Towards more and more Radiative Shocks

Or

When radiation changes the material flow behavior

Astrophysical motivations

Radiation in astrophysics

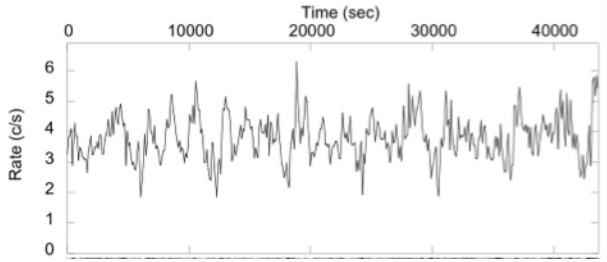
radiation is a diagnostic

- from the Universe, all informations arrive transported by photons
- radiative transfer calculations are needed to understand sources

radiation is a dynamical actor

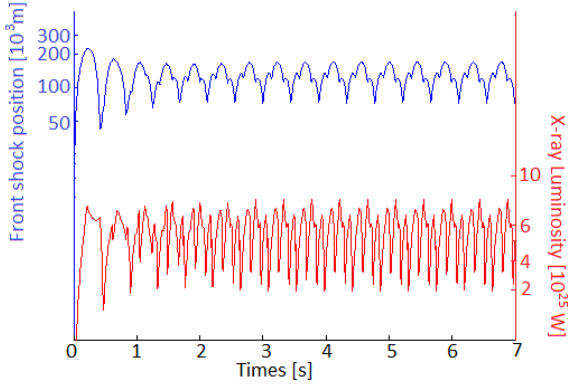
- in accretion/ejection systems, strong matter movements
- radiative transfer has to be coupled with hydrodynamics

