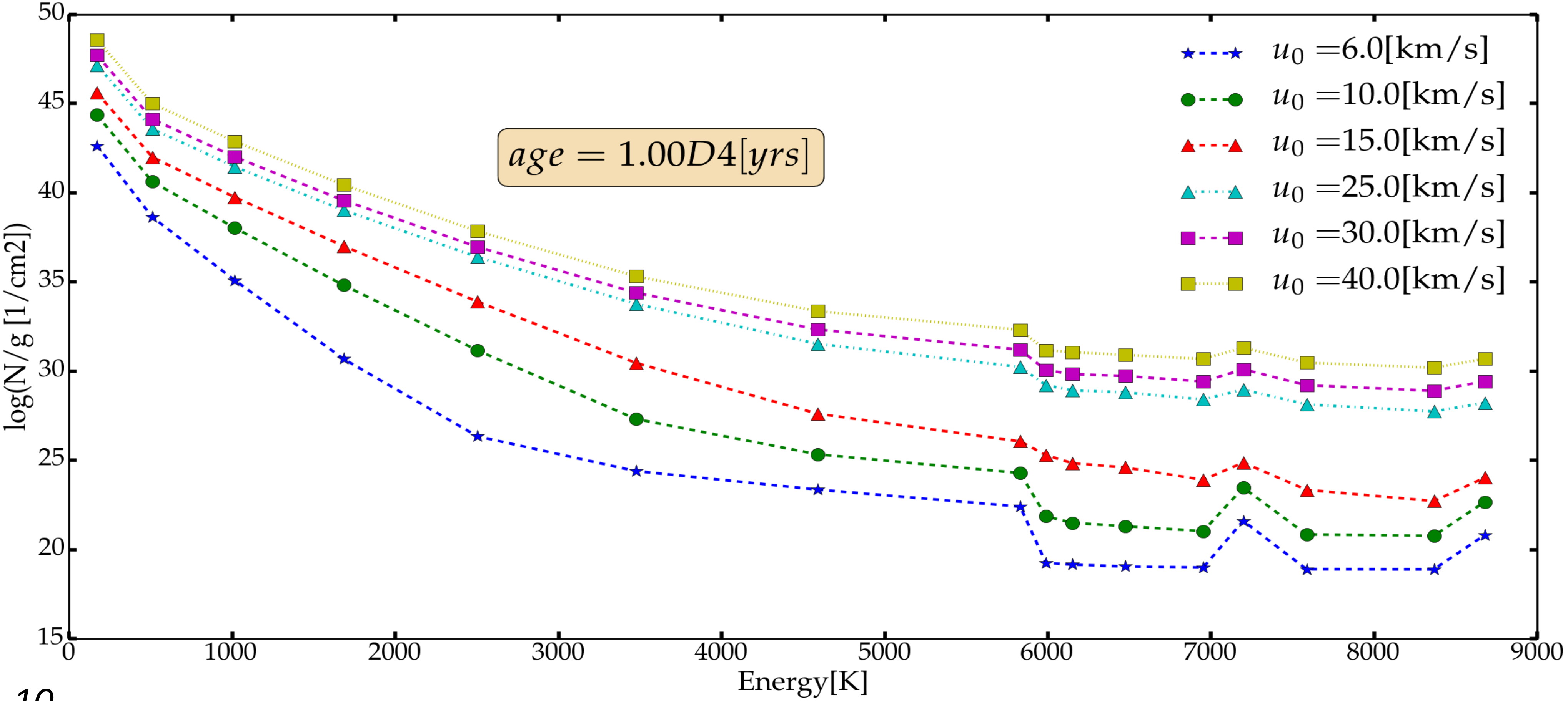
H2 emission of bow-shock in different angles

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

Ambient shock

5. H2 excitation diagram

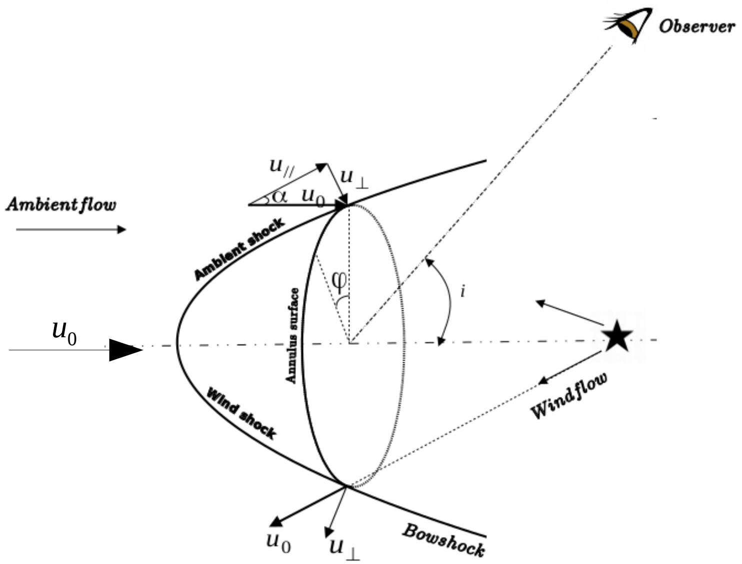


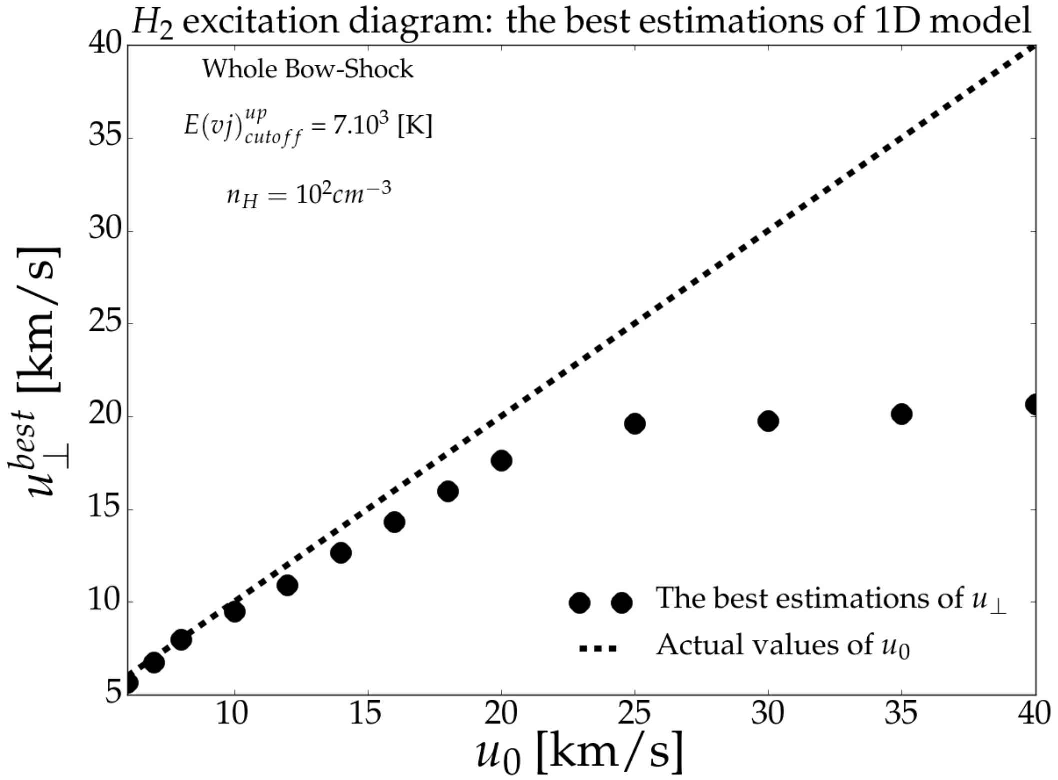

Excitation diagram in a bow-shock

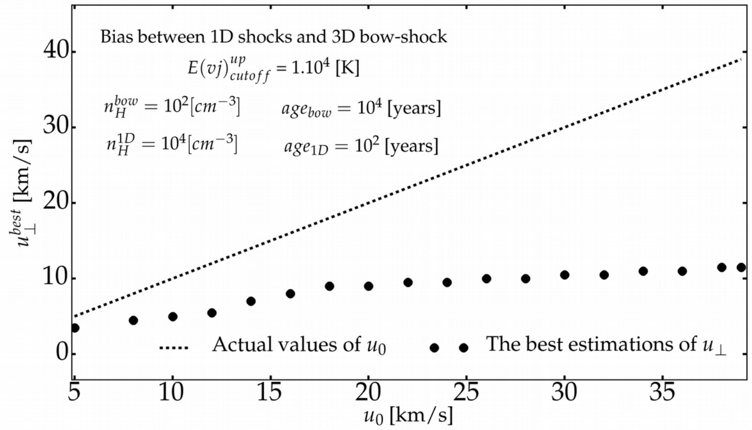
Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

