Radiative shocks: a combined analysis from experiments and simulations

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Protostellar jets in context
Rhodes, Greece, July 7-12, 2008

Context

Radiative shocks

In strong shocks in H, $T_{shock} \approx 1.5\ 10^5 \left(\frac{\mathrm{v}}{100} \right)^2$ in K, km/s

-> **the hot gas radiates**

The effect of the radiation on the shock structure depends on the **opacity**.

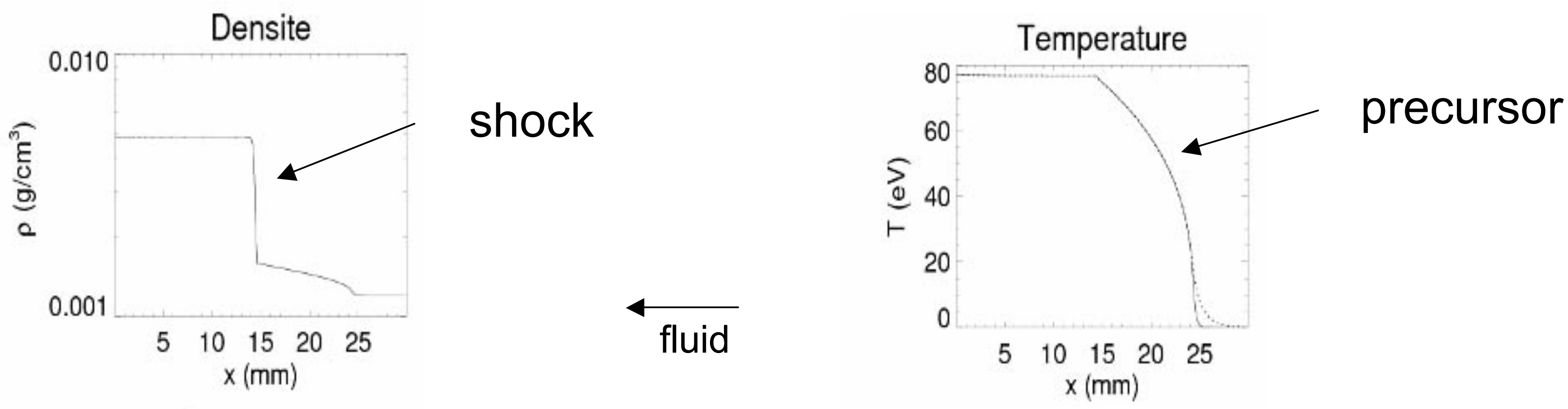
In practice : two numerical approaches

1. Radiation is considered only as a *cooling mechanism*
   -> radiative cooling included in the hydrodynamics equations as a sink term in the energy budget (optically thin case)

2. Radiation transport equations are solved simultaneously to give the *flux, energy & pressure* which are included in hydrodynamics equations (non optically thin case)

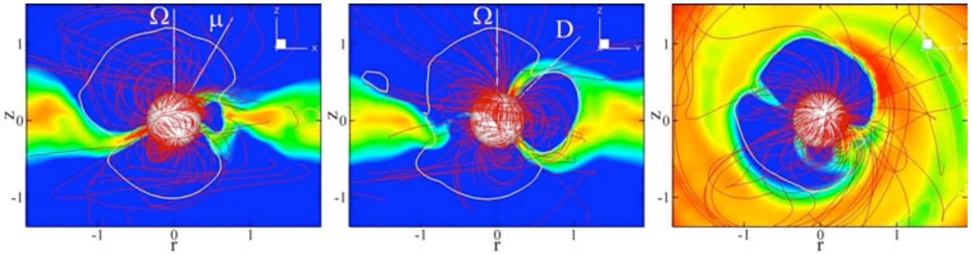
A manifestation of the coupling between hydro & radiation: **the radiative precursor**

When the **opacity** is large enough, **the photons emerging from the shock front ionize the unshocked gas**



The radiative precursor can only be obtained with fully radiative hydrodynamical simulations.

