Radiation hydrodynamics

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Outline

The radiation hydrodynamics

What is it ? dynamic effects of the radiation

When do we have to deal with radiation hydrodynamics ?

We have to compare the hydrodynamic energy (or flux) with the radiation one.

$$\frac{E_r}{e} = \frac{a_r T^4}{3/2NkT} \simeq 36\frac{T^3}{N} \qquad \frac{F_r}{F} = \frac{\sigma T^4}{ue} = \frac{1}{4}\frac{c}{u}\frac{E_r}{e} \simeq 9\frac{c}{u}\frac{T^3}{N}$$

Relevant applications for radiation hydrodynamics :

In astrophysics :

- accretion shocks on massive objects or in formation...

In laboratory plasmas :

- radiative shocks...

How to solve the transfer equation ?

$$\left(\frac{1}{c}\frac{\partial}{\partial t} + \mathbf{n}\cdot\nabla\right) I(\mathbf{x}, t; \mathbf{n}, \nu) = \eta(\mathbf{x}, t; \mathbf{n}, \nu) - \chi(\mathbf{x}, t; \mathbf{n}, \nu) I(\mathbf{x}, t; \mathbf{n}, \nu)$$

7 parameters : space (3), time (1), direction (2) and frequency (1)

- Direct integration
  - high cost (time/memory), not (yet) suitable for hydro coupling
  - post-processing approach (cf. RADMC, IRIS code, C. Stehlé's talk)
- Monte-Carlo methods
  - high cost in optically thick regions
  - Poisson noise
- Moments models
  - approximations of the physical model

$$\left\{\begin{array}{lllrl} E_r^\nu & = & \frac{1}{c} & \oint I(\mathbf{x}, t; \mathbf{n}, \nu) \quad d\Omega & \text{Radiative energy} \\ \mathbf{F}_r^\nu & = & & \oint I(\mathbf{x}, t; \mathbf{n}, \nu) \quad \mathbf{n} d\Omega & \text{Radiative flux} \\ \mathbb{P}_r^\nu & = & \frac{1}{c} & \oint I(\mathbf{x}, t; \mathbf{n}, \nu) \quad \mathbf{n}\otimes\mathbf{n} d\Omega & \text{Radiative pressure} \end{array}\right.$$

The moments models

Hierarchy of moments equations

If LTE and no scattering with the two first equations :

$$\begin{cases} \partial_t E_r^\nu & + & \nabla \cdot \mathbf{F}_r^\nu & = & \sigma^\nu (4\pi B^\nu - c E_r^\nu) \\ \frac{1}{c}\partial_t \mathbf{F}_r^\nu & + & c\nabla \cdot \mathbb{P}_r^\nu & = & -\sigma^\nu \mathbf{F}_r^\nu \end{cases}$$

Needs to truncate it and specify a closure relation

$$\mathbb{P}_r^\nu = f(E_r^\nu, \mathbf{F}_r^\nu)$$

The closure relation

- Flux Limited Diffusion (FLD)
  - isotropic radiation field, stationary radiative flux
  - rapid BUT
  - ad-hoc flux limiter λ to enforce causality
  - flux always colinear and proportional with the energy gradient

- M1 model
  - Lorentz transformation of Planck function (Levermore 1984)
  - Maximization of radiation entropy (Dubroca & Feugeas 1999)
  - local analytical formulation
  - take radiation anisotropies into account
  - exact in both diffusive and free streaming limits

The different possible moment approximations

- FLD vs M1 :
  FLD in stellar interiors
  use M1 if
  - optically thick/thin regions co-exist
  - radiation anisotropies (multi-D effects)

- grey vs multigroup
  Example in protoplanetary disk use of an hybrid scheme (e.g. Kuiper et al. 2010, Flock et al. 2013 with the PLUTO code) :
  - grey FLD for disk
  - multigroup ray-tracing for star irradiation

- Reduced speed of light approximation (RSLA) :
  - to save computational time (explicit vs implicit scheme)

  e.g. Rosdahl et al. 2013 (galaxy formation) with the RAMSES code

Numerical implementation

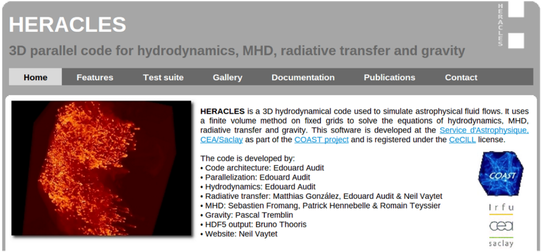
The HERACLES code : `http://irfu.cea.fr/Projets/Site_heracles`

González et al. A&A 2007

3D, MPI parallelized

Operator splitting

- hydro : explicit scheme (MUSCL)
- radiation : implicit scheme (preconditioned Gauss-Seidel)



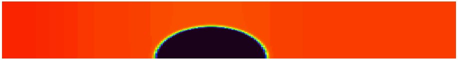
In our simulations, radiation step takes about 90% to 99% of total CPU time !

hydro step $\sim$ 10 μs per cell

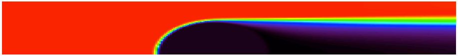
radiation step $\sim$ few 100 μs per cell

Numerical tests

(González et al. 2007)



