3D Spectral Radiative Transfer with IRIS
3D Radiation Magnetohydrodynamics with PLUTO
results and perspectives

Laurent Ibgui **(LERMA, Observatoire de Paris-Meudon, Sorbonne Université)**

Main Collaborators :
I. Hubeny (2),
A. Ciardi (1)
S. Orlando (3), S. Colombo (3,4)

(1) LERMA, Observatoire de Paris, Sorbonne Université, CNRS, France
(2) Steward Observatory, Tucson, AZ, USA
(3) INAF – Osservatorio Astronomico di Palermo, Italy
(4) Università di Palermo, Italy

AIPS Workshop: Stellar physics at Paris Observatory (30 June 2022)

Outline

3D spectral radiative transfer for spectral diagnostics: IRIS
- Major physics and numerical features
- application to a laboratory radiative shock
- irradiance from any 3D structure
- on-going and future developments

3D radiation magnetohydrodynamics modeling with PLUTO
- magnetospheric accretion on a CTTS
- NLTE RMHD equations
- precursor UV emitter in accretion column
- future perspectives

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**:

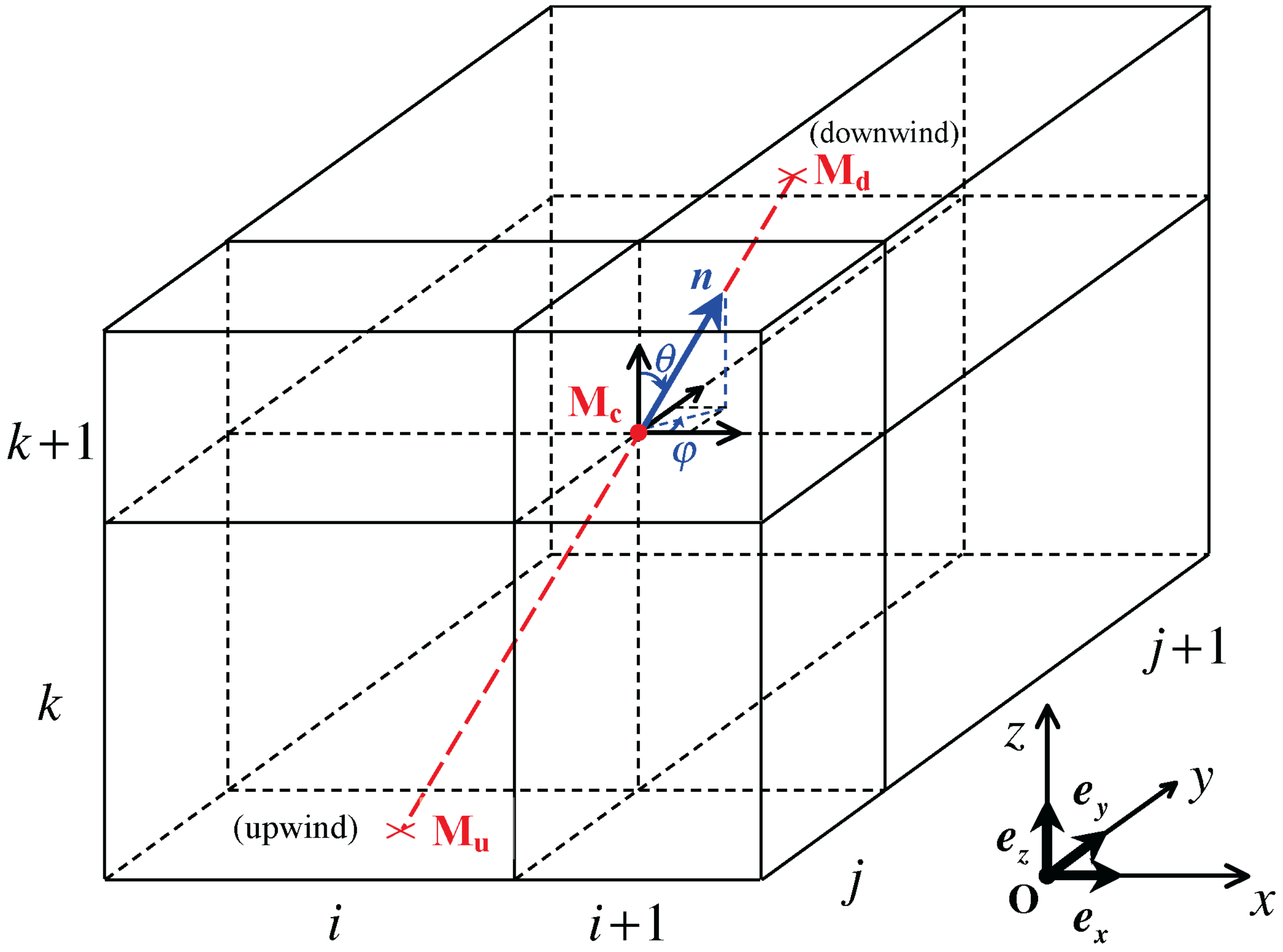
$$I(\vec{r}, \vec{n}, \nu, t)$$