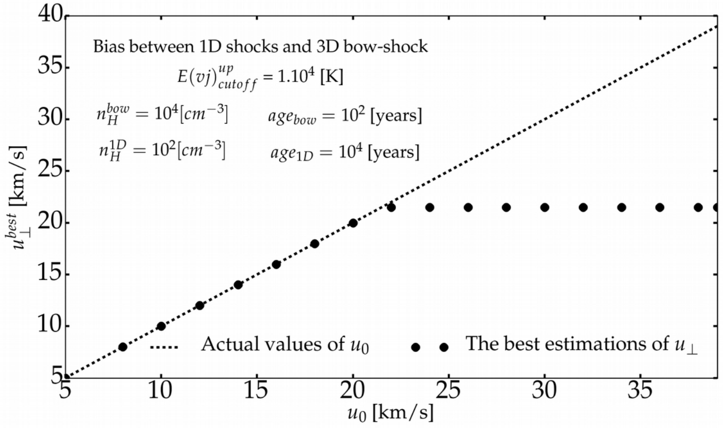
Ambient shock

5 H2 excitation diagram





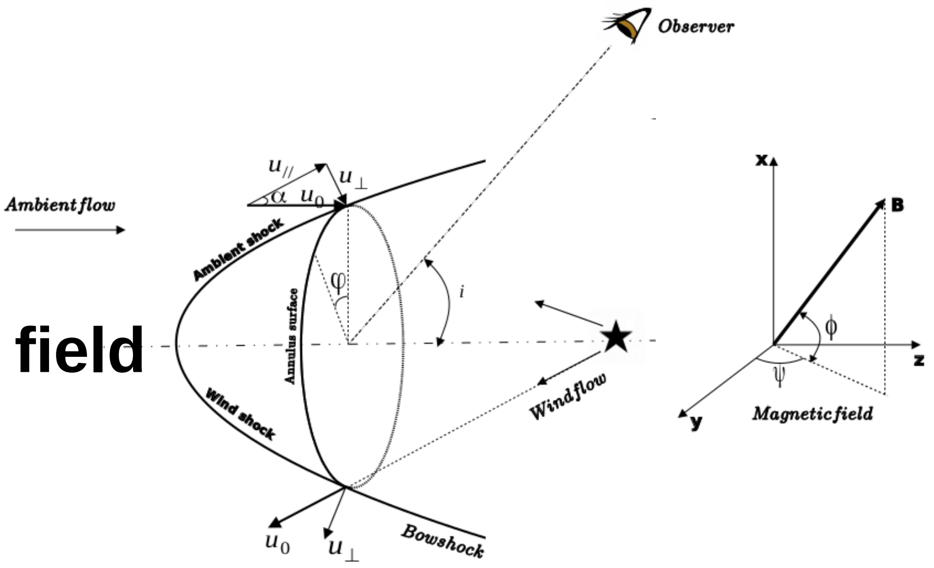


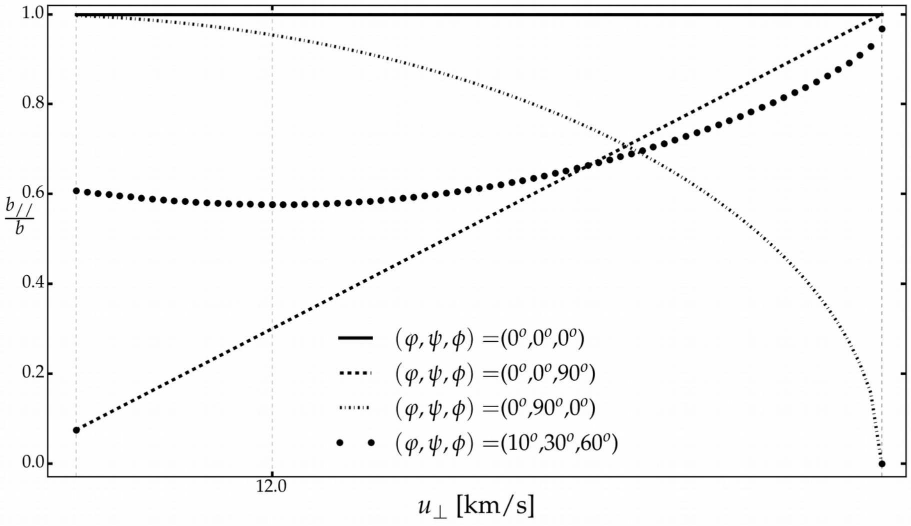


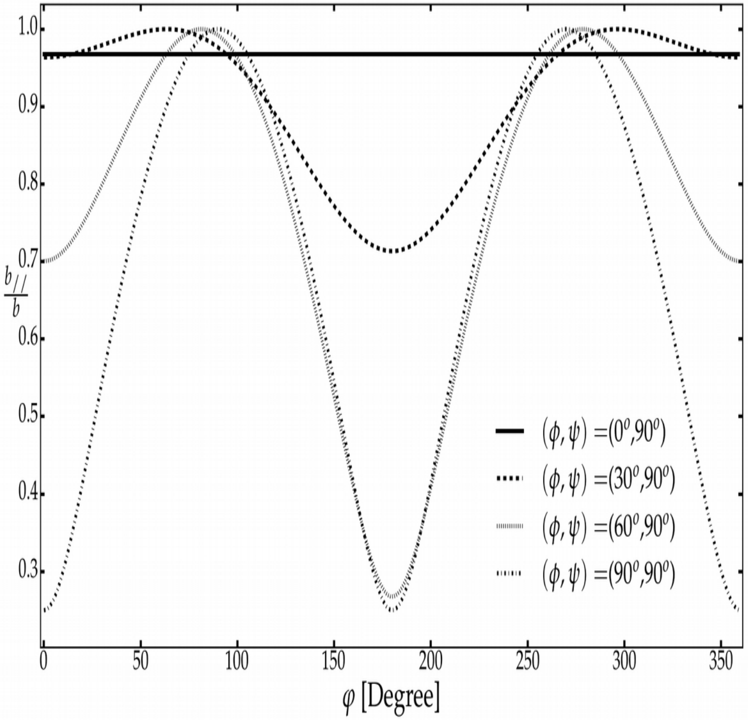
Fitting 1D to 3D model

Laboratoire d’Étude du Rayonnement et de la Matière en Astrophysique

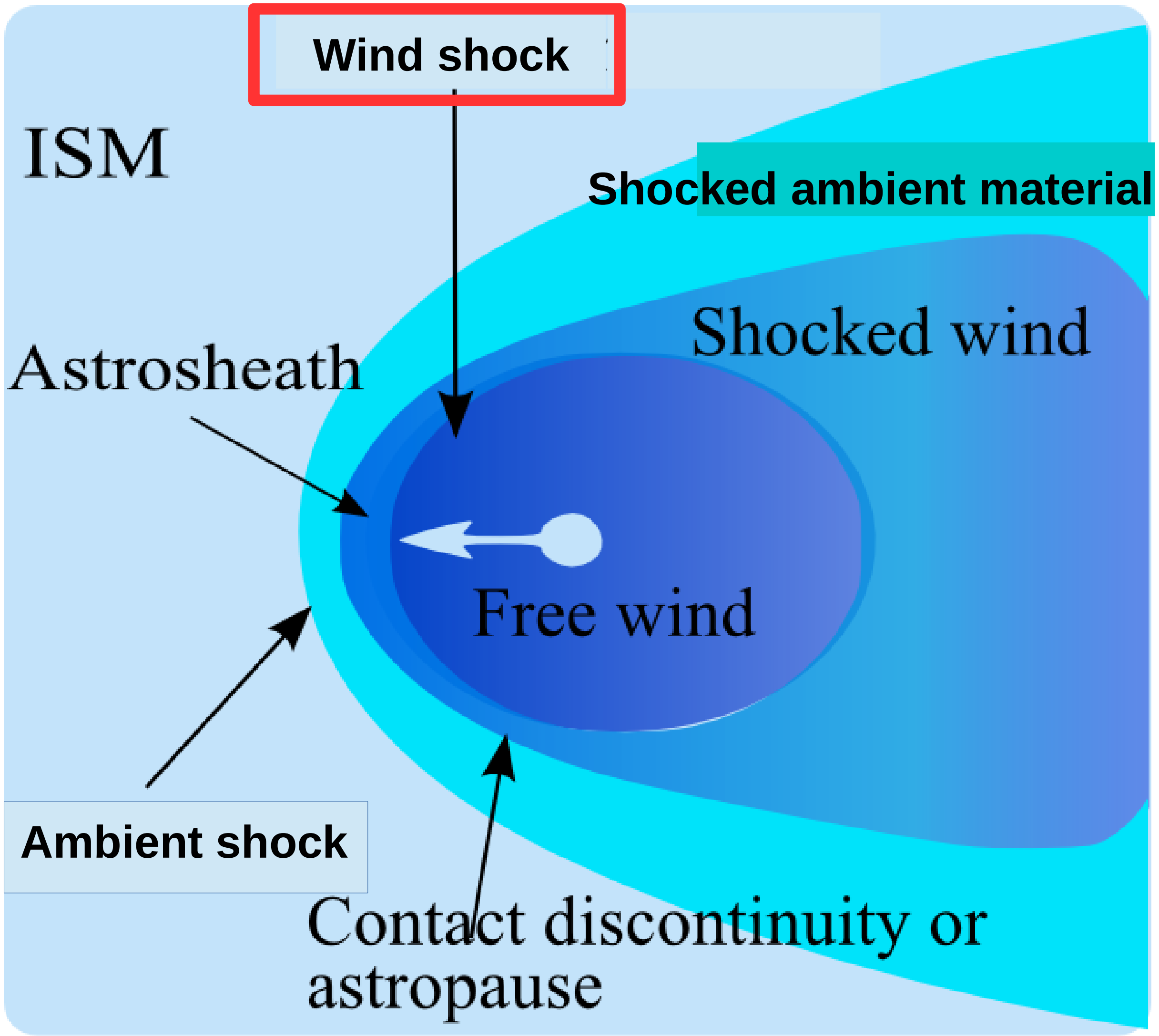
Discussion on orientation of magnetic field





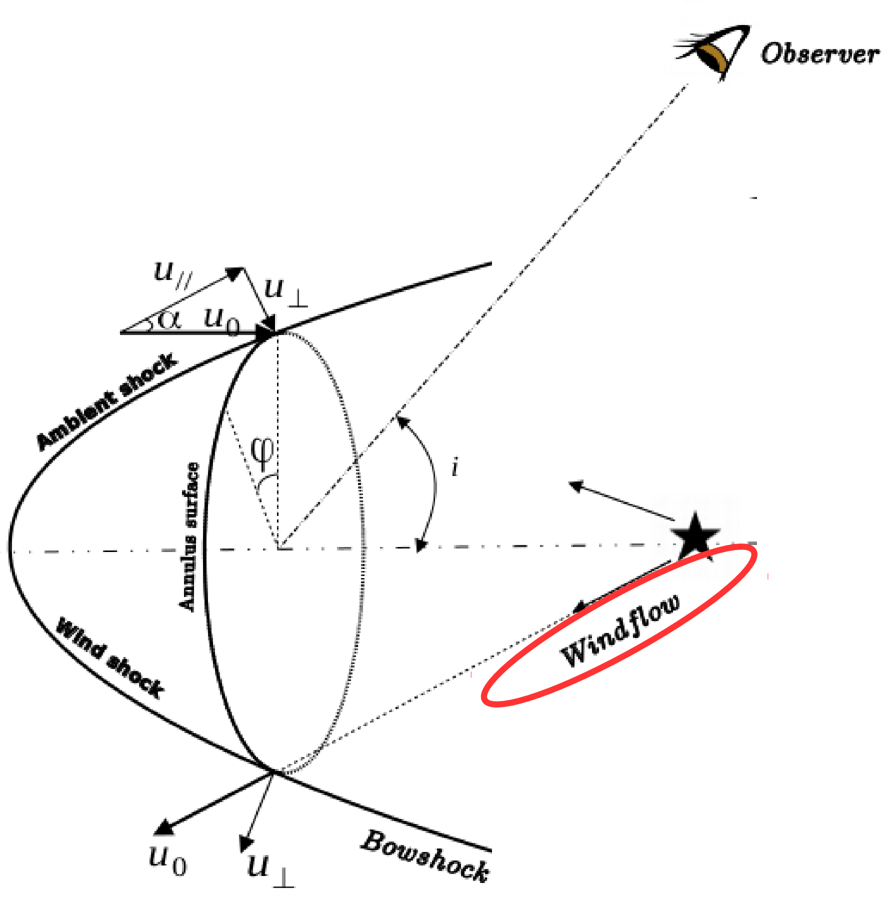


$$\frac{b_{//}}{b} = [1 - \sin^2\alpha[\tan^{-1}\alpha(\cos\varphi\sin\phi + \sin\varphi\cos\phi\cos\psi) - \cos\phi\sin\psi]^{2}]^{-1/2}$$



Sketching of bow-shock

Wind shock



Contents

Stellar wind

- *1. Stellar wind equations*
- *2. Ratio radiative force to gravitational force*
- *3. Preliminary results*

…

Stellar wind

1. Stellar wind equations

Dust component		Gas component
$\nabla \rho_d v_d = 0$	Mass conservation	$\nabla \rho v = 0$
$m_d v_d \partial \frac{v_d}{\partial} r = (\beta \frac{\rho_d}{\rho} - 1) F_{grav} - F_{drag}$	Momentum conservation	$\rho v \frac{\partial v}{\partial r} + \nabla P = -F_{grav} + F_{drag}$
	Energy conservation	$\nabla \rho v (\frac{1}{2} v^2 + \omega) = (H - C) - v F_{grav} + v F_{drag}$

$H : Heating \quad C : Cooling \quad \omega : enthanpy$

- *Radiative force on dust* $F_{rad} = \frac{L_{star}}{4 \pi r^2 c_l} \sigma_d \bar{Q}rp$
- *Gravitational force on dust* $F_{grav} = G \frac{M_{star} \rho_d}{r^2}$
- *Drag force on dust* $F_{drag} = \rho_g \sigma_d (v_d - v)[c_s^2 + (v_d - v)^2]^{1/2}$