Accretion shocks in CTT's



Long et al 08

- Dynamics of the accretion flow : free fall velocity

  $v_{ff} \sim (2 GM/R)^{0.5}$ -> **400 km/s** (for $M = 1 M_{\odot}$, $R = 2 R_{\odot}$)

- Accretion shock is close to the surface

  Highly supersonic : for $T_{*} \sim 5000$ K -> M = 70 (strong)

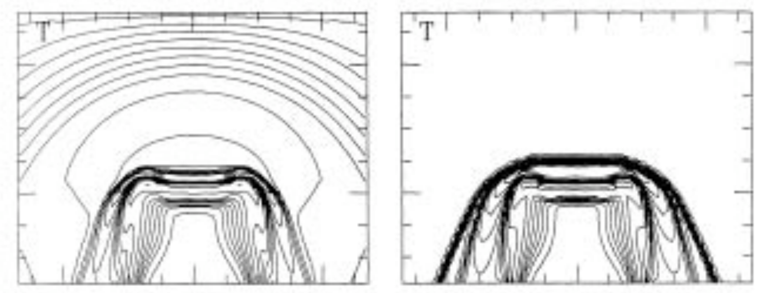
  Shock temperature $T_{shock} \sim v_{ff}^2 \sim$ **2. 10⁶K** (X ray emission)

Depending on the shock location (i.e. respective to the surface), **the opacity will change and the regime of the radiative transport may differ** (presence of a radiative precursor ?)

-> important for accretion **signatures (**X ray, veiling etc**).**

Bow shocks of YSO jets

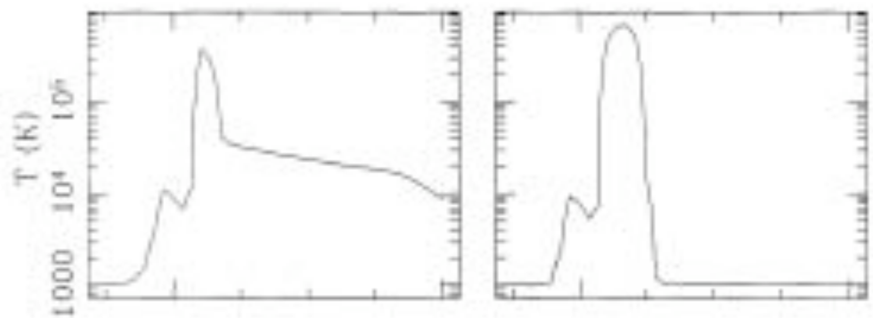
high velocities: 100 km/s -> 600-700 km/s (i.e. HH80/HH81)
=> strong bow shock at the head of the jet



Temperature at the top of the jet with and without radiative transfert (Raga et al 99)

Radiation from the shock **preionizes the gas**, as seen from simulations of Raga & al. for a jet velocity of **~ 200 km/s**

(*Raga et al 99*)



T in K on the z axis, with and without RT (Raga et al 99)

Radiation transport **reduces T at shock front by ~ a factor 2**

(3 10^5 K instead of 7 10^5 K)

Softer X ray emission than expected from standard analysis.

Experimental studies of (*non optically thin*) radiative shocks

The objective is to obtain

(1) strong sustained shocks (M>>1) in gases
(2) with a strong impact of the radiation.
(3) in the simplest geometry (1D)
(4) on laboratory scales

This has been achieved on high energy laser installations, like :

LULI (60J, 1ns), PALS (200 J, 0.3 ns) and Rochester (4000J, 1ns)

Typical setup

-> **1D geometry**: cylindric or parallelipedic target (mm scale)