Physics:
-3D geometry, structured non uniform Cartesian grid
-non relativistic velocities (velocity gradient effects due to Doppler shifts) (~~Sobolev approx.)~~
-boundary conditions: specified or periodic
-radiation moments (energy, flux, pressure) are calculated by angular integration

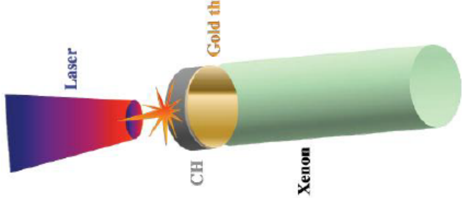
Numeric:
-Fortran 2003
-CPU optimized (0.2 sec / frequency / direction on a Mac Book Pro)
-short-characteristics method (Kunasz & Auer, JQSRT 1998)
-monotonic cubic interpolation (Auer, ASP 2003)
-angular quadratures (Carlson A4 1963, Carlson & Lathrop 1965, Gauss)

The short-characteristics method

(3D application)

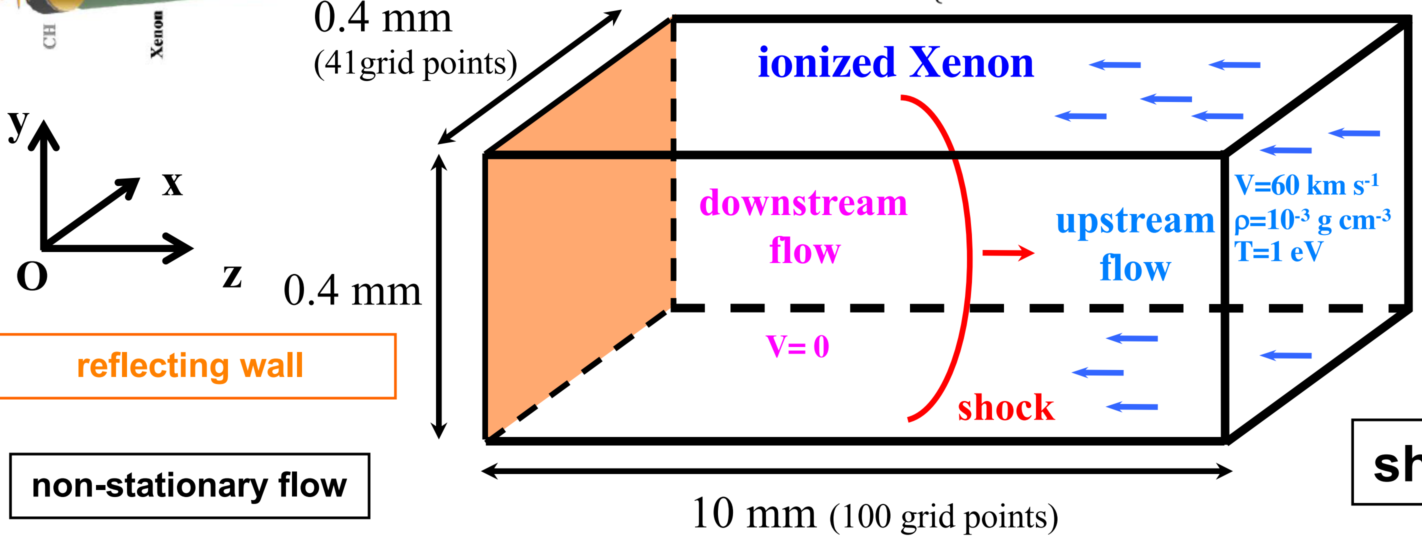


A 3D model of a laboratory radiative shock
(Ibgui et al. 2015)



PALS laser, Prague

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



reflecting wall

non-stationary flow

shock tube

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

Equation of State:
$$e=\left(1+\underset{\uparrow}{\langle Z\rangle}\right)\frac{kT}{(\gamma-1)\,m_{Xe}}$$
mean ionization stage