→ $\boxed{\beta = \frac{F_{rad}}{F_{grav}}} > \frac{\rho}{\rho_d}$ *(Threshold)*

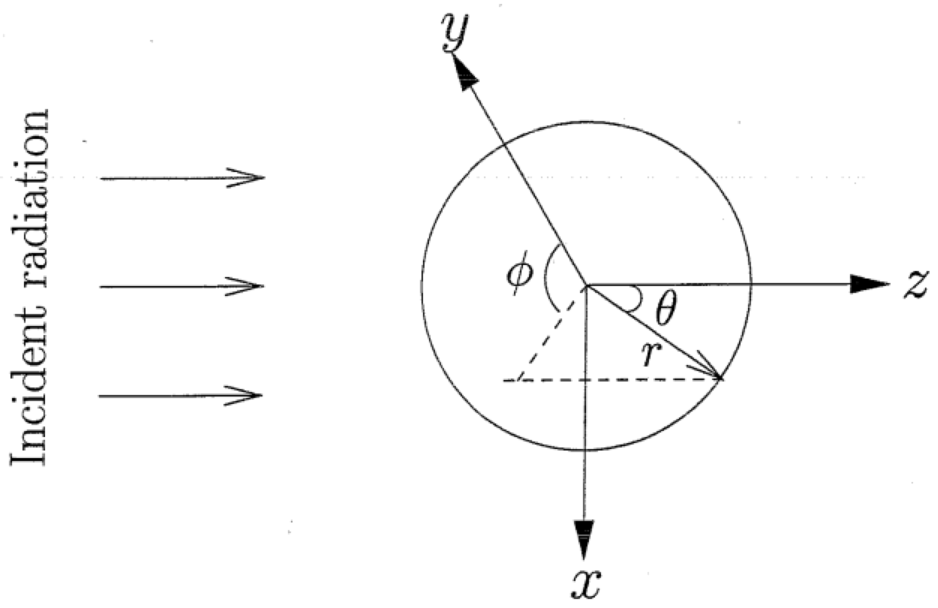
Stellar wind

2. Ratio radiative to gravitational forces

$$\boxed{\beta_d = 0.57 \overline{Q}_{rp} (a/\mu m)^{-1} (L_{star}/L_{sun}) (M_{sun}/M_{star}) (\rho_{rock}/gcm^{-3})^{-1}}$$

Where: $Qrp = Qsca + Qext(1 - <\cos(\theta)>)$

- *Qrp: Radiation pressure efficiency*
- *Qsca: Scattering coefficient*
- *Qext: Extinction coefficient*
- *<cos(theta)>: Phase function*



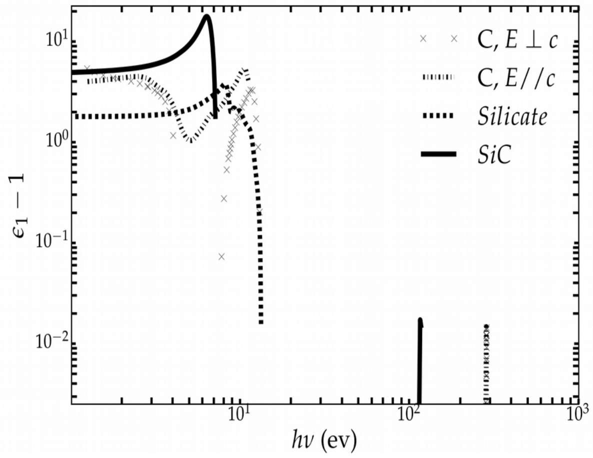
Spherical dust-grain particle

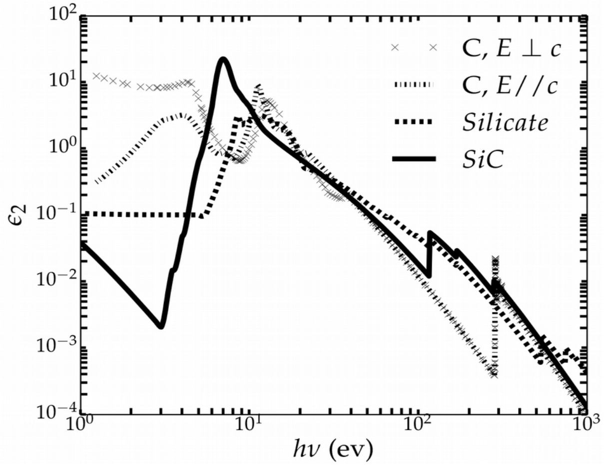
Stellar wind

2. Ratio radiative to gravitational forces

$$\beta = 3.10^{-5}\,\overline{Qrp}\left(L_{star}/M_{star}\right)\left(a/\mu m\right)^{-1}\left(\rho/g\,cm^{-3}\right)^{-1}$$

- *Where:* $Qrp = Qsca + Qext\left(1 - <\cos(\theta)>\right)$





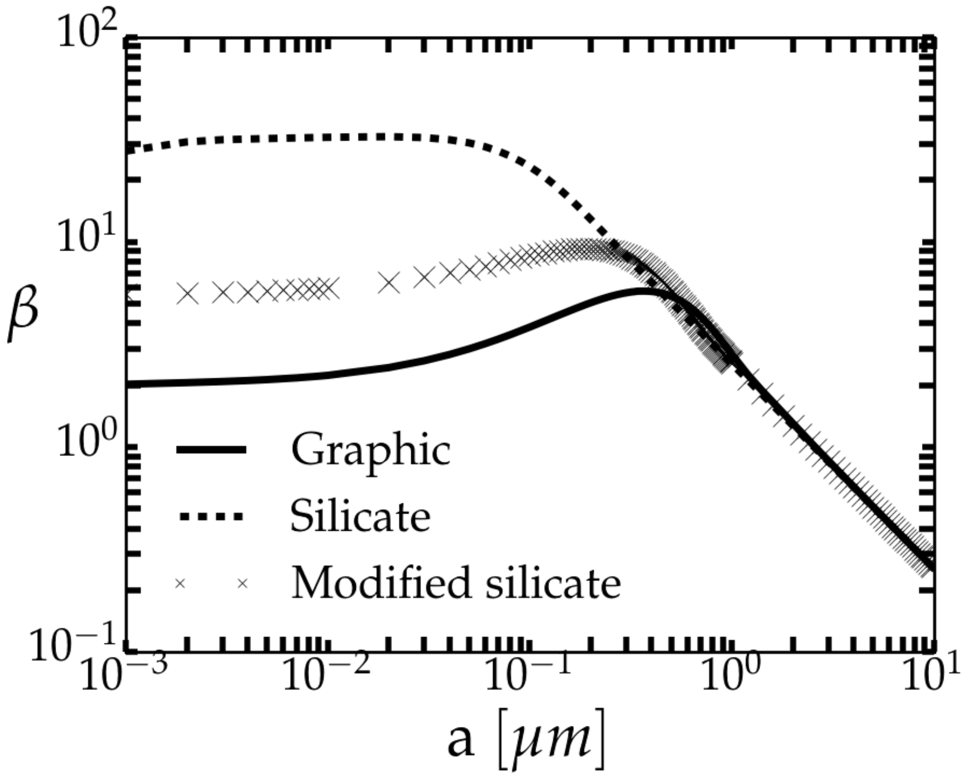
- *Using Mie theory with updated model by B.T.Draine, Princeton Univ. Obs.,*
- *Choosing dust-grain forms:*
  - *Amorphous silicate Mg(x)Fe(1-x)SiO3 (J.Dorschner et al 1995.),*
  - *Astronomical silicate (Draine & Lee 1984; Laor & Draine 1993),*
  - *Modified astrosilicate (Draine 2003b),*
  - *Graphic (Draine & Lee 1984; Laor & Draine 1993)*
  - *Graphic cabide (Laor & Draine 1993)*

