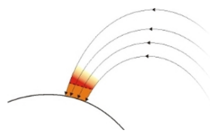
3D Grey Radiative Properties of Accretion Shocks in Young Stellar Objects.

Laurent Ibgui



(LERMA, Observatoire de Paris-Meudon, CNRS, UPMC)

Collaborators (ANR STARSHOCK project ANR-08-BLAN-0263-07 – 2009/2013):

C. Stehlé (1), I. Hubeny (3), T. Lanz (4), R. Bonito (2,7) : **radiative transfer / opacities**
J.-P. Chièze, M. González, L. de Sá : **RHD simulations**
S. Orlando (2), T. Matsakos (5) : **MHD simulations**

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(2) INAF – Osservatorio Astronomico di Palermo, Italy
(3) Steward Observatory, Tucson, AZ, USA
(4) Laboratoire Lagrange, Observatoire de la Côte d'Azur, Nice, France
(5) CEA/DSM/IRFU/Sap-AIM, CEA Saclay, France
(6) Université Paris Diderot, Sorbonne Paris Cité, France
(7) UNIPA, Palermo, Italy

(Ibgui, Hubeny, Lanz, & Stehlé (2013), A&A, 549, A126)
(Ibgui, González, Stehlé, Chièze, Lanz, Hubeny, et al. 2013, in prep.)
(Ibgui, Orlando, Stehlé, Chièze, de Sá, Hubeny, Lanz, Matsakos, et al. 2013, in prep.)

ASTRONUM 2013 (Biarritz, France, 5 July 2013)

Outline

- **IRIS**, a new 3D spectral radiative transfer code for spectral diagnostics

-3D model of a **laboratory radiative shock**
(RHD structure and radiative properties)

-Two models of an **accretion shock** on a classical T Tauri star (CTTS) :
2D axisymmetric MHD
1D RHD model

3D grey radiative properties

IRIS: major features

(Ibgui et al. 2013, A&A, 549, A126)

generic 3D spectral radiative transfer code
for the analysis of any radiating object

IRIS post-processes 3D (radiation) (magneto) hydrodynamics (RMHD) simulations in order to calculate **synthetic spectra** (and emissivity maps).

IRIS solves the 3D radiative transfer equation to determine the **spectral specific intensity**:

$$\underbrace{I(\boldsymbol{r},\boldsymbol{n},\nu,t)}_{\text{depends on 7 variables in 3D}}$$

Physics:
-3D geometry, structured non uniform Cartesian grid
- non relativistic velocities (velocity gradient effects due to Doppler shifts) ~~Sobolev (LVG) approx.~~
-boundary conditions: specified or periodic (small part of a large structure: box in an atmosphere)
-Local Thermodynamic Equilibrium (LTE) for the moment
-unpolarized radiation
-moments and Eddington tensor are then calculated by angular integration

Numeric:
-Fortran 95, 2 years of development (from scratch)
-CPU optimized (0.2 sec / frequency / direction on a Mac Book Pro)
-short-characteristics method (Kunasz & Auer, JQSRT 1998)
-monotonic cubic interpolation (Auer, ASP 2003)
-angular quadratures : Carlson A4 1963, Carlson & Lathrop 1965, Gauss

Extensions and applications of IRIS

Future extensions to IRIS:
- scattering (dust, Thomson, Rayleigh)
- NLTE
- polarized radiation

• Current and future applications, modeling (spectra and/or maps) of:
- Young Stellar Objects (T Tauri accretion shocks, outflows), laboratory radiative shocks
- stellar atmospheres,
- accretion disks,
- cosmology Lyman-α forest,
- exoplanet atmospheres.

Radiative shocks: overview, astrophysical context

- shocks affected by radiation through energy and momentum exchange

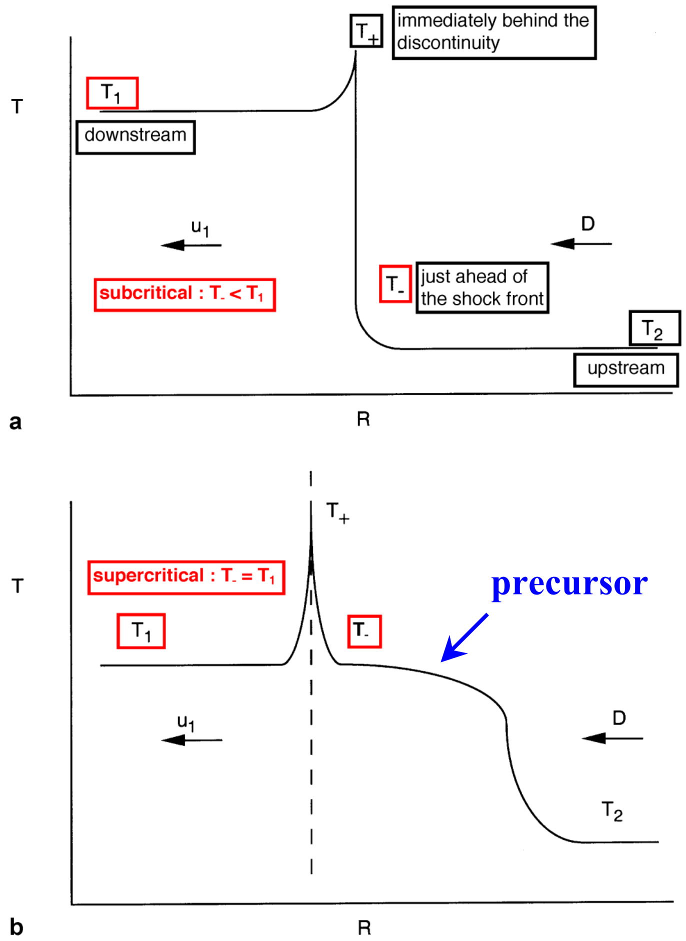
- radiative shocks occur in stellar winds, accretion flows, jets in Young Stellar Objects, supernovae, SNR

-Accretion shocks in classical T Tauri Stars (CTTS):
important X-ray source,

observational diagnostics with Chandra and XMM:

V4046 Sgr: Argiroffi et al. 2012, Günther et al. 2006)
V2129 Oph: Argiroffi et al. 2011,
TW Hya (Brickhouse et al. 2010, ...)
MP Mus (Argiroffi et al. 2007)