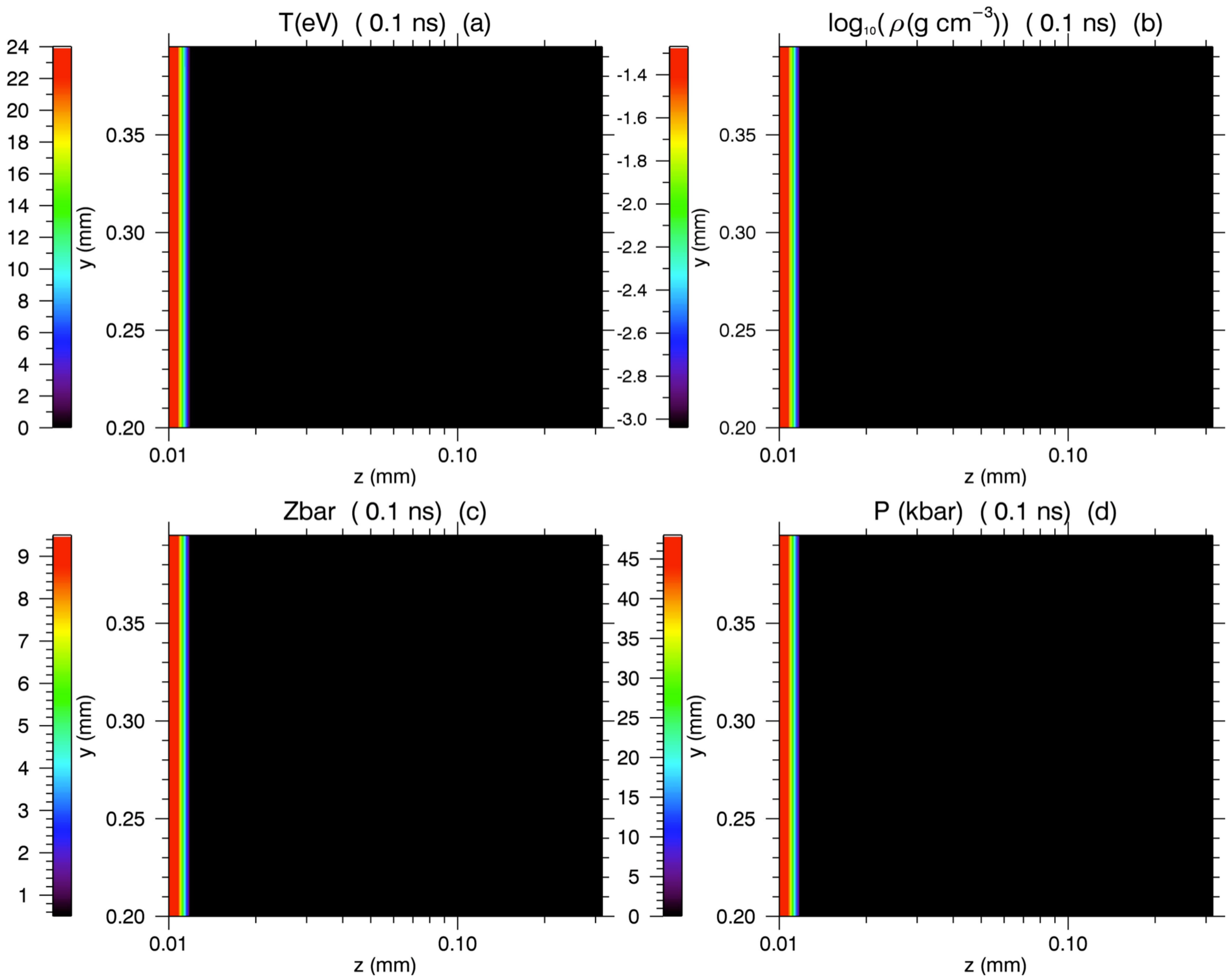
grey opacities (Mirone, Gauthier et al. JQSRT 1997)