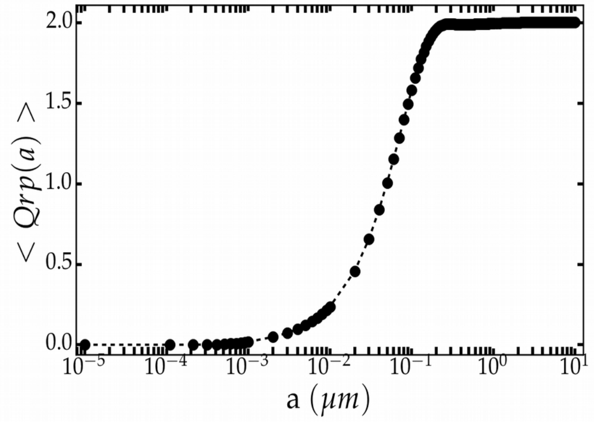
Stellar wind

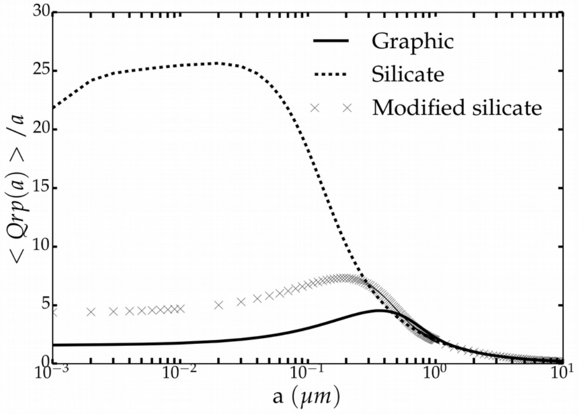
2. Ratio radiative to gravitational forces

$$\beta_d = 0.57\,\overline{Q}_{rp}\,(a/\mu m)^{-1}(L_{star}/L_{sun})(M_{sun}/M_{star})(\rho_{rock}/gcm^{-3})^{-1}$$

- *Where:* $Qrp = Qsca + Qext(1 - <\cos(\theta)>)$







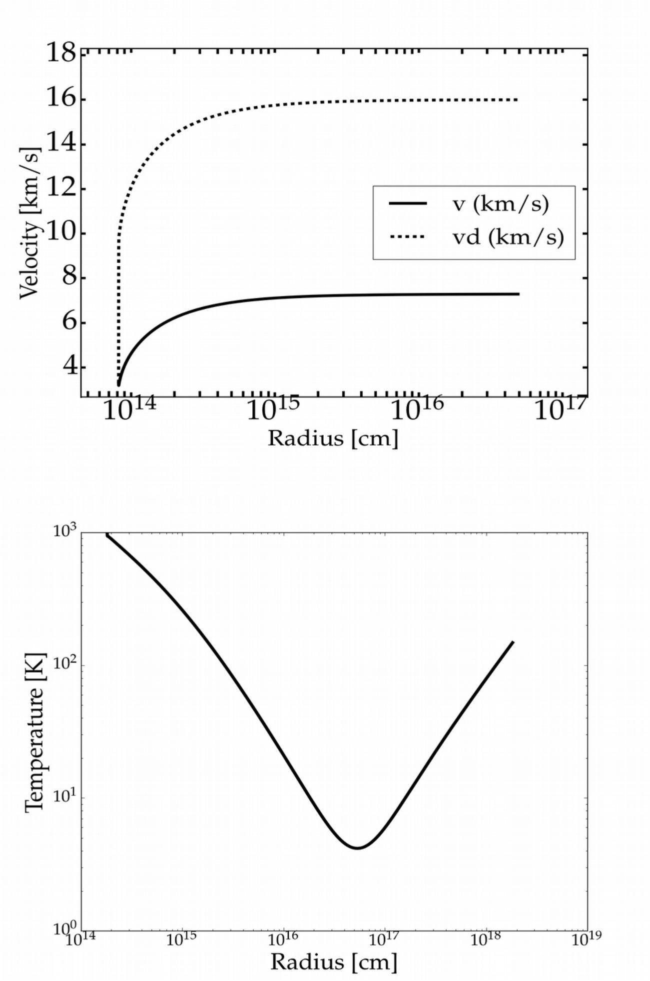
Stellar wind

3. Preliminary results

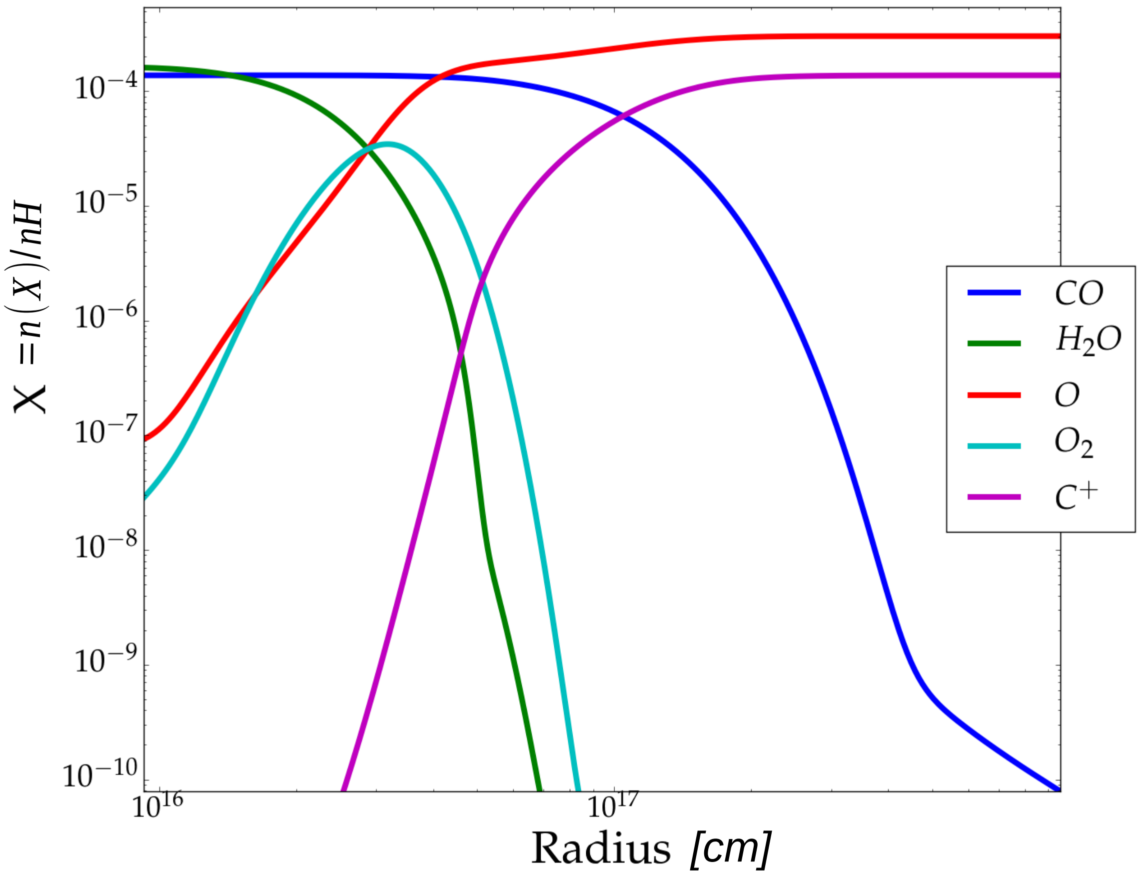
$$\boxed{\beta_g = \beta \frac{\rho_d}{\rho} = 2}$$

IRC +10011 star configurations

- $M = 0.8\, M_{sun}$
- $\dot{M} = 2.10^{-5}\, M_{sun}$
- $L = 2.1\, 10^4\, L_{sun}$
- $T = 1600\, K$