X-ray curve light from polar



J.-M. Bonnet-Bidaud et al, A&A 2015

Modelling of curve light from polar

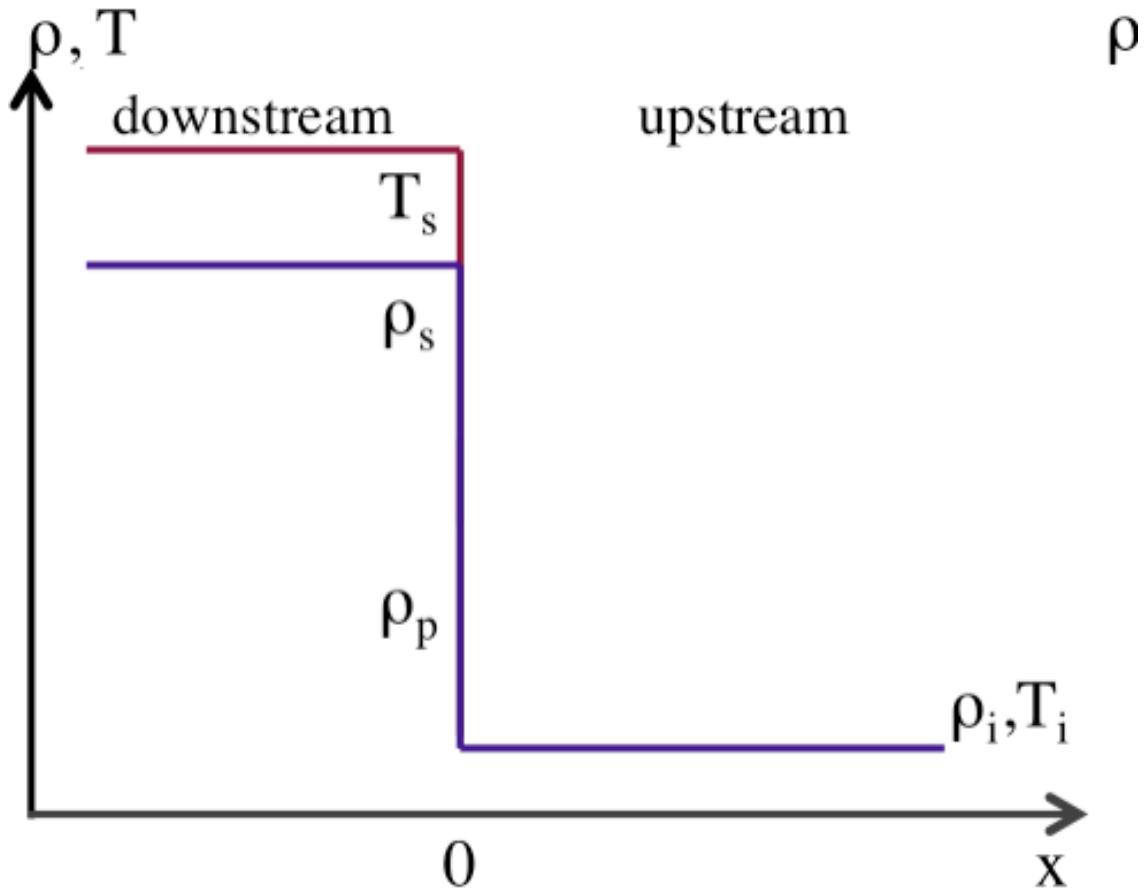


C. Busschaert et al, A&A 2015

Radiative shocks in astrophysics

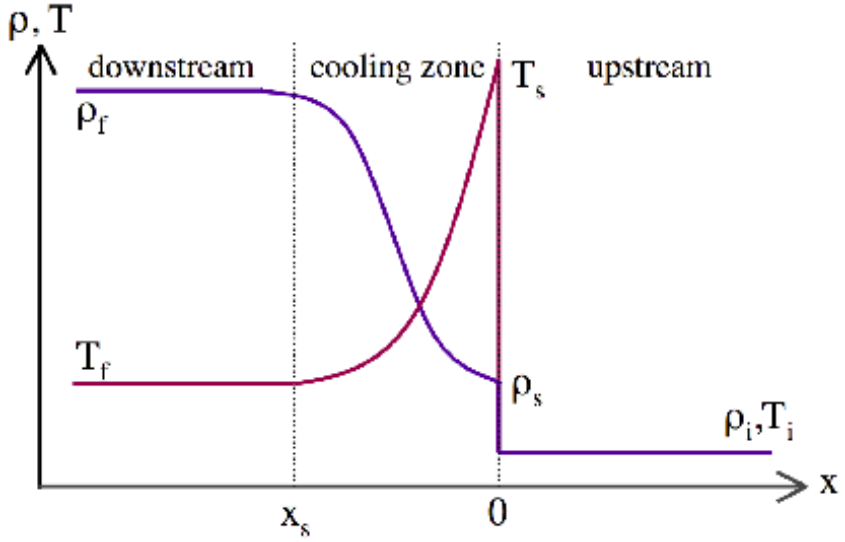
- Radiative shocks are found in novae outbursts, supernovae, stellar atmospheres, accretion processes as star formation or cataclysmic variables, ejection processes as jets
- As velocities are often huge
- Supersonic (M>1) and hypersonic (M>>1) shock waves form frequently
- The three moments of radiation (flux, pressure, energy) are coupled to the three moments of matter (flux, pressure, energy)
- Experiments are performed in order to understand nonlinear physics and to validate numerical codes
- Laser/matter interaction codes are used to understand experiments