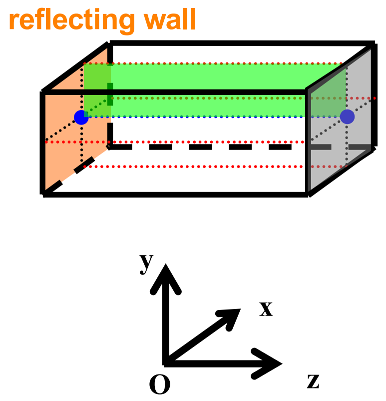
3D **spectra** : **IRIS** code
(Ibgui et al. 2013, A&A, 549, A126)
post-processes RHD snapshots

spectral opacities: Screened Hydrogenic Model (Michaut, Stehlé et al. 2004, EPJD 28, 381)

transitions:
- bound-bound
- bound-free (photoionization)
- free-free

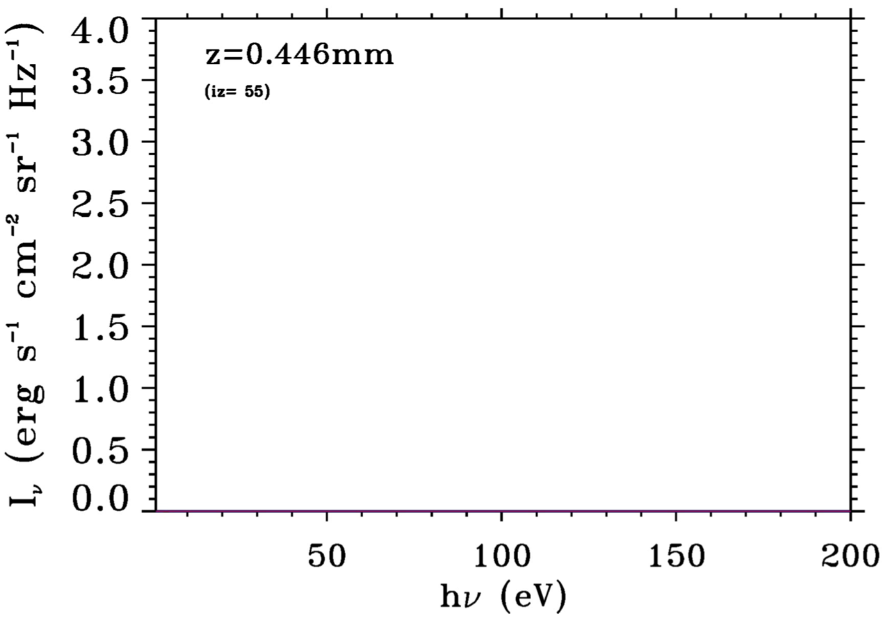
3D structure and radiative properties of a radiative shock:
Radiation Hydrodynamic simulation: non stationary evolution (HERACLES)

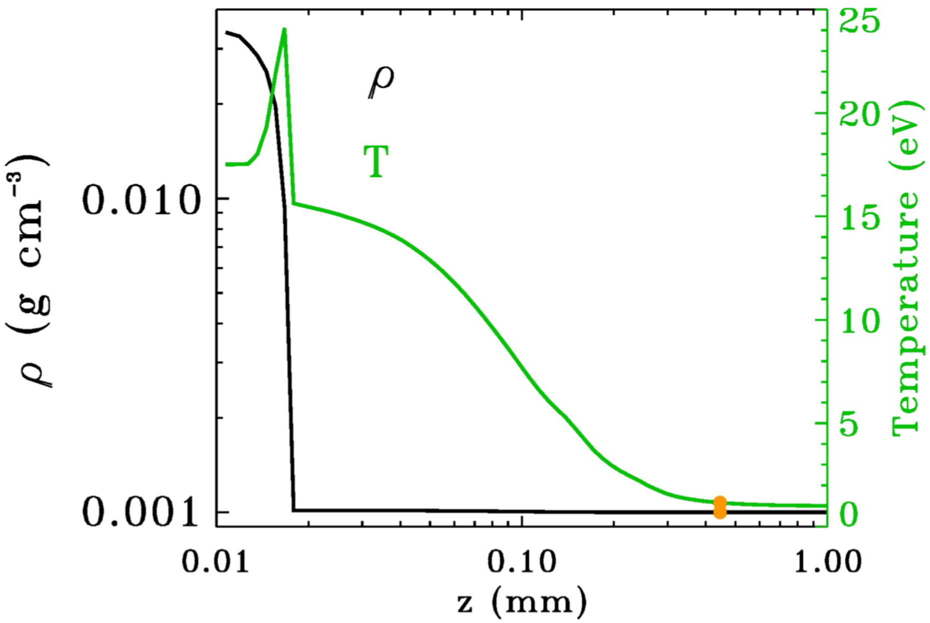




(Matthias González)