Dynamical processes



Chemical Abundances

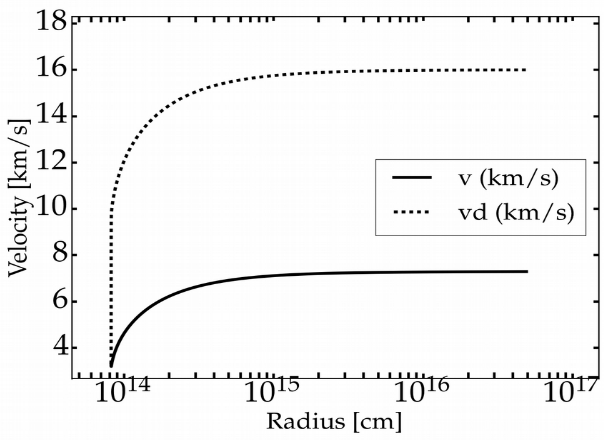
Stellar wind

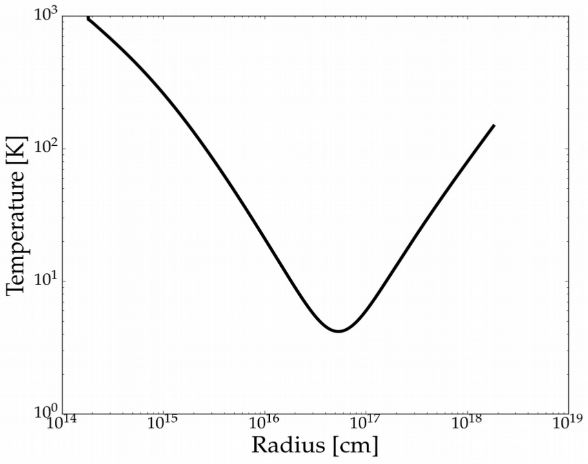
3. Preliminary results

IRC star configurations

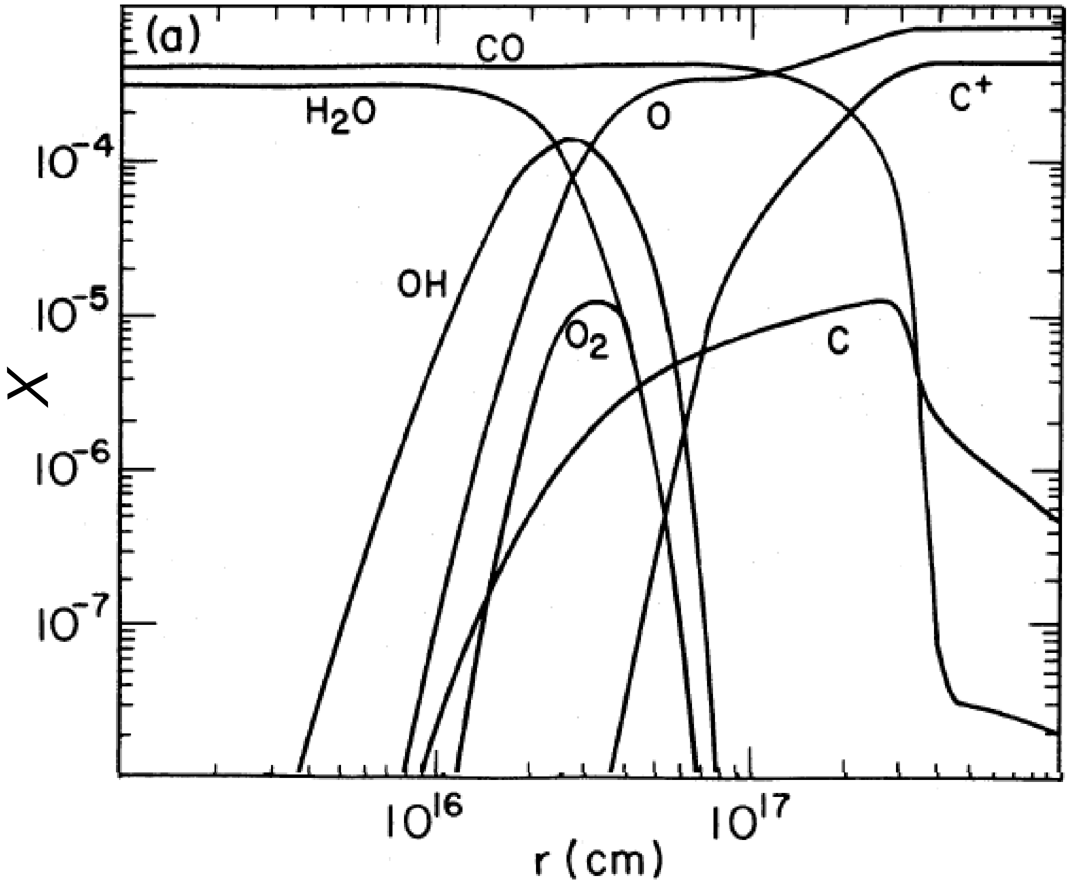
- $M = 0.8\, M_{sun}$
- $\dot{M} = 2.10^{-5}\, M_{sun}$
- $L = 2.110^{4}\, L_{sun}$