Radiative shocks: 1D structure



Sincell et al. (1999),
Shock Waves, 9, 391

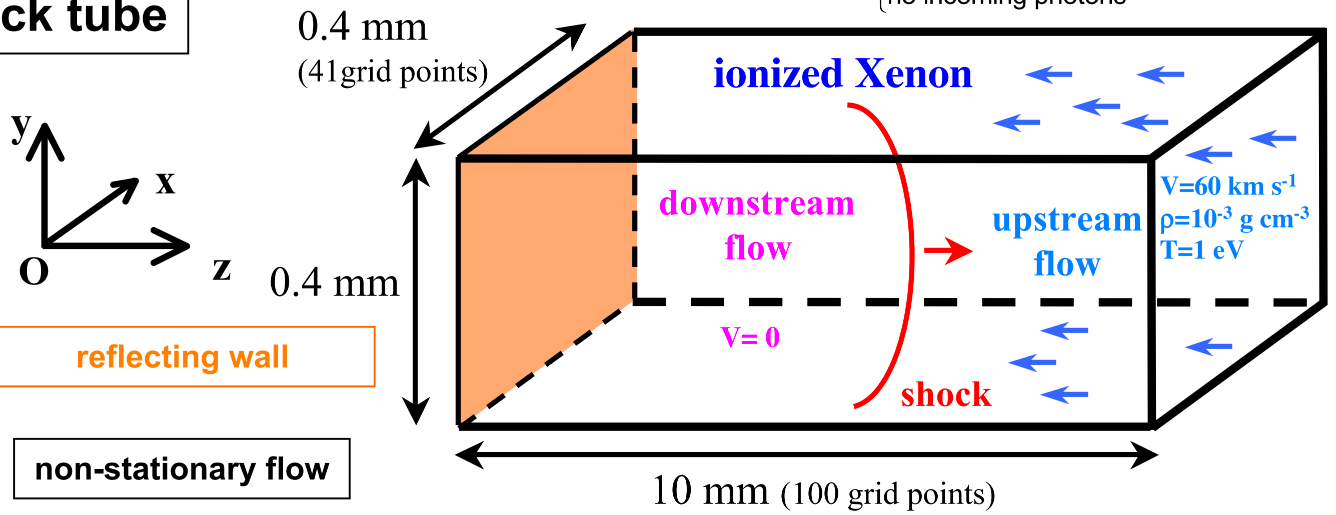
A 3D RHD model of a laboratory radiative shock

(Ibgui, González, Stehlé, Chièze et al. 2013, in preparation)

(experimental runs: PALS laser, Prague, Stehlé et al. 2010, 2012)

lateral walls:
- reflecting for the flow
- transparent for the photons
- no incoming photons

shock tube



reflecting wall

non-stationary flow

3D **RHD**: **HERACLES** code
(González et al. 2007, A&A, 464, 429)

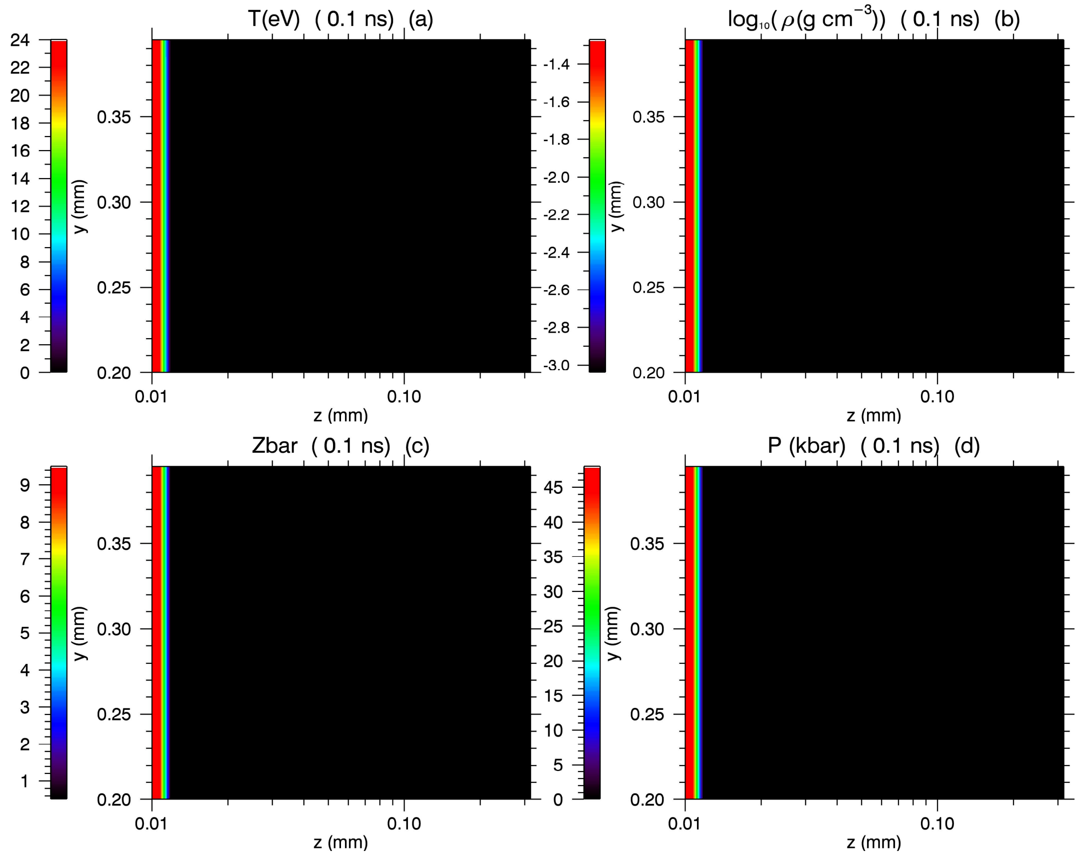
- Equation of State: $e = \left(1 + \langle Z \rangle\right) \dfrac{kT}{(\gamma - 1)\, m_{Xe}}$
  ($\langle Z \rangle$: mean ionization stage)
- grey opacities (Mirone, Gauthier et al. JQSRT 1997)

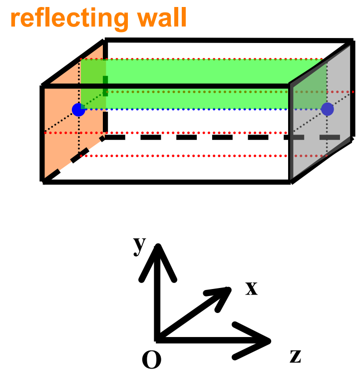
3D **spectra** : **IRIS** code
(Ibgui et al. 2013, A&A, 549, A126)

post-processes RHD snapshots

- spectral opacities: Screened Hydrogenic Model (Michaut, Stehlé et al. 2004, EPJD 28, 381)
- transitions:
  - bound-bound
  - bound-free (photoionization)
  - free-free