choc morphology

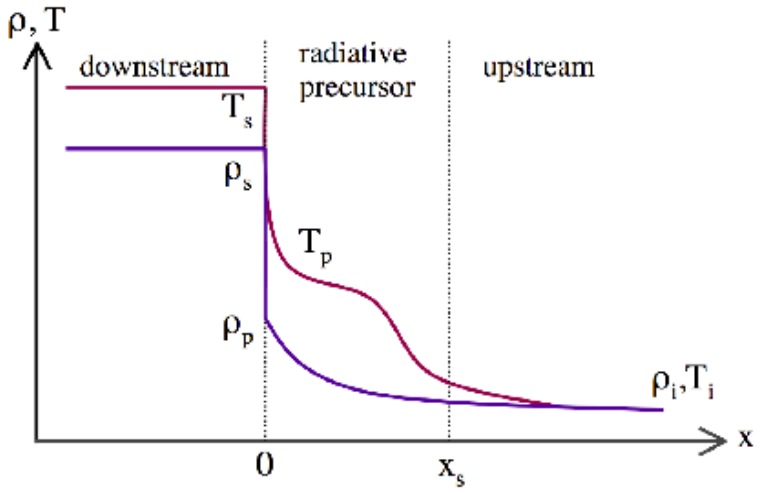


RS morphology

optically thin



optically thick



Strong compression - Photons are emitted
A part is absorbed in the upstream region
now, RS propagates in medium with new physical properties
Shock conditions are changed, which change the upstream region…
A recursive system combining hydrodynamic conditions and radiative transport takes place

Intensité radiative spécifique, Planckienne

- Champ radiatif caractérisé par

$$I(\mathbf{x}, t; \Omega, \nu) = c\, h\nu\, \psi(\mathbf{x}, t; \Omega, \nu)$$

  - **x** position ; t temps
  - Ω direction du photon ν
  - c vitesse de la lumière
  - h constante de Planck
  - $h\nu$ énergie d'un photon
  - $\psi(\mathbf{x}, t; \Omega, \nu)$ densité des photons

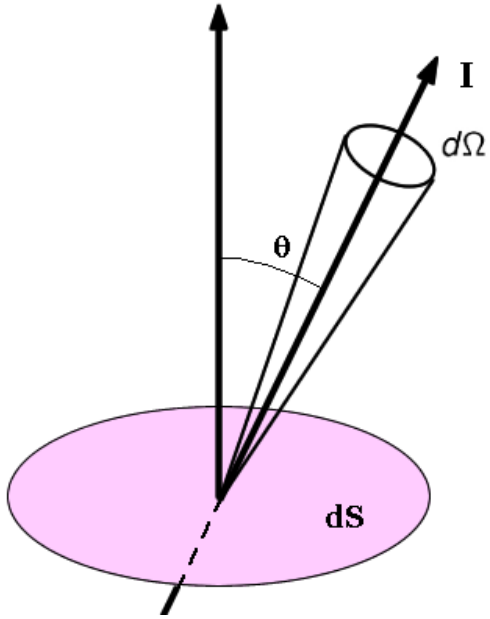


FIGURE: Intensité radiative

- Champ radiatif homogène et isotrope

$$I = B(\nu, T) = \frac{2h\nu^3}{c^2}\left(\exp(h\nu/(k_B T)) - 1\right)^{-1}$$

  - T température de la matière (à l'équilibre thermodynamique)
  - k_B constante de Boltzmann

Une description macroscopique

- *Notation :*

$$\langle \bullet \rangle = c^{-1} \int_0^\infty \int_{S^2} \bullet \, d\Omega \, d\nu$$

- Trois moments sur l'espace des fréquences et des directions :
  - $E_R = E_R(\mathbf{x}, t) = \langle I \rangle$: énergie radiative totale
  - $\mathbf{F}_R = \mathbf{F}_R(\mathbf{x}, t) = \langle c\Omega I \rangle$: flux radiatif total
  - $\mathbf{P}_R = \mathbf{P}_R(\mathbf{x}, t) = \langle (\Omega \otimes \Omega) I \rangle$: pression radiative totale
- Sans interaction avec la matière (I constante)

$$\begin{aligned} \partial_t E_R + \nabla \cdot \mathbf{F}_R &= 0, \\ \partial_t \left(c^{-2} \mathbf{F}_R \right) + \nabla \cdot \mathbf{P}_R &= 0. \end{aligned}$$

Interaction photon-matière, ETR, opacités

Couche mince statique ($\mathbf{u} = 0$) d'épaisseur ds (ETL)

- $\chi(\nu)$ coefficient d'absorption totale

$$dI/ds = -\chi I = -(\kappa + \sigma)I$$

- $\eta(\nu)$ coefficient d'émission totale

$$dI/ds = \eta = \eta^t + \eta^s$$

$$\eta(\nu) = \kappa(\nu)B(\nu, T) + \frac{\sigma(\nu)}{4\pi}\int_{S^2} I(\Omega', \nu)d\Omega'$$