FLD

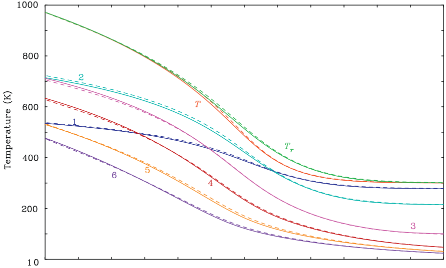


M1

⟹ anisotropy/multi-dimensional effects

(Vaytet et al. 2011)

- source at T=1000 K in domain with T=300 K
- constant or frequency-,T-dependent opacities
- comparison with a kinetic model : error about 0.5%

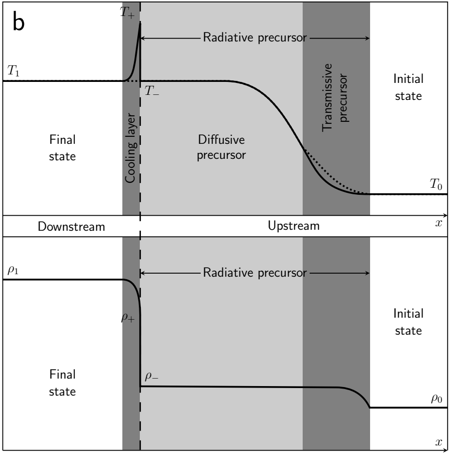


⟹ Validation of M1 in all the regimes

Introduction to radiative shocks

(cf. J.P. Chièze/C. Stehlé's talk)

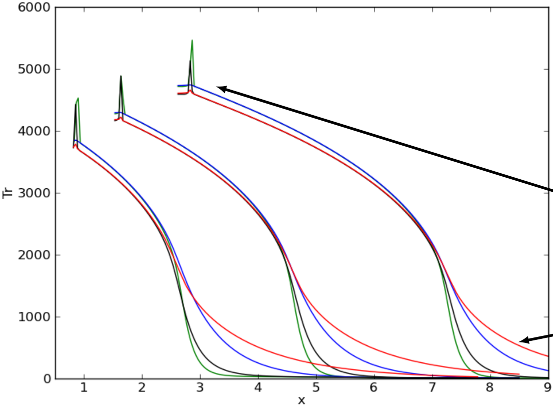
Reproduced on laser facilities
Measures of radiography/spectrum, electron densities



supercritical

M1 vs FLD for grey radiative shock

Radiative supercritical shock with v=20 km/s



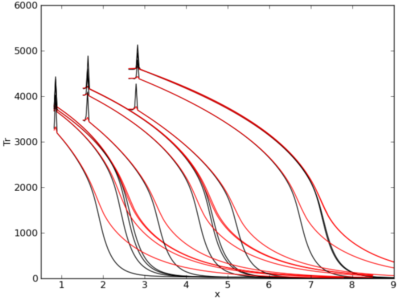
	FLD	M1
T	green line	black line
T_r	blue line	red line

Tpost-shock different

Precursor extent different

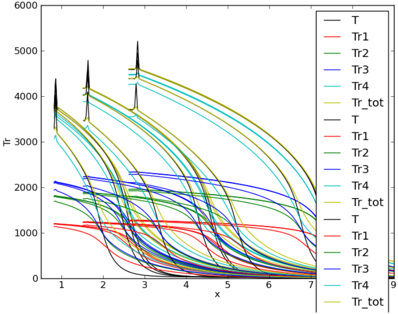
M1 implicit vs M1 explicit with RSLA

supercritical - 1 group



Factor	CPU time (s)	Exp/Imp
1	1.460E+01	-
10^{-1}	3.966E+02	27.16
10^{-2}	3.833E+01	2.63
10^{-3}	3.875E+00	0.27

supercritical - 4 groups

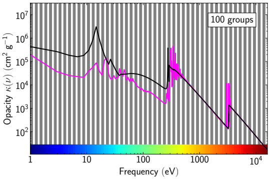


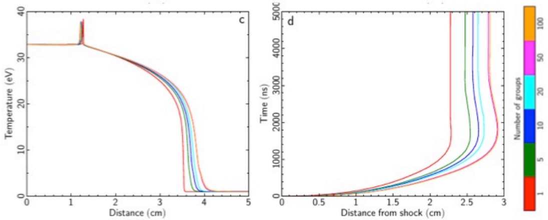
Factor	CPU time (s)	Exp/Imp
1	6.383E+01	-
10^{-1}	1.447E+03	22.67
10^{-2}	1.470E+02	2.30
10^{-3}	1.441E+01	0.23

Multigroup radiative shocks

(Vaytet et al. 2013)

- Argon gas in laser-driven conditions
- Ar opacities from the ODALISC database
- simulations with 1-5-10-20-50-100 groups





- The precursor size increases as a function of the groups number
- Seems to converge for 50-100 groups

$\Longrightarrow$ Crucial importance of multigroup effects

Summary and perspectives

- Summary
  - development of M1 multigroup model
  - application to (laboratory) radiative shocks
    - influence of multigroup on the precursor size
    - effects on electron densities detectable in experiments
    - detection of adaptation zones
  - application to star formation (cf. Vaytet et al. 2012, B. Commerçon's talk)
    - in 1D, no big changes compared to FLD

- Perspectives
  - development of multigroup scheme in the 3D AMR RAMSES code
    - FLD model (almost done)
    - M1 model (in progress)
  - fair comparison between methods/numerical improvements
  - applications to star formation simulations
    - should have more impact in 3D (anisotropy due to the disk)