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

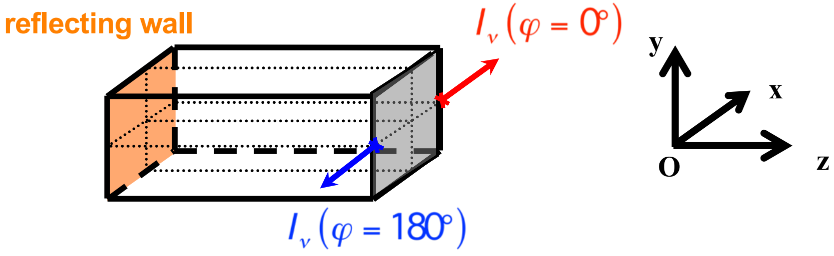




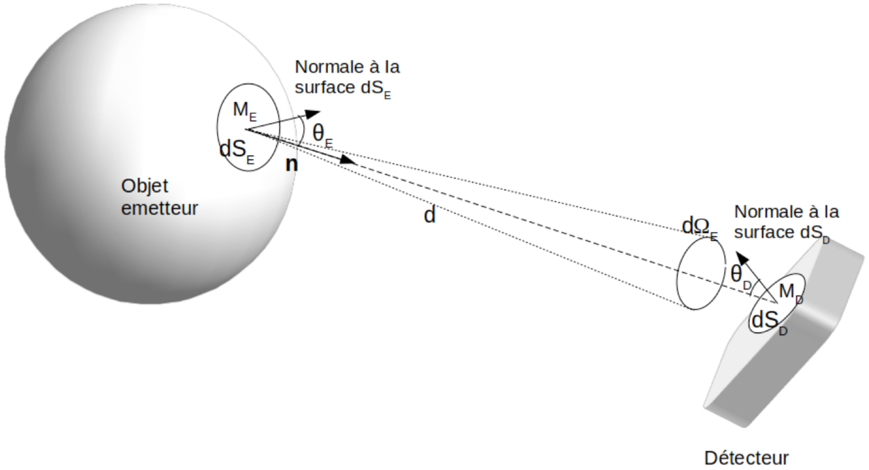
$$I_\nu\left(x_{border}, y_{center}, z, \ \theta = 90^\circ, \ \varphi = 0^\circ\right)$$

=

$$I_\nu\left(x_{border}, y_{center}, z, \ \theta = 90^\circ, \ \varphi = 180^\circ\right)$$



Irradiance (éclairement) from *any* 3D structure



Avila Orta, June 2022

unresolved object at infinite distance

irradiance

$$\varepsilon(M_D,\nu,t)=\frac{\cos\theta_D}{d^2}I_{\text{ray}}(n,\nu,t)$$

$(\mathrm{W\ m^{-2}\ Hz^{-1}})$

$(\mathrm{erg\ s^{-1}\ cm^{-2}\ Hz^{-1}})$

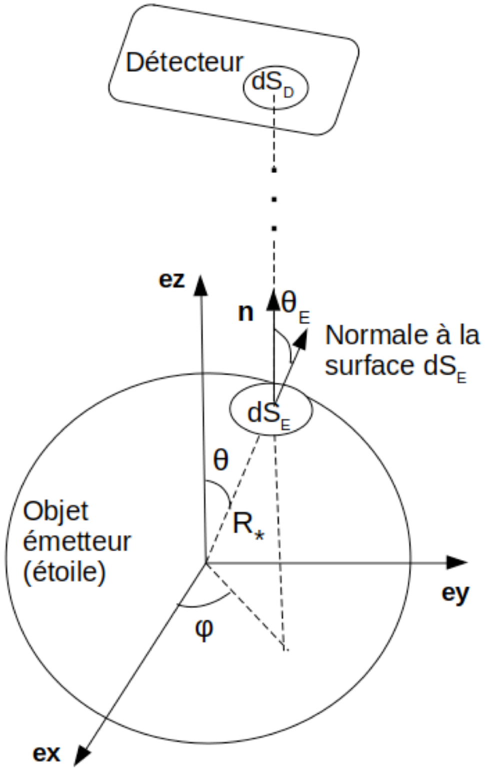
radiant intensity

$$I_{\text{ray}}(n,\nu,t)=\int_{S_E} I(M,\theta_E,\varphi_E,\nu,t)\cos\theta_E\, dS_E$$