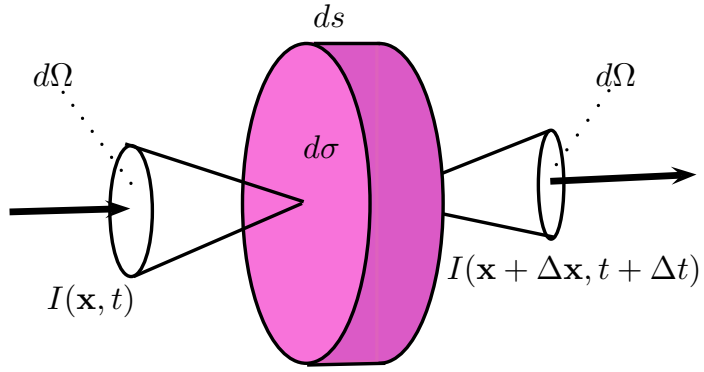


FIGURE: Couche infinitésimale

- Équation du transfert radiatif (ETR) : $\left(\frac{1}{c}\partial_t + \Omega \cdot \nabla\right) I = \eta - \chi I$
- Équations aux moments : $\langle \bullet \rangle$, $\langle \Omega \bullet \rangle$

$$\partial_t E_R + \nabla \cdot \mathbf{F}_R = -cS^0, \quad S^0 := \langle \chi I - \eta \rangle = \kappa_P \left(E_R - a_R T^4\right)$$

$$\partial_t \left(c^{-2}\mathbf{F}_R\right) + \nabla \cdot \mathbf{P}_R = -\mathbf{S}, \quad \mathbf{S} := \langle (\chi I - \eta)\Omega \rangle = \kappa_R \mathbf{F}_R/c$$

Opacités grises et multigroupes, modèle multigroupe

Définition (Opacités grises)

- Opacité de Rosseland κ_R

$$\kappa_R{}^{-1} \equiv \frac{\langle \chi^{-1}(\nu)\partial_T B(\nu, T)\rangle}{\langle \partial_T B(\nu, T)\rangle}$$

- Opacité de Planck κ_P

$$\kappa_P \equiv \frac{\langle \kappa(\nu) B(\nu, T)\rangle}{\langle B(\nu, T)\rangle}$$

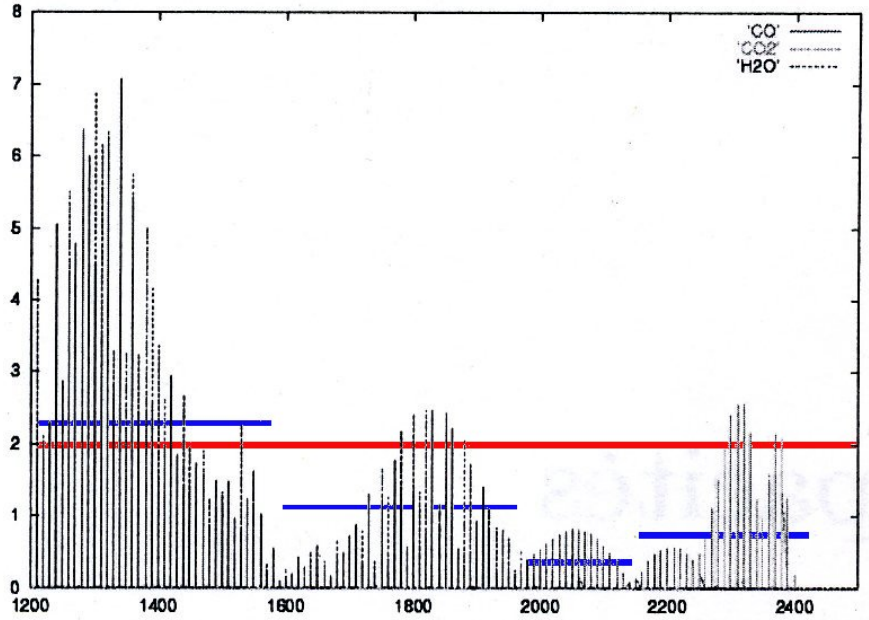


FIGURE: Spectre de fréquences

- Variation brutale $\rightarrow$ pas bien représentée
- $\rightarrow$ plusieurs valeurs représentatives