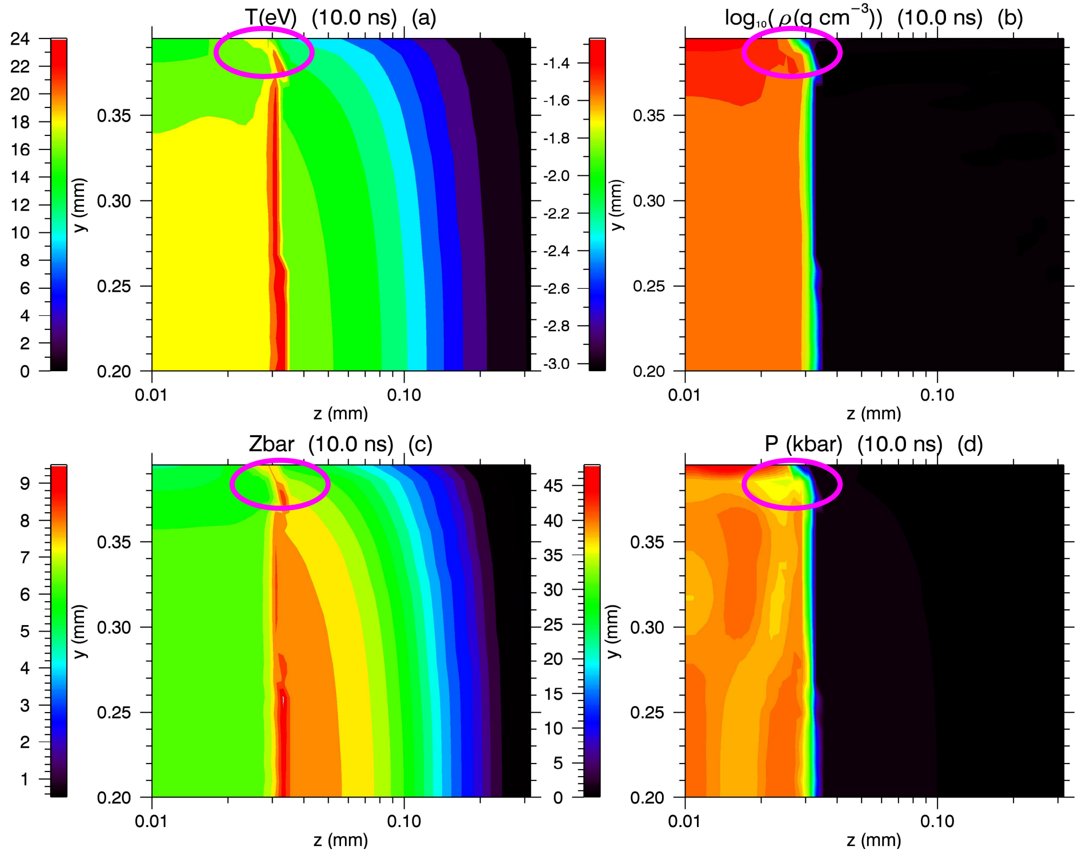
3D structure and radiative properties of a radiative shock:
RHD simulation: non stationary evolution (HERACLES)

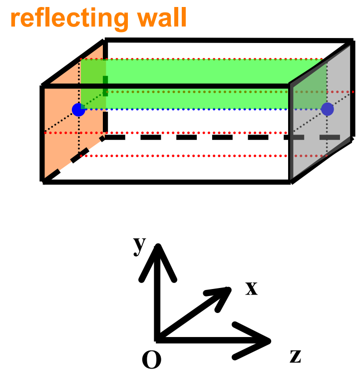




3D structure and radiative properties of a radiative shock:
RHD simulation: non stationary evolution (HERACLES)

shock curvature

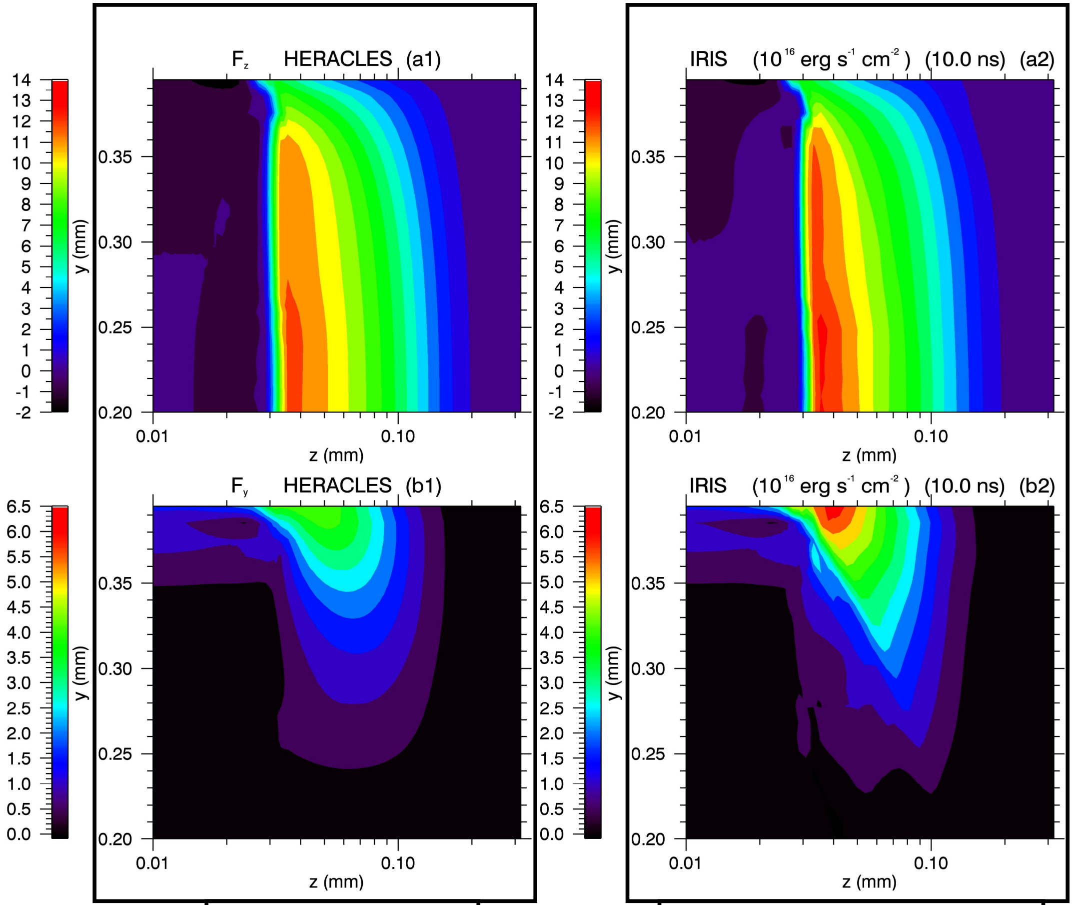




3D structure and radiative properties of a radiative shock:
comparison of the radiation moments: HERACLES - IRIS

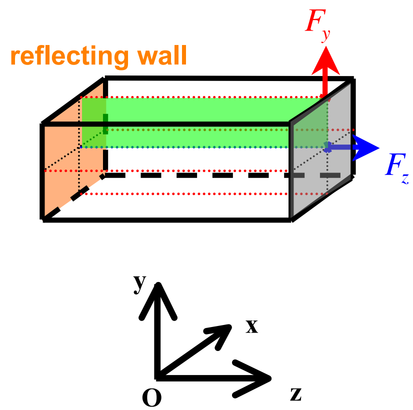
F_z

F_y



grey M1 model (HERACLES)

grey exact calculation (IRIS)



3D structure and radiative properties of a radiative shock:
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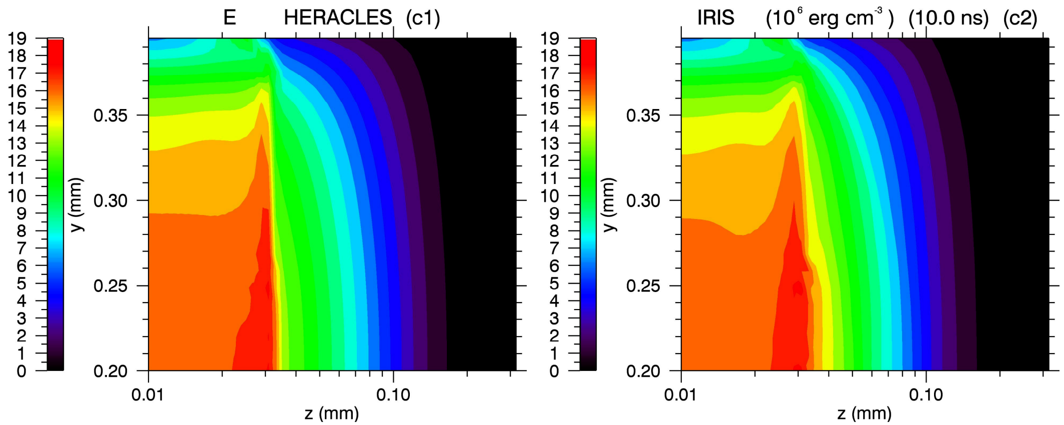
E