$(\mathrm{W\ sr^{-1}\ Hz^{-1}})$

$(\mathrm{erg\ s^{-1}\ sr^{-1}\ Hz^{-1}})$

Irradiance (éclairement) from a spherical blackbody



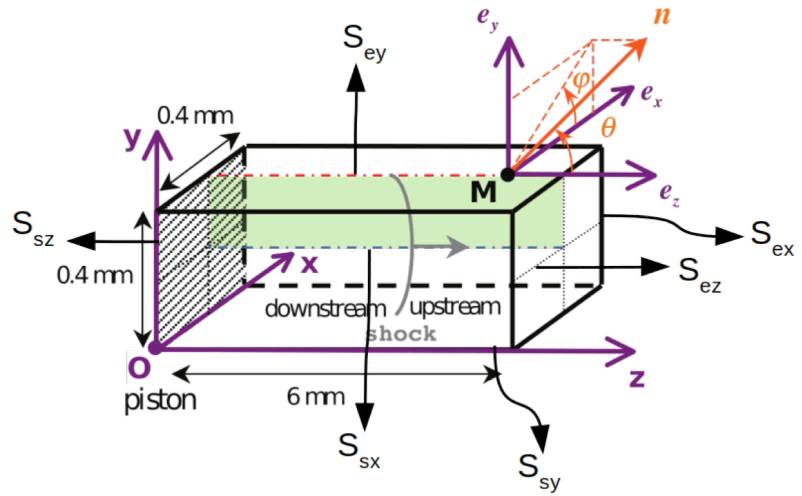
Avila Orta, June 2022

$$\varepsilon(M_D,t)=\frac{\cos\theta_D}{d^2}\sigma T^4 R_*^2$$

$(\mathrm{W\ m^{-2}})$

$(\mathrm{erg\ s^{-1}\ cm^{-2}})$

Test case : laboratory radiative shock



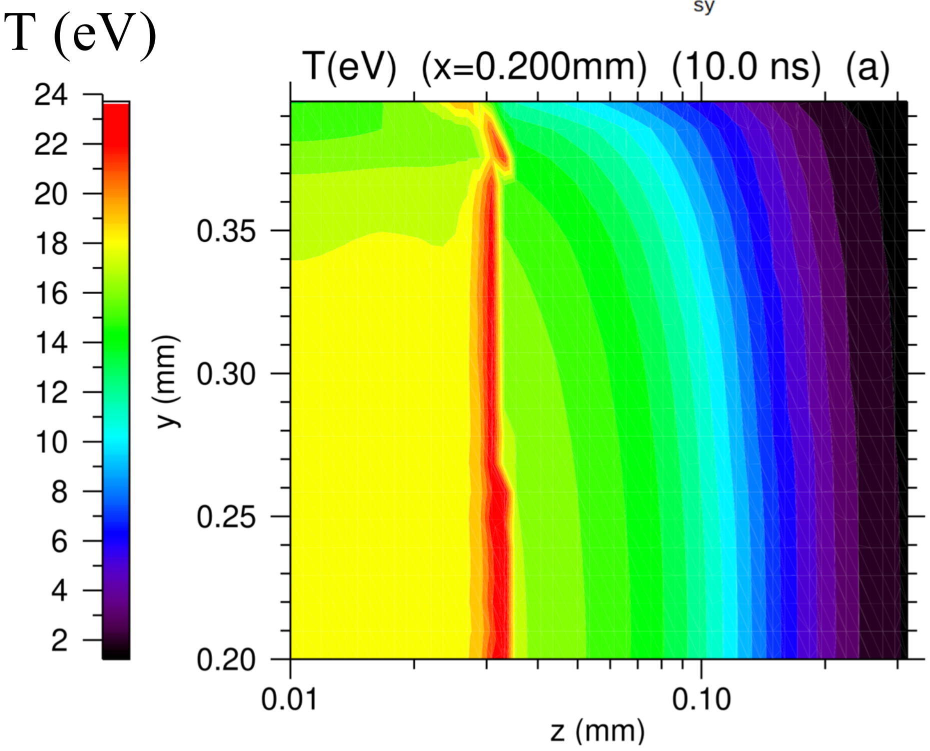
Avila Orta, June 2022

T (10^4 K)

28

12

1,2

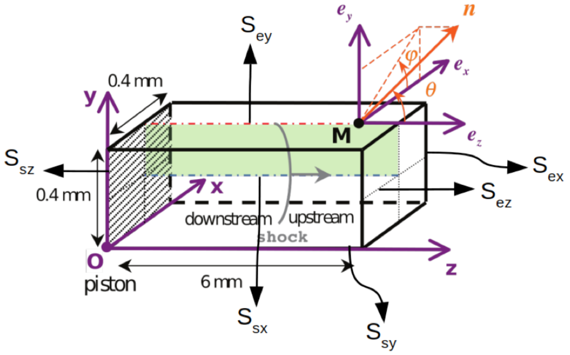


(Ibgui+15)