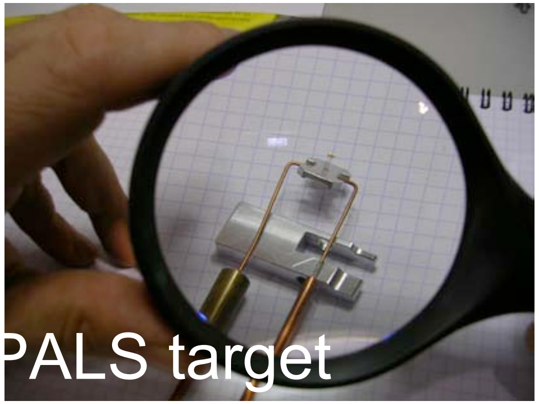
-> shock launched by a piston with ~ **constt velocity**

-> **high Z gas (xenon)** favorable to radiation

-> **moderate/low pressures** $\rho \sim 10^{-4}$ g/cm^3 (opacity adjustments)

$\tau = 1$ (for 1 mm, xenon @ 300K) -> $\rho = 5\ 10^{-4}$ g/cm^3 (0.1 bar)

LULI	**60 km/s**	$5\ 10^{-4}$ g/cm^3	60 J, 1ns
PALS	**55 km/s**	$5\ 10^{-4}$ g/cm^3	200 J, 0.3 ns
Rochester	**150 km/s**	$6\ 10^{-3}$ g/cm^3	4000 J, 1 ns

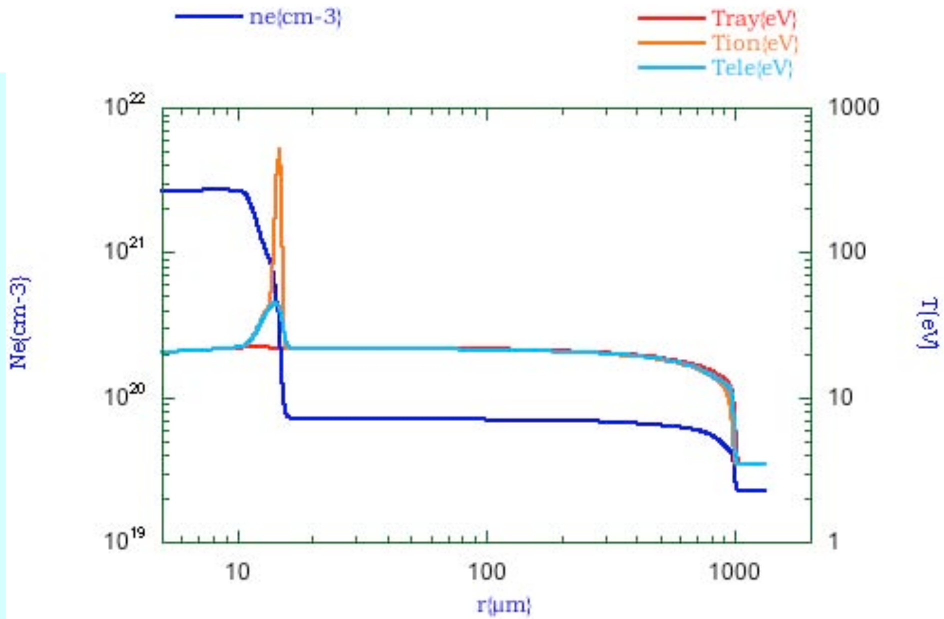


In this regime, we expect

that the shock is 1D, cf design of the targets (parallelipipedic)

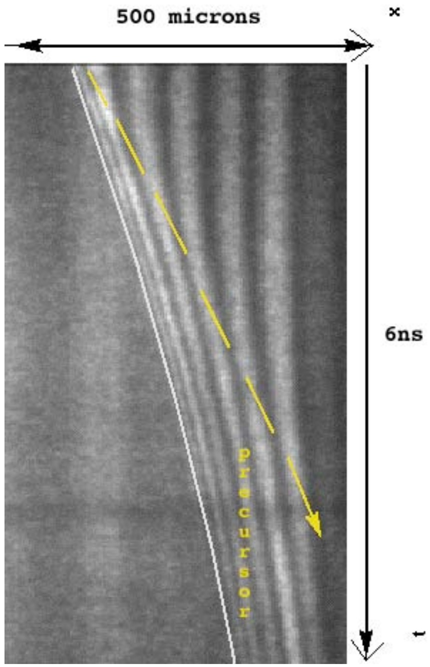
From 1 D simus, we expect:

1. that the shock in Xe is in the **supercritical regime** (T identical before and after the discontinuity).
2. **High compression >4** (strong shock with radiation and ionization effects)
3. **Te ≠Ti** in the front



C. Stehlé, J.P. Chièze, proceedings of SF2A, 2002, Paris, ed. by F. Combes and D. Barret (2002),

Summary of experimental results



- Extended **radiative precursor** deduced from visible time resolved interferometry

(Fleury et al, LPB 2002)

- **Different ionic and electronic temperatures** in the shock front obtained by visible Thomson scattering

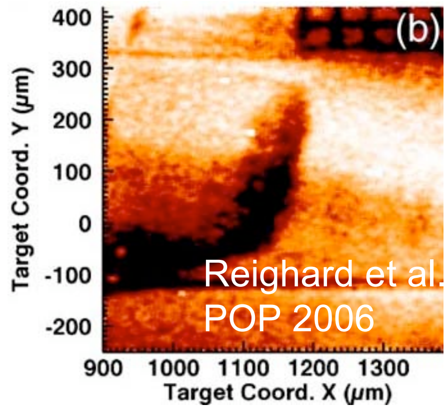
(Reighard et al. POP 2006)

Fleury et al. LPB (2002), Bouquet et al PRL (2005) The shock velocity at the launching time is 65km/s

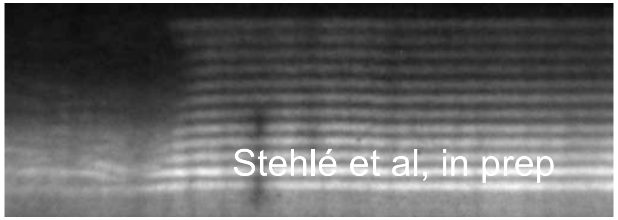
N_e, T, velocity of the shock in qualitative agreement with 1D simulations.

Summary of experimental results

- **Precursor dynamics** deduced from visible interferometry is **slower** than expected from 1D simus
  - in the launching phase (< 10ns), less acceleration (Fleury & al, LPB 2002, Bouquet & al. PRL 2004).
  - at larger times (> 50 ns) it slows down more rapidly, tending to converge earlier towards the stationary limit (González et al. LPB 2006).



- **Shock deformation** (compared from expected 1D), observed
  - by instantaneous 2D imaging: XUV radiography (*Reighard et al. POP 2006*) or gated visible optical imaging (*Vinci et al. Journal de Physique 4 2006*)
  - by time resolved transverse visible interferometry1D image on the slit of a streak camera (Stehlé et al, in prep)

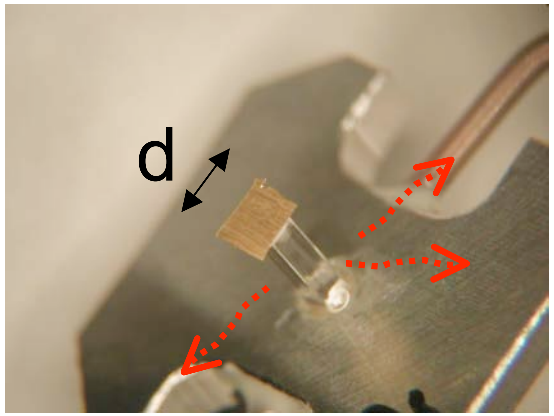


2D picture

2D Radiation transport

In our parallelepipedic cells, the pure hydro would be 1D

But the photons "escape" laterally (are lost) from the tube if $\tau_{lateral}=\kappa d << 1$