Opacités grises et multigroupes, modèle multigroupe

Définition (Opacités multigroupes)

- *Notation :*

$$\langle \bullet \rangle_g = c^{-1} \int_{\nu_{g-1/2}}^{\nu_{g+1/2}} \int_{S^2} \bullet \, d\Omega d\nu$$

- *Opacité de Rosseland* $\kappa_{R,g}$

$$\kappa_{R,g}^{-1} \equiv \frac{\langle \chi^{-1}(\nu) \partial_T B(\nu, T) \rangle_g}{\langle \partial_T B(\nu, T) \rangle_g}$$

- *Opacité de Planck* $\kappa_{P,g}$

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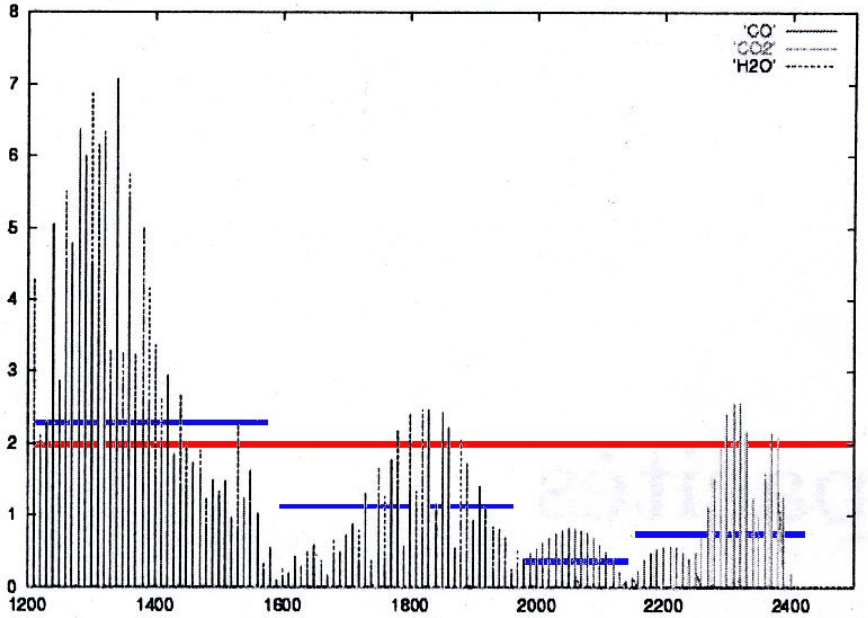

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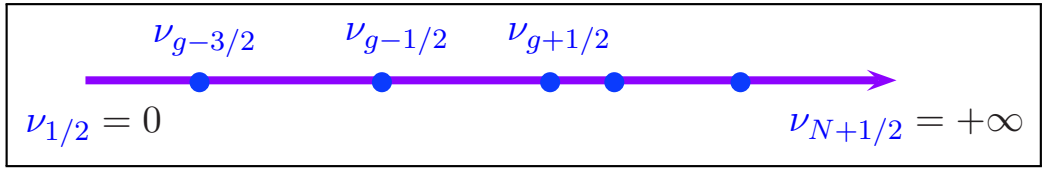

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$$\kappa_{P,g} \equiv \frac{\langle \kappa(\nu) B(\nu, T) \rangle_g}{\langle B(\nu, T) \rangle_g}$$

Remarque (Modèle multigroupe)