$T = 1600\, K$





Dynamical processes



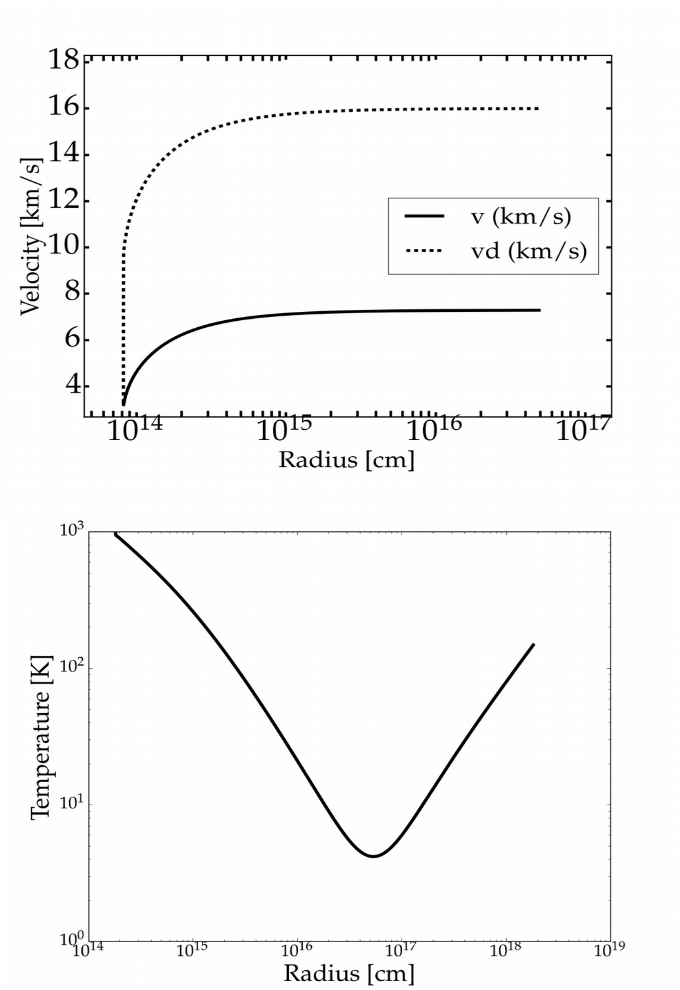
G.A Mamon, 1987

Stellar wind

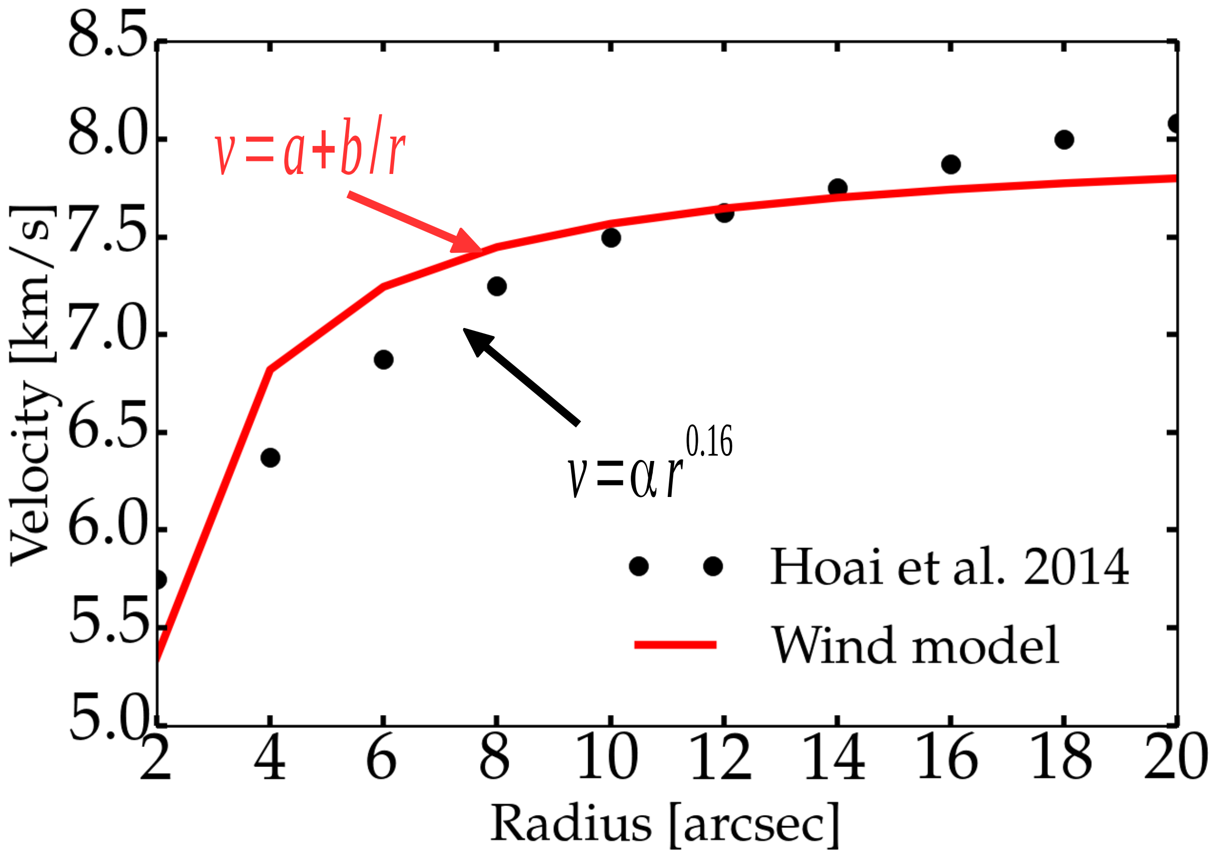
3. Preliminary results

RSCNC star configurations

- M = 1.6 Msun
- L = 4945 Lsun
- T = 3226 K



Dynamical processes



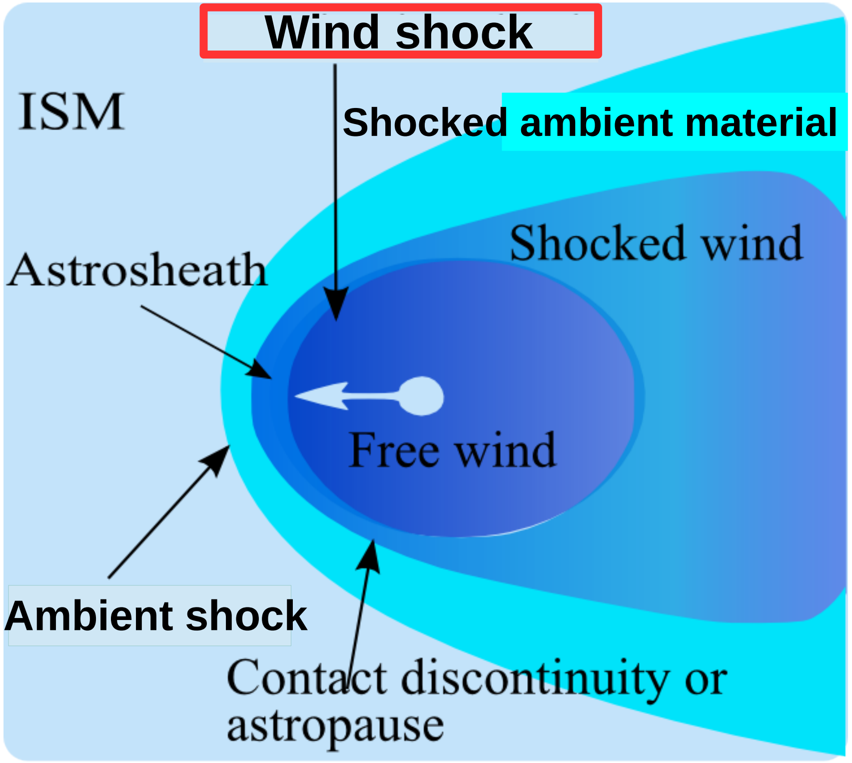
$v = a + b/r$

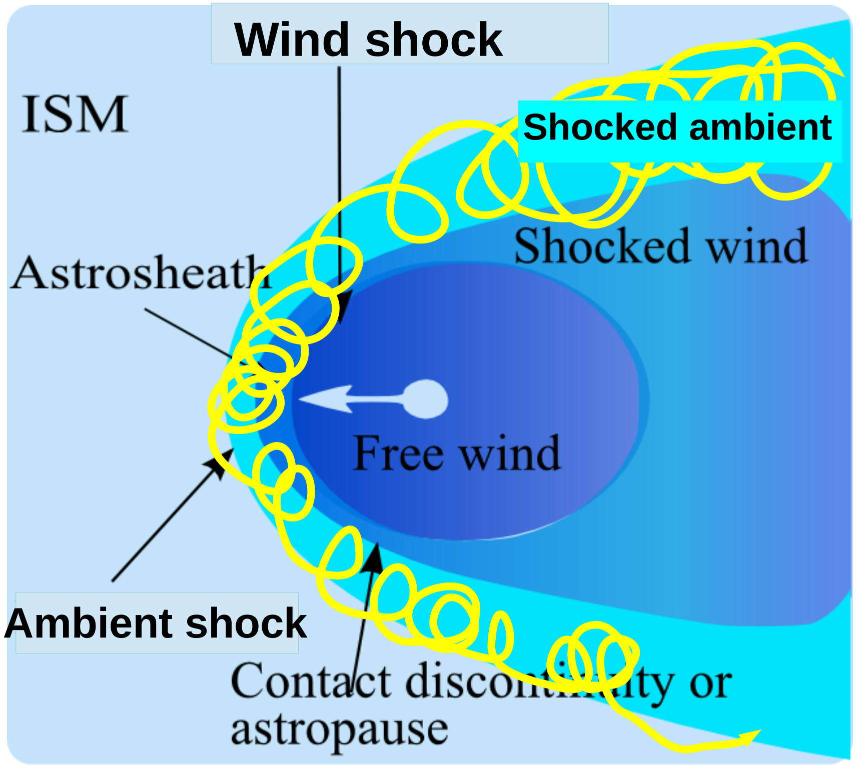
$v = \alpha r^{0.16}$

4. Upcoming and perspectives

- **Work in progress:**
  - *Mapping CO emission from the stellar wind*

- **Near future**





- **Perspective** Comparison with observations