Thus 1D RHDM is valid when $\tau_{lateral}=\kappa d >> 1$

In these radiative shocks experiments $\tau_{lateral}$ may be smaller than 1

Radial radiation losses induce departures from 1D

(Leygnac et al. PoP 2006)

2D simulation of PALS radiative shocks

HERACLES a 3D parallel Eulerian RHD code

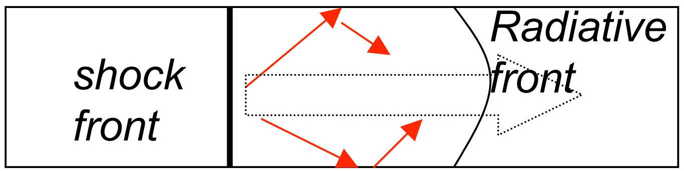
- ✓ radiative transfer: moments methods, grey **M1 model**
- ✓ catches naturally the optically thick and thin limits

González & Audit ApSS 2005
González *et al.* A&A 2007

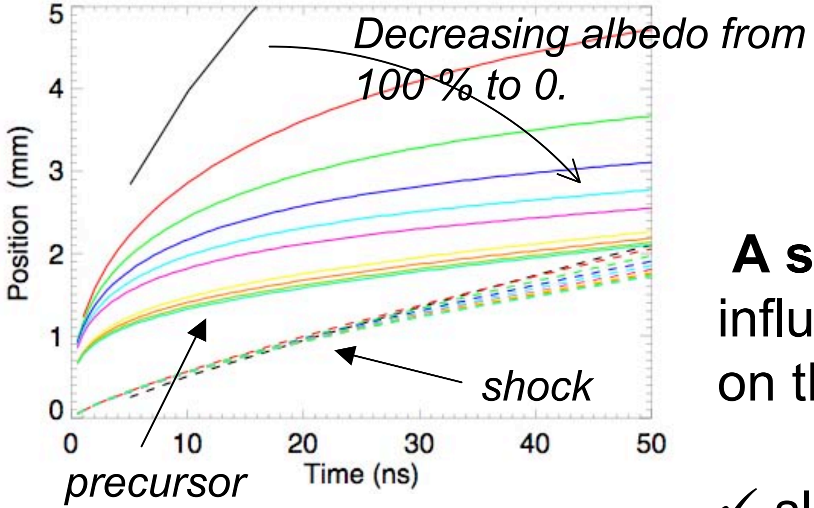
Hereafter applied to conditions of PALS experiments **but for variable radiative losses at the walls**

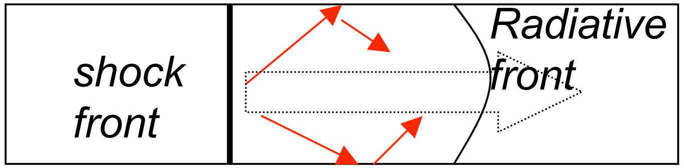
- ✓parallelipipedic target 0.7^2x4mm
- ✓ Xe at 0.2bar, v_{shock}~60km/s

Radiative losses: albedo *a* (% of radiation reinjected in the gas by the walls.)