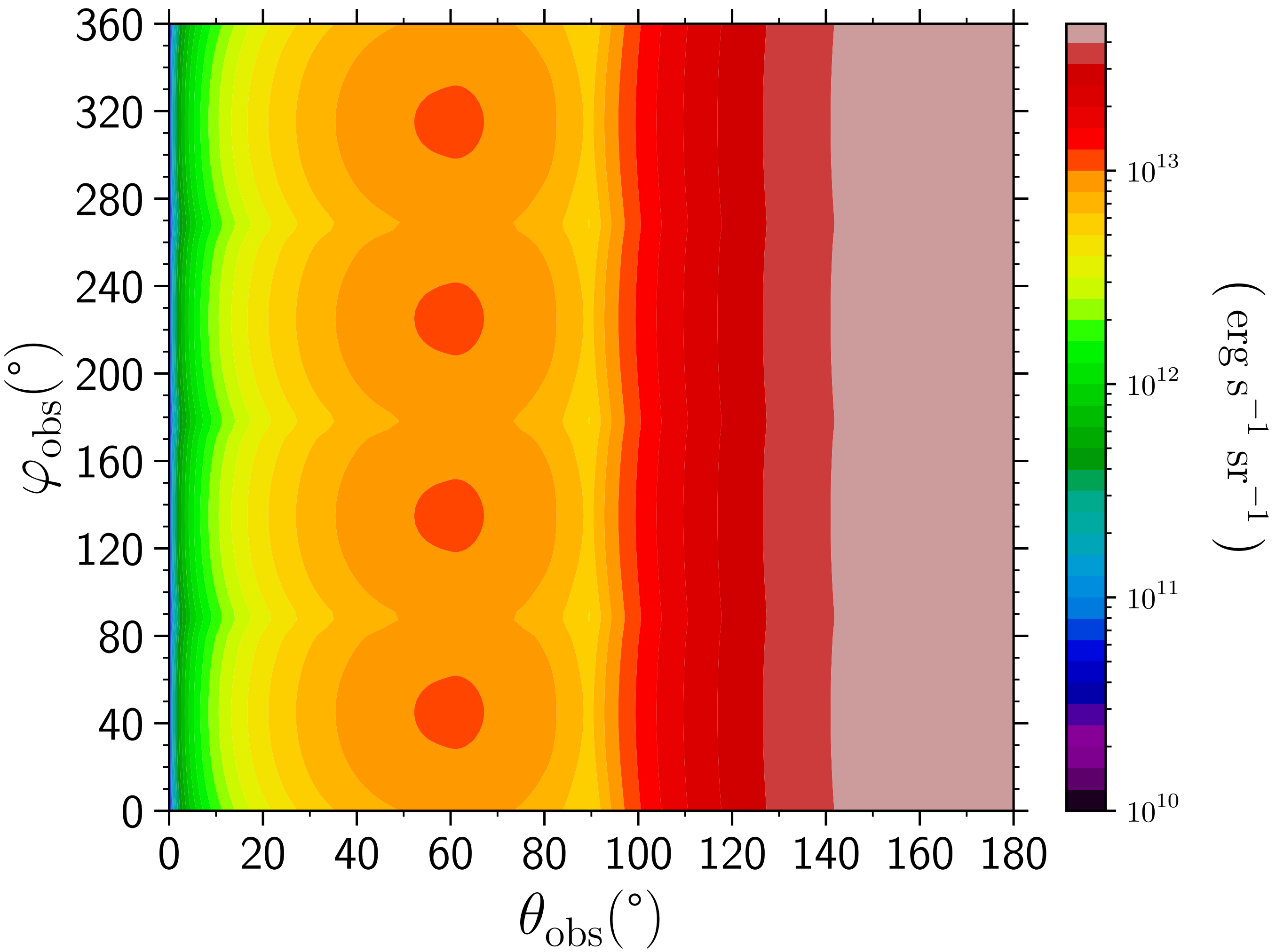
$$1\ \mathrm{eV} \leftrightarrow 11604.5\mathrm{K}$$

Test case : laboratory radiative shock

Avila Orta, June 2022



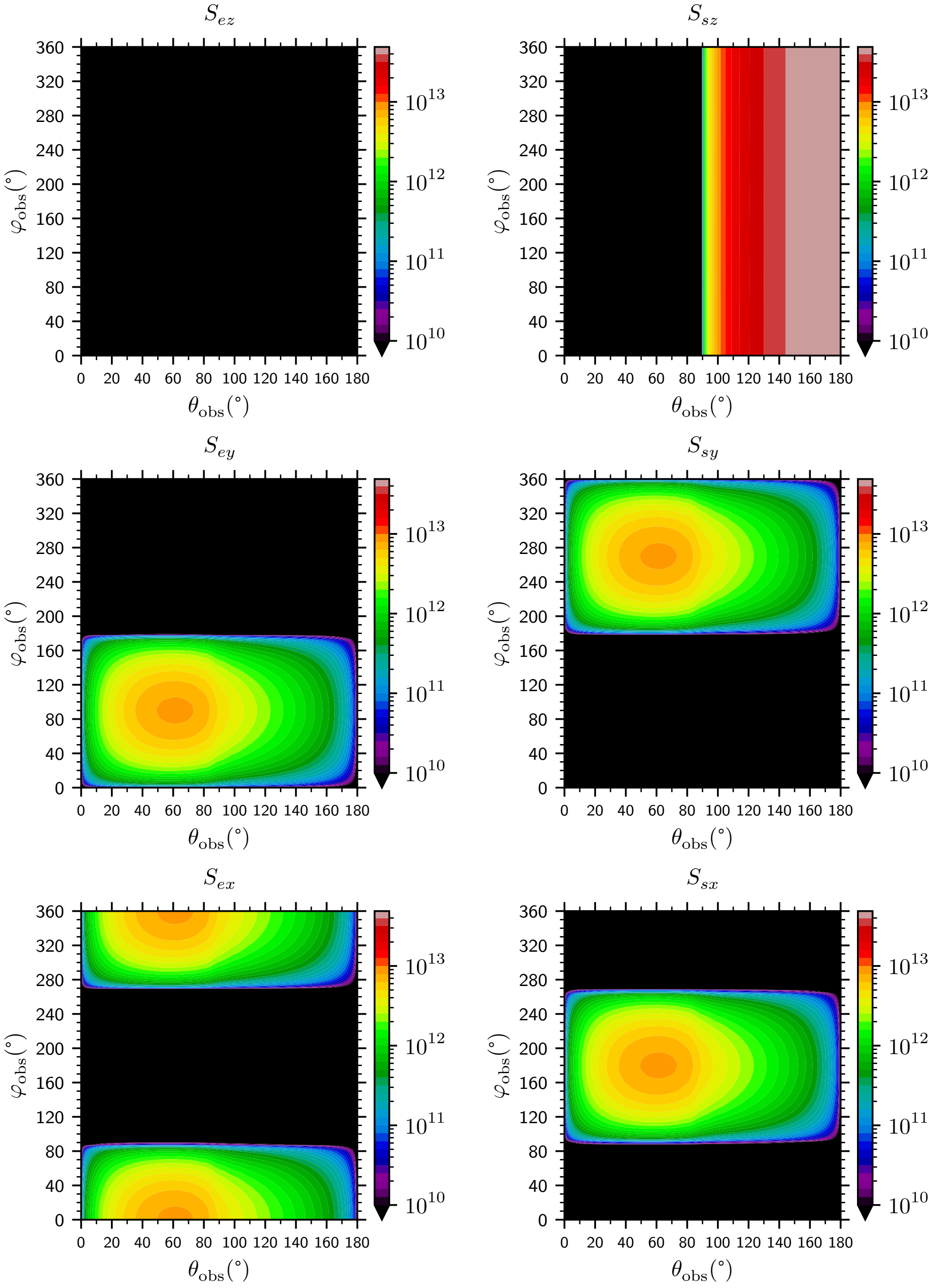
radiant intensity

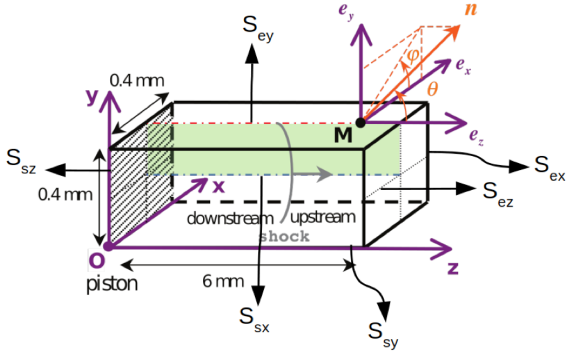