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

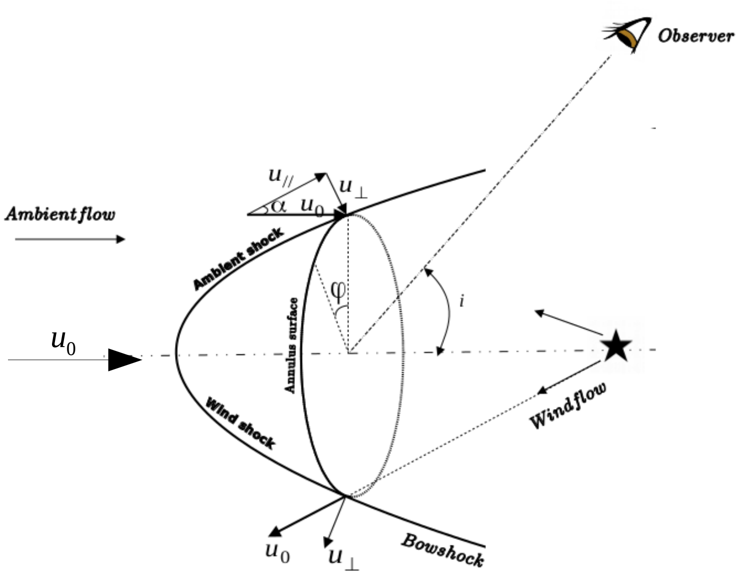
THANK YOU

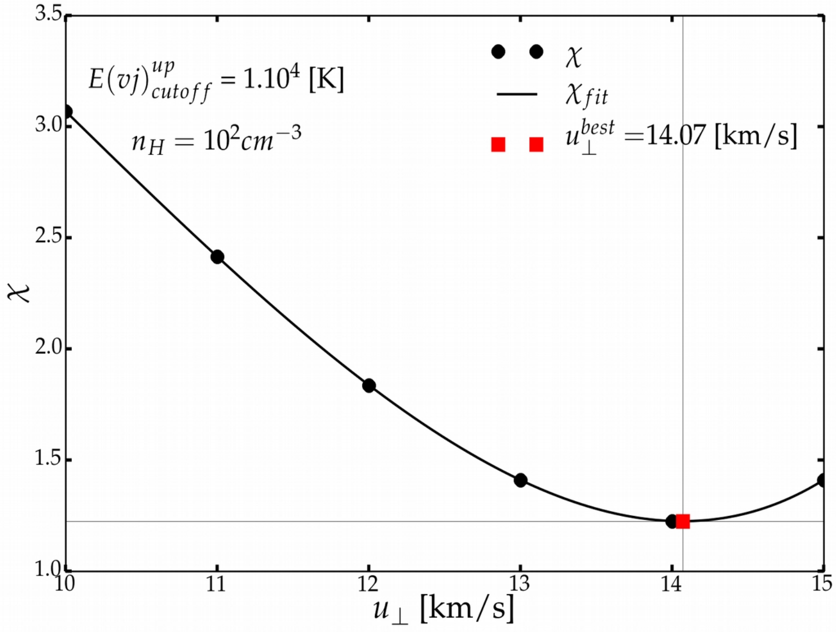
"In a pure meritocracy, everyone must begin de novo"

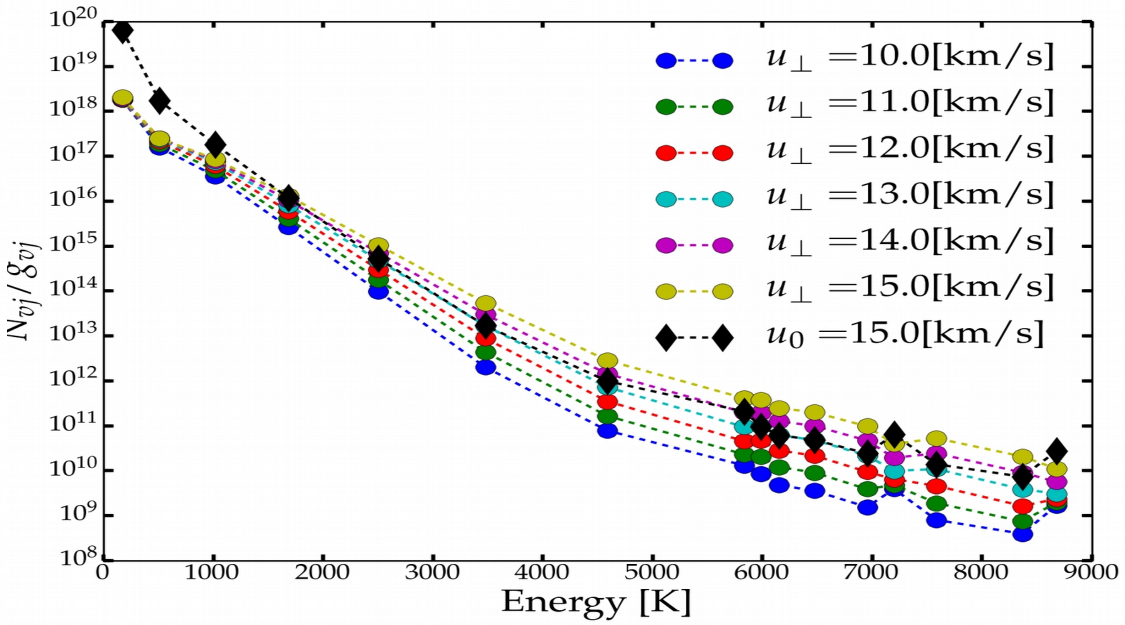
Email: le.ngoctram@lra.ens.fr

Appendix: Ambient shock

Fitting H2 excitation diagram



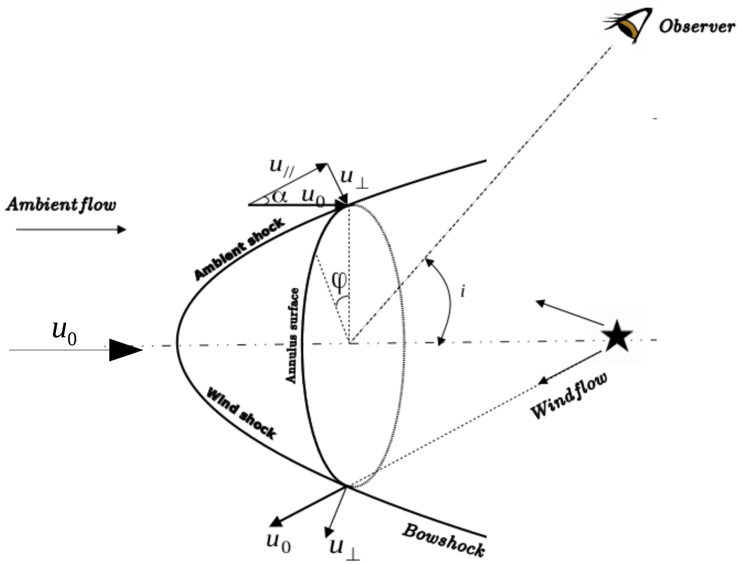


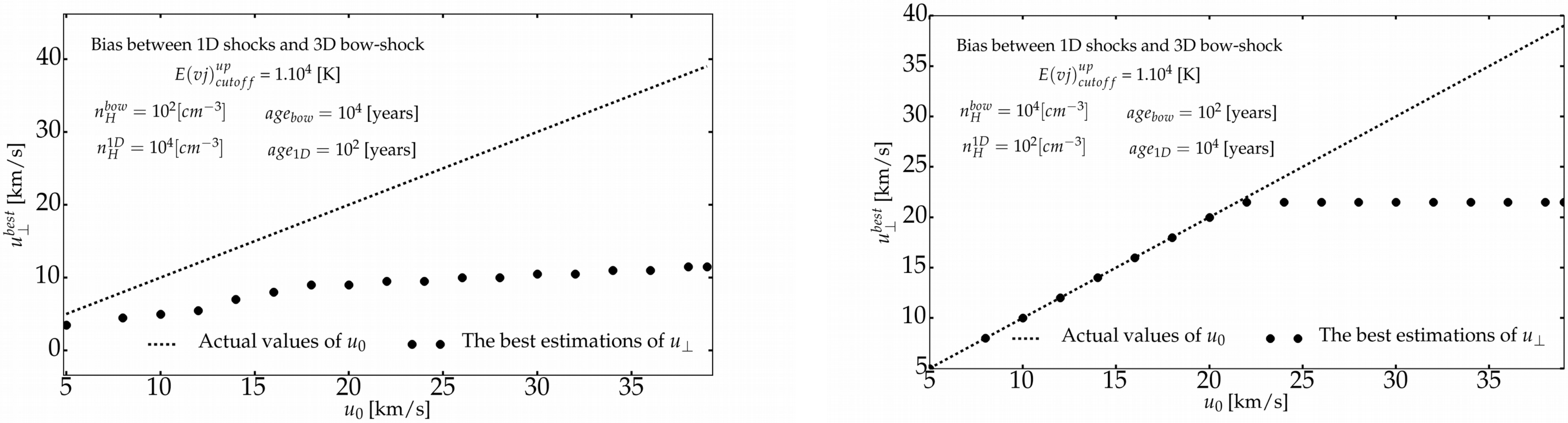


Fitting 1D to 3D model

Appendix: Ambient shock

Fitting H2 excitation diagram





Fitting 1D to 3D model