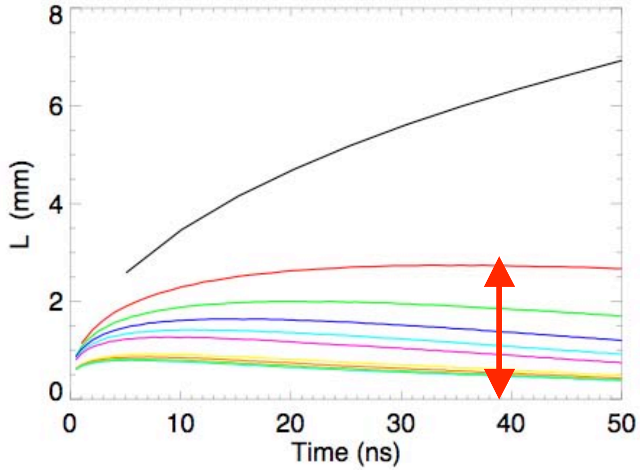
Precursor extension



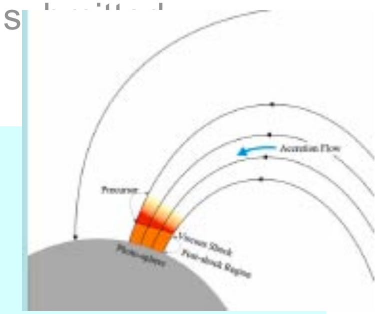


A small albedo (strong losses) has ~ no influence on the shock front, but a large impact on the precursor:

✓ slows down the radiative front
✓diminishes the distance between the radiative and shock fronts.
✓drastically reduces the time for which this distance is maximum *(consequently reduces the time needed to reach the stationary limit).*



González *et al.* A&A s

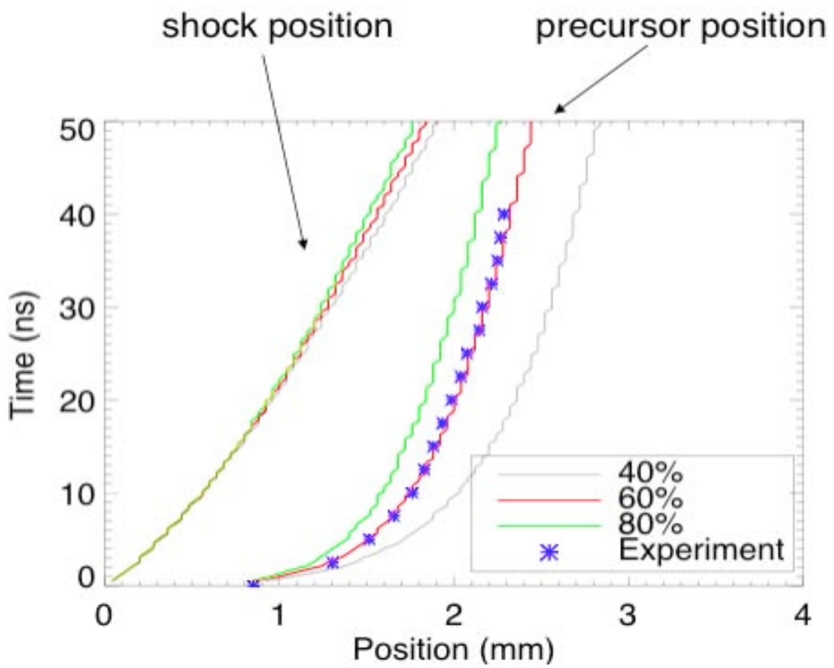


Astrophysical relevance :
albedo 0% : case of **magnetospheric funnels of T Tauri stars**
Albedo 100% mimics the 1D case (atmospheres of evolved stars)

Experimental confrontation

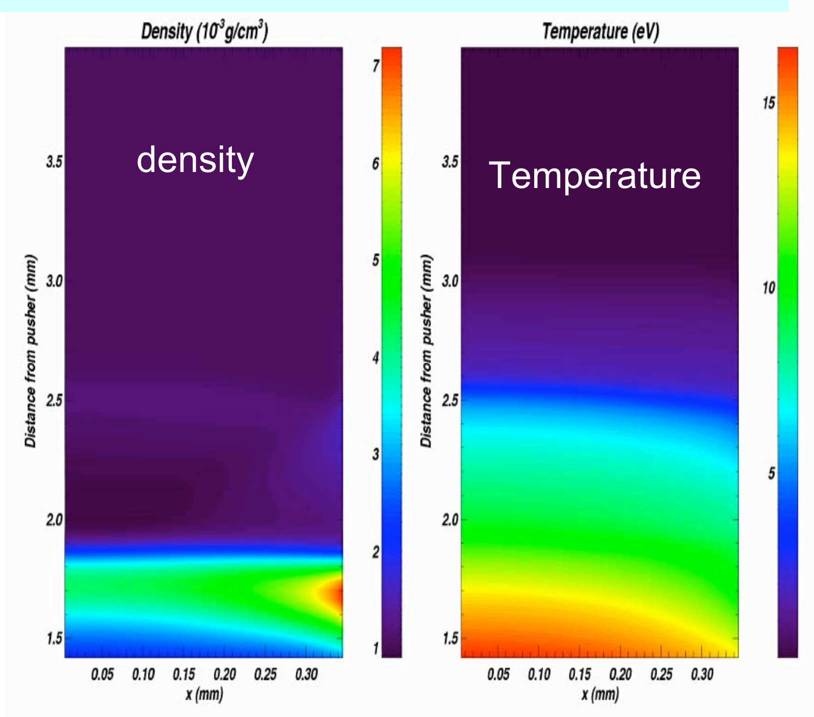
Experimental results recovered by HERACLES with an albedo of 40%