- Pour groupe g, $\nu \in \left[\nu_{g-1/2}, \nu_{g+1/2}\right[$:

$$\begin{aligned} \partial_t E_g + \nabla \cdot \mathbf{F}_g &= -c S_g^0 \\ \partial_t \left(c^{-2} \mathbf{F}_g\right) + \nabla \cdot \mathbf{P}_g &= -\mathbf{S}_g \end{aligned}$$

où

$$S_g^0 = \kappa_{P,g} \left(E_g - a_R \theta_g^4(T)\right)$$

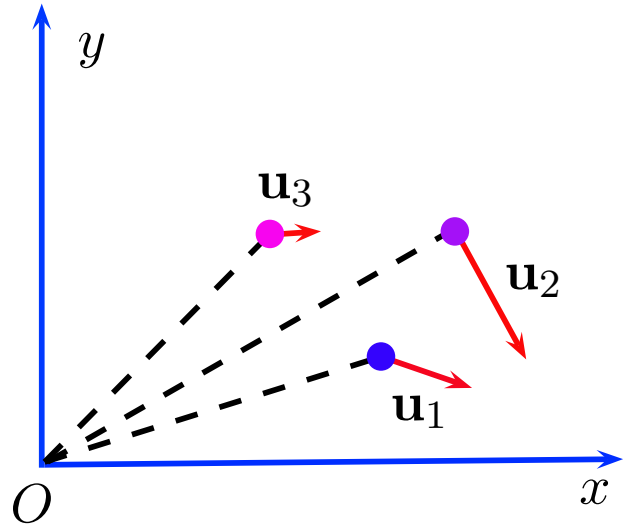
$$\mathbf{S}_g = \kappa_{R,g} \mathbf{F}_g / c$$

$$\theta_g^4(T) = \langle B(\nu, T) \rangle_g / a_R$$

- Milieu statique $\equiv$ repère comobile

Repère fixe, effet Doppler, termes sources

- Dans le repère du labo :
  - opérateur différentiel inchangé
  - vitesse $\mathbf{u} \not\equiv 0$
  - prise en compte du décalage Doppler
  - transformation de Lorentz
  - termes sources modifiés



- Quantités supplémentaires de termes sources ($\mathcal{O}(\|\mathbf{u}\|^2/c^2)$, $\|\mathbf{u}\|/c \ll 1$) :

$$S_g^0 = \kappa_{P,g}\left(E_g - a_R\theta_g^4(T)\right) + \left(\kappa_{R,g} - 2\kappa_{P,g}\right)\left(\mathbf{u}\cdot\left(c^{-2}\mathbf{F}_g\right)\right)$$

$$\mathbf{S}_g = \kappa_{R,g}\mathbf{F}_g/c - \left(\left(\kappa_{R,g} - \kappa_{P,g}\right)E_g + \kappa_{P,g}a_R\theta_g^4(T)\right)\mathbf{u}/c - \kappa_{R,g}\mathbf{u}\cdot\mathbf{P}_g/c$$

- À l'ordre plus élevé de $\|\mathbf{u}\|/c \longrightarrow$ plus compliqué

Hydrodynamique, couplage, conservation totale

HADES 2D

- Équations d'Euler modifiées

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho(\mathbf{u} \otimes \mathbf{u}) + p\mathbf{I}) = \sum_{g=1}^{N} \mathbf{S}_g$$

$$\frac{\partial E}{\partial t} + \nabla \cdot ((E + p)\mathbf{u}) = \sum_{g=1}^{N} cS_g^0$$

- Modèle multigroupe

$$\begin{aligned} \partial_t E_g + \nabla \cdot \mathbf{F}_g &= -cS_g^0, \quad g = 1, \cdots, N \\ \partial_t \left(c^{-2}\mathbf{F}_g\right) + \nabla \cdot \mathbf{P}_g &= -\mathbf{S}_g, \quad g = 1, \cdots, N \end{aligned}$$

- $\longrightarrow$ conservation de masse (/ quantité de mouvement / énergie) totale
- $\longrightarrow$ même forme conservative : $\partial_t \mathbf{q} + \operatorname{div} \mathbf{f}(\mathbf{q}) = \mathbf{s}(\mathbf{q})$
- $\longrightarrow$ utilisation du même type de méthodes numériques

- Opacities are tabulated or calculated
- HADES code is fully parallelized
- Expensive calculation time
- We use also 2 asymptotic radiative transfer description
- Optically thin medium → cooling function
- Optically thick medium → diffusion approximation