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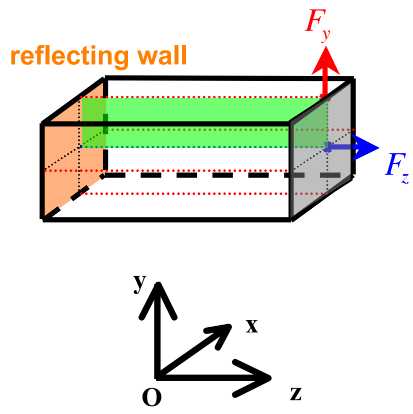
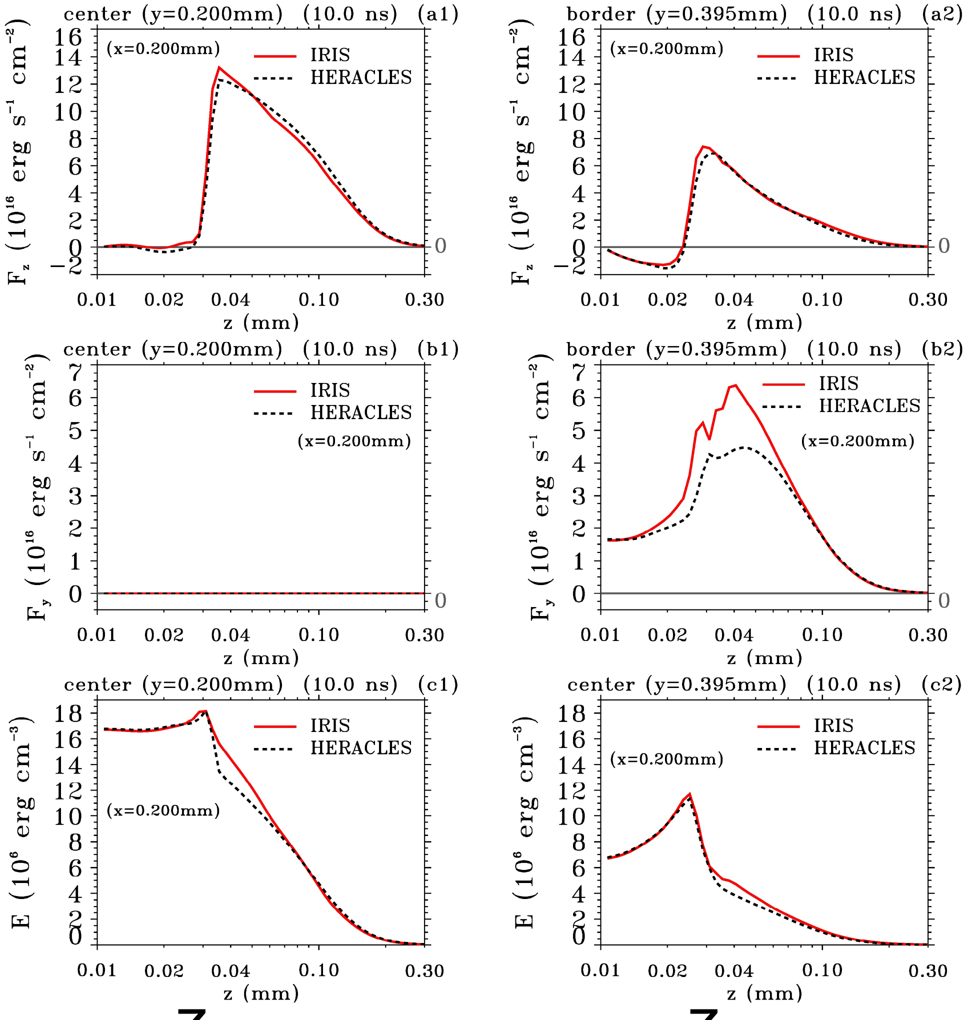


3D structure and radiative properties of a radiative shock:
comparison of the radiation moments: HERACLES - IRIS

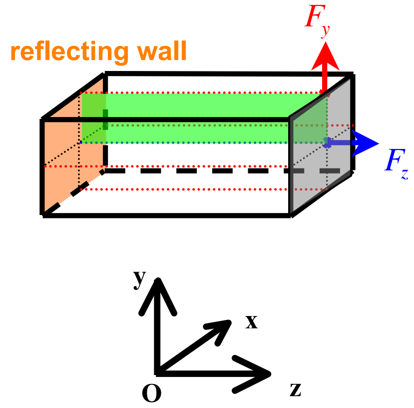
F_z

F_y

E



Z_{center} Z_{border}

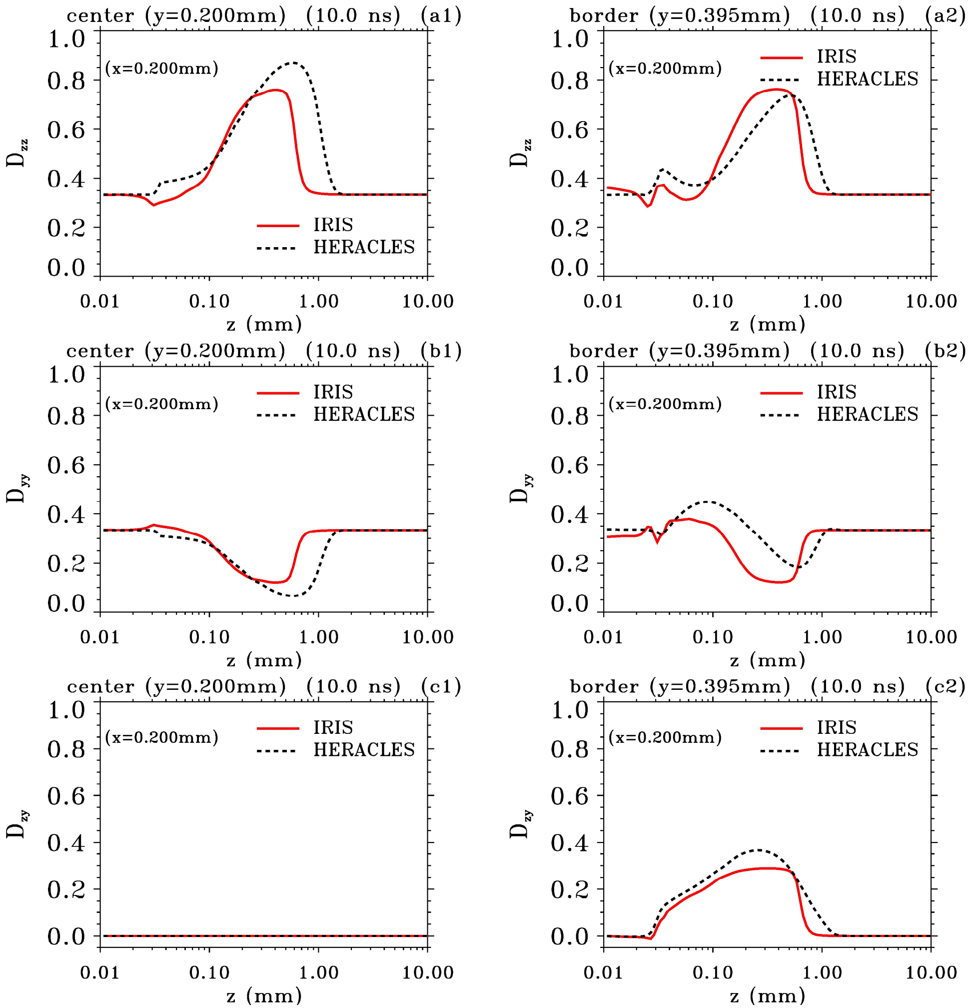


3D structure and radiative properties of a radiative shock:
comparison of the radiation moments: HERACLES - IRIS

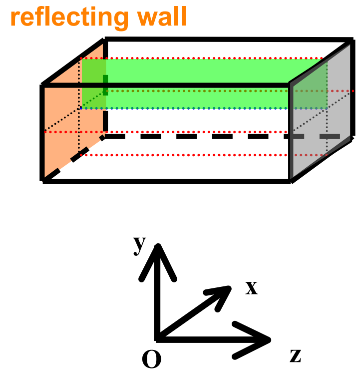
D_{zz}

D_{yy}

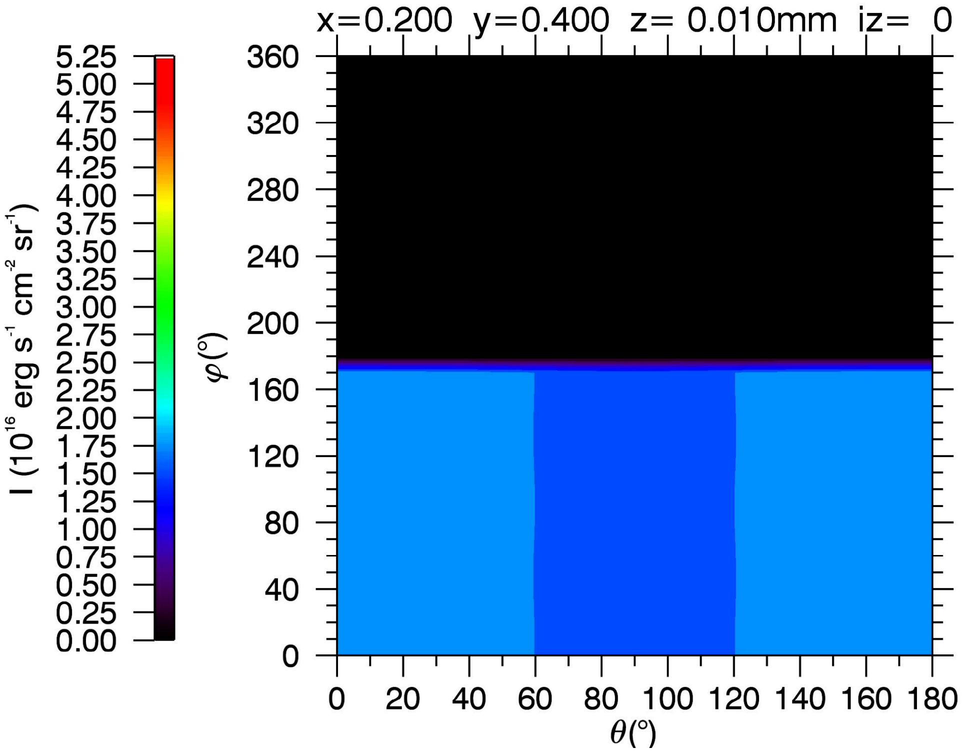
D_{zy}

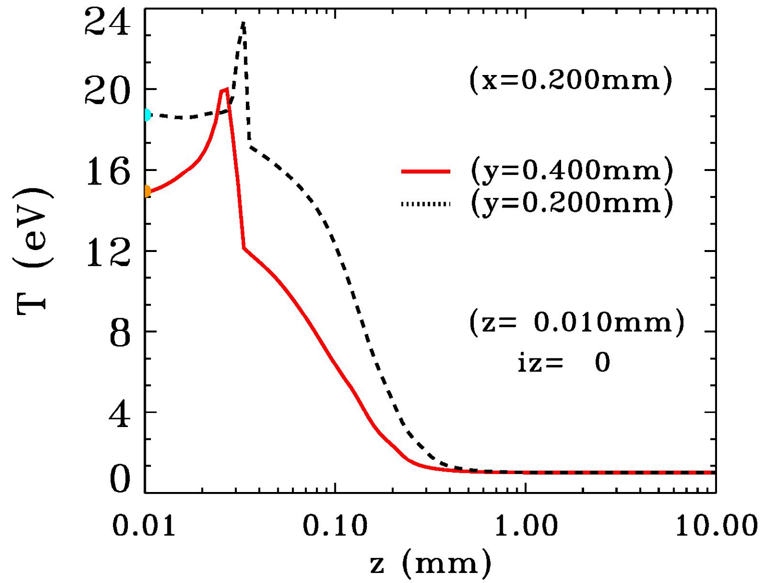


Z_{center} Z_{border}



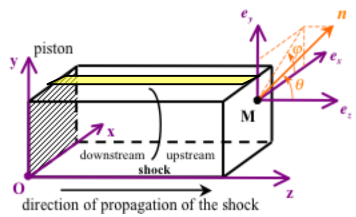
3D structure and radiative properties of a radiative shock: **angular distribution of the grey specific intensity (IRIS)**





snapshot t=10ns

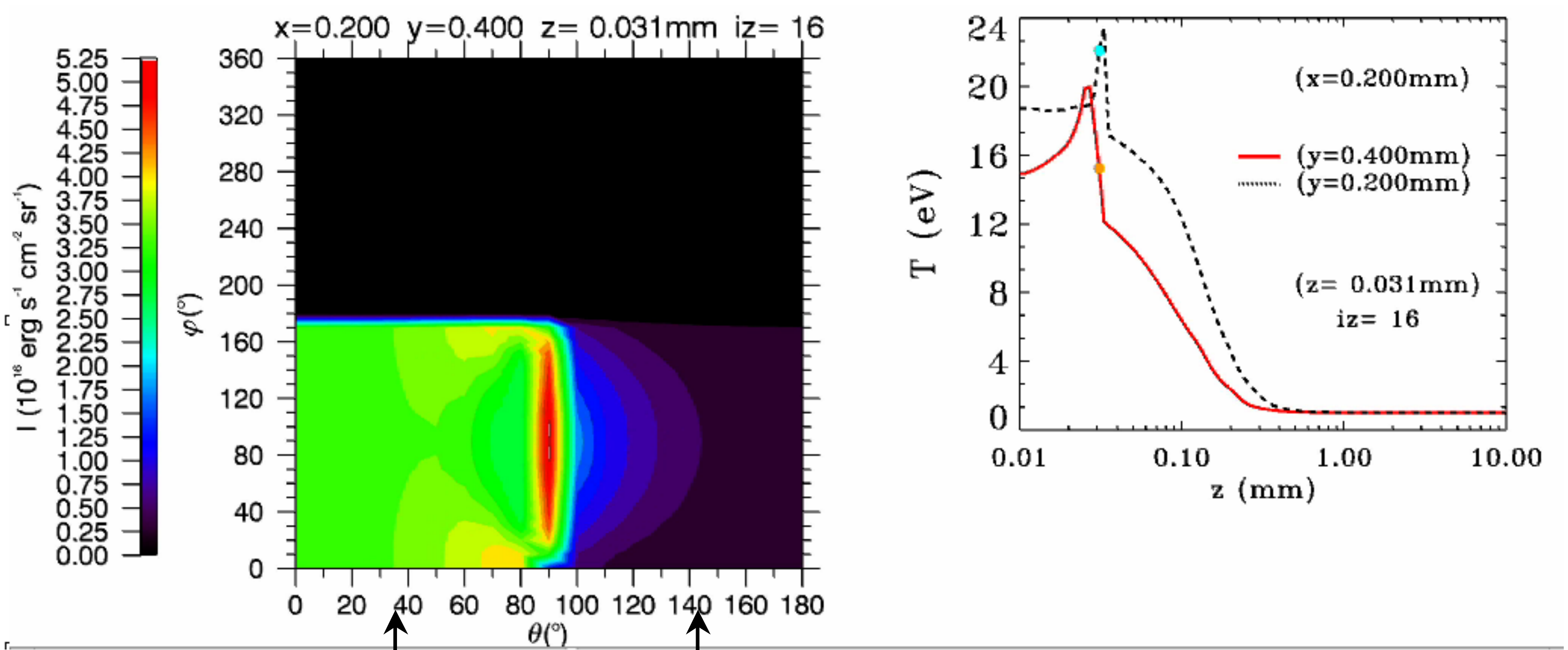
along a border



☞ max (I) : at θ=90°, φ=90°

☞ moving upstream, beam becomes dimmer and narrow

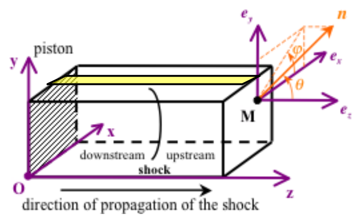
3D structure and radiative properties of a radiative shock:
angular distribution of the grey specific intensity (IRIS)



shocked part upstream

snapshot t=10ns

along a border



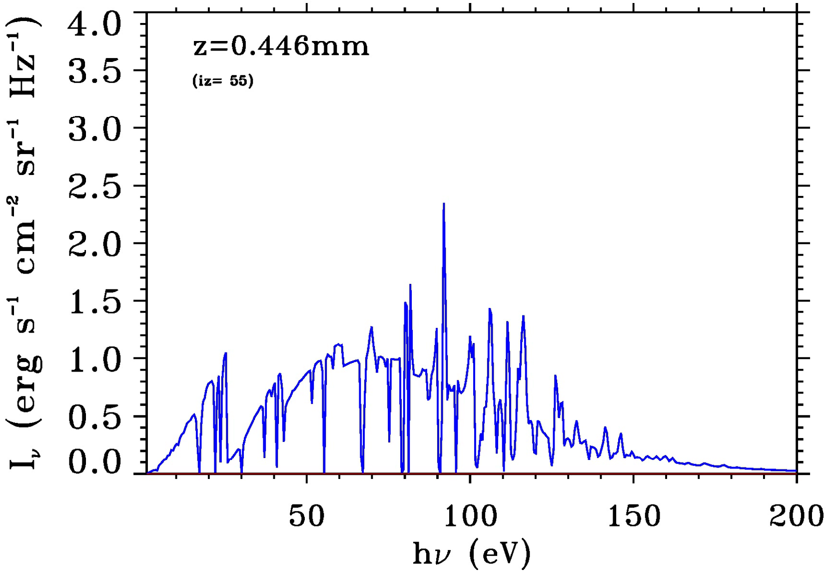
☞ max (I) : at θ=90°, φ=90°

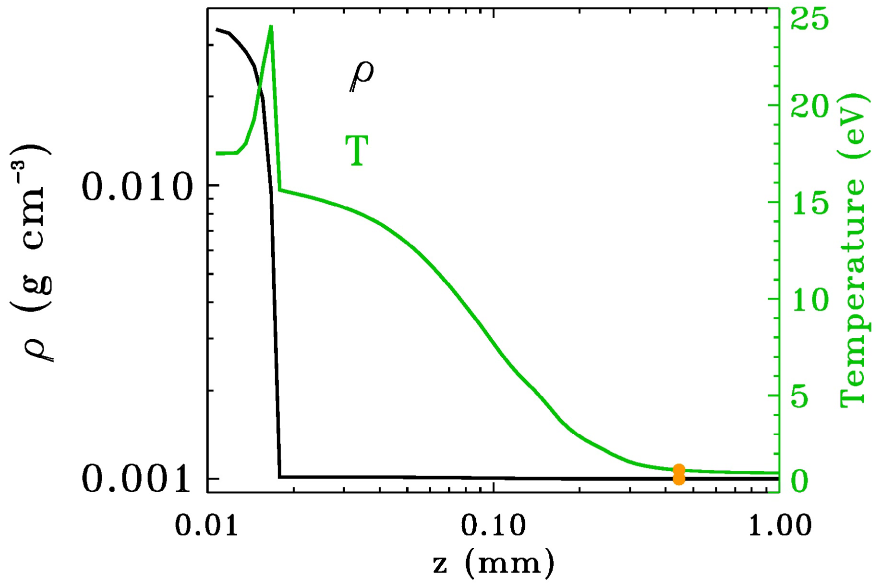
☞ moving upstream, beam becomes dimmer and narrow

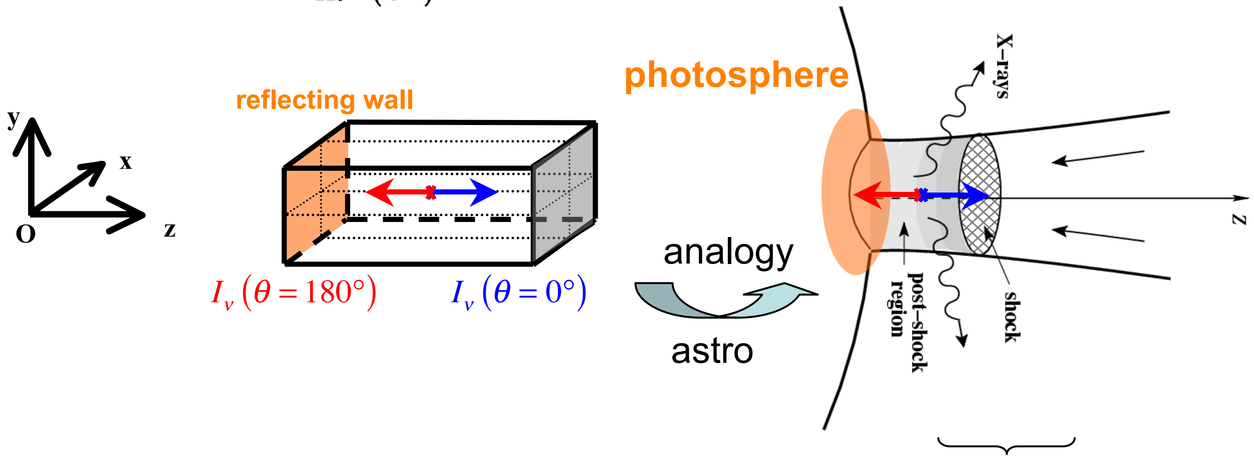
3D structure and radiative properties of a radiative shock:
spectral specific intensities in axial directions (IRIS)

X - UV radiation

(snapshot t= 4ns)

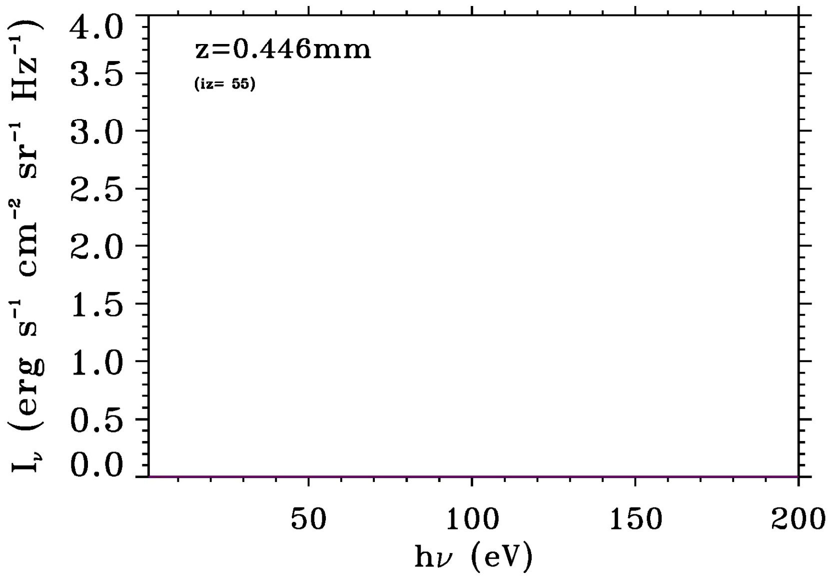


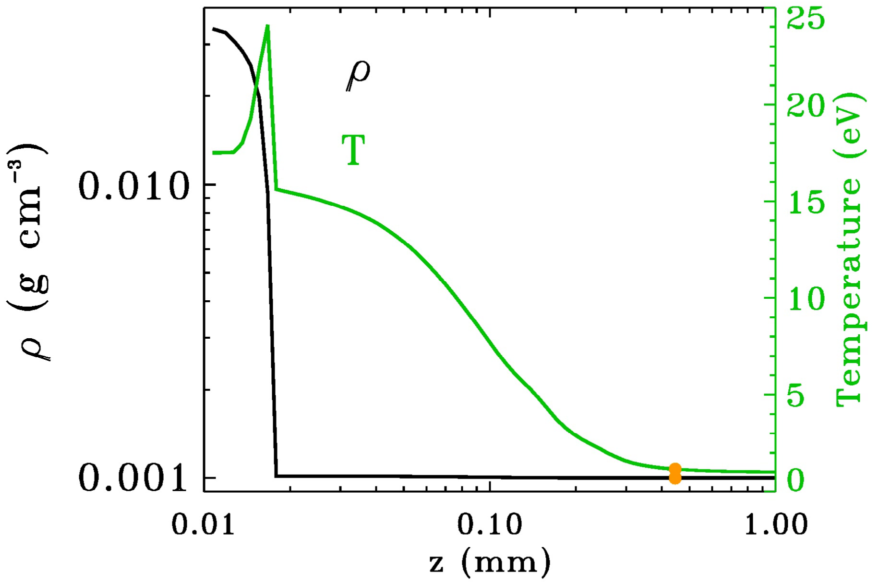


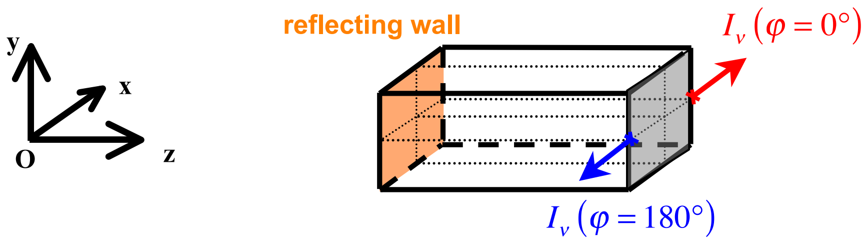


photosphere might be heated by the shock (feedback)

3D structure and radiative properties of a radiative shock: **spectral specific intensities in lateral directions (IRIS)**







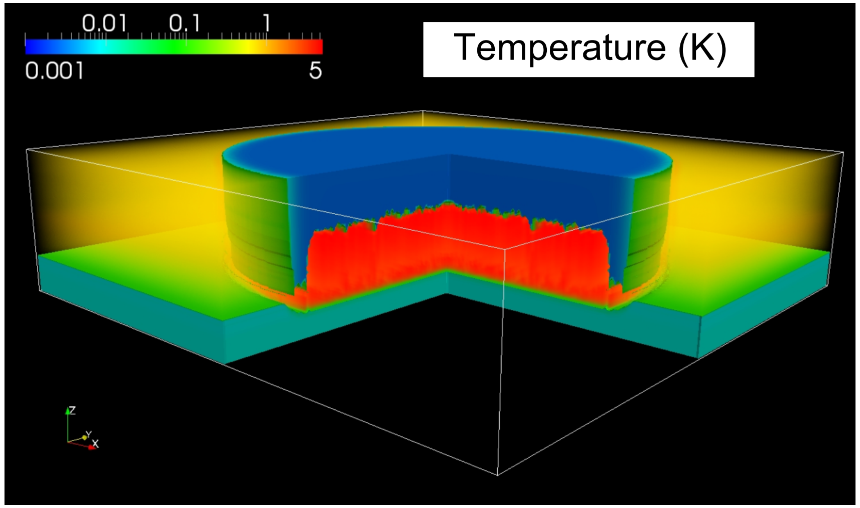
Structure of an accretion shock on a young stellar object

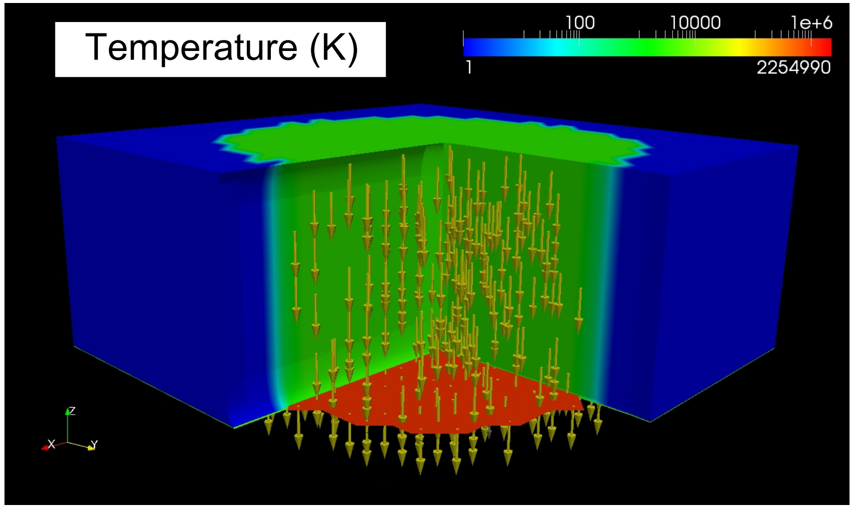
2D axisymmetric **MHD** model (S. Orlando)

PLUTO code (Mignone et al. 2007,12)

1D **RHD** model (L. de Sa)

ASTROLABE code (Dorfy & Drury 1987, Lesaffre, Chièze et al. 2004)





- no radiation in momentum equation
- energy equation:

no absorption

optically thin grey radiative losses: $n_e \, n_H \, \Lambda_{(T)}$

<<

LTE grey radiative transfer (M1 model)

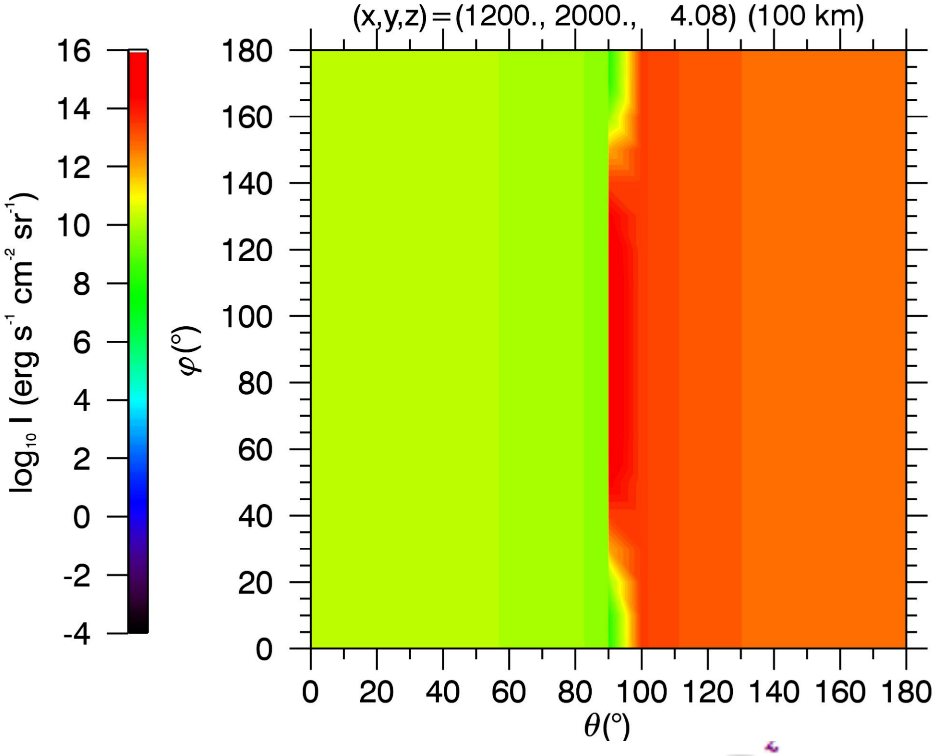
radiation in momentum and energy equation:

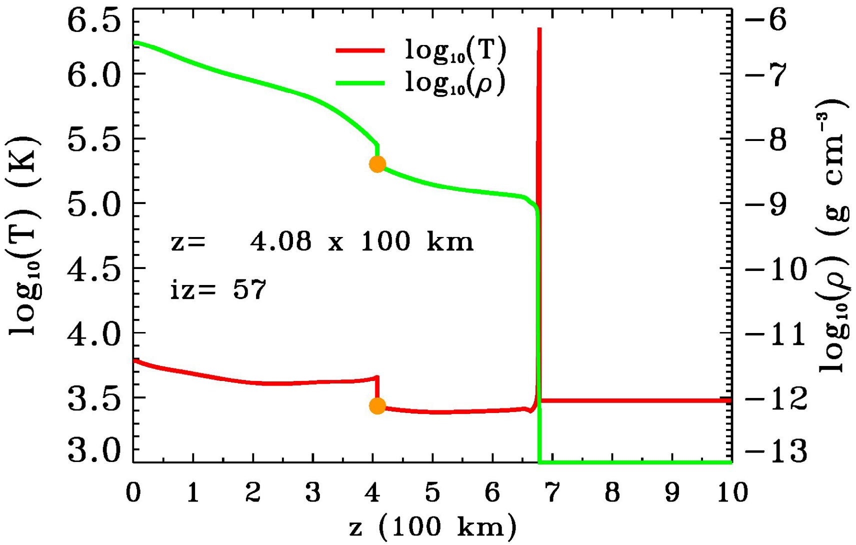
absorption

radiative losses: $c \, \kappa_P \, a T^4$

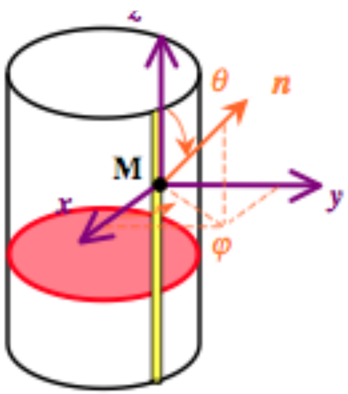
radiation plays a key role in the determination of the structure (and therefore the signature) of an accretion shock on classical T Tauri stars.

angular distribution of the grey specific intensity emitted by the RHD accretion structure (IRIS)





along a border



☞non uniformity and anisotropy of the emission

Accretion Shocks: Conclusion and Further Perspectives

- Structure and qualitative characterization of an accretion shock
  - crucial influence of the radiation on the shocked accretion column structure
  - 3D nature and anisotropy of the emitted radiation

- Test, with IRIS, of the M1 radiation moment model, in the context of a 3D radiative shock:
  - gray M1 model : rather good agreement with the exact solution, except near boundaries

- **Further perspectives:**

  -better characterization of the radiative properties in the shocked region:

  ☞ 1D RHD: transition between the two regimes (thick with M1, thin with coronal approx.) function of the photon escape probability (L. de Sa, JP Chièze)

  ☞ NLTE opacity data (C. Stehlé, I. Hubeny, T. Lanz)

  ☞ 3D MHD: including radiative transfer in PLUTO (T. Matsakos, S. Orlando, M. Flock) ➔ 3D RMHD

  - 1D detailed RHD models (ASTROLABE)
    presence of a precursor ?

  - 3D RMHD models of accretion shocks (PLUTO)
    influence of the shocks on the surrounding stellar region, fluctuations?. (Matsakos et al. 2013)

  - Spectral diagnostics of accretion shocks: high resolution NLTE spectra with IRIS (to be compared with observations)
    (L. Ibgui, I. Hubeny, T. Lanz, C. Stehlé)