The position of the precursor is obtained by time resolved shadowgraphy of the center of the cell (imaged on the slit of a streak camera)



González *et al.* LPB 2006

Simulations indicate a shock curvature

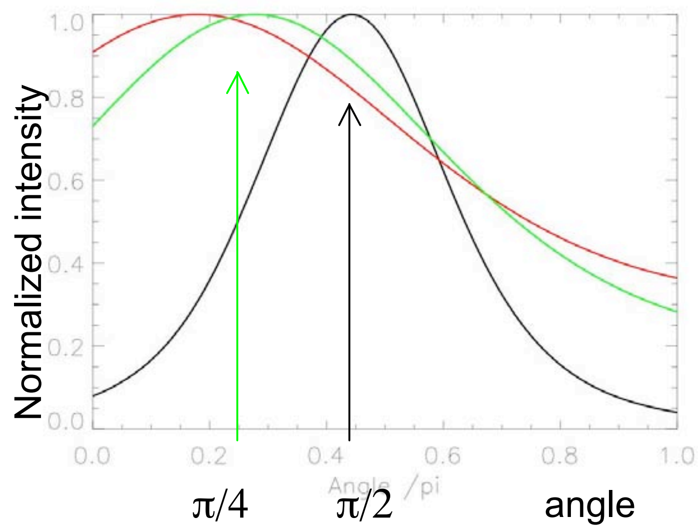


Anisotropy of the shock luminosity

The angular distribution of the flux is *peaked* at an angle *which depends on the albedo :*

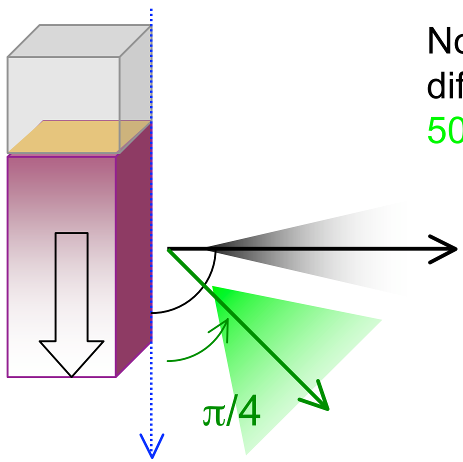
π/2 for a=0 (fully transparent windows)

π/4 for a= 50%



Normalized intensity at 50 ns for different values of albedo (70% red, 50% green, 0% black)

This angular variation may affect the photometric signature of the accretion shock (the angle of observation may vary during the rotation)



M. González et al., submitted to A&A

Conclusions

A correct description of radiative shocks is necessary to predict correctly the observations : X ray, veiling etc ..

The coupling between radiation and temperature depends on several parameters, especially the longitudinal and transverse optical depths.

More work is to be done to be applied to astrophysical accretion shocks, starting from the knowledge of the local and geometrical conditions of the accretion flows.

The numerical modelling has to be improved (non gray approximation, NLTE) .

Experiments are required to constrain the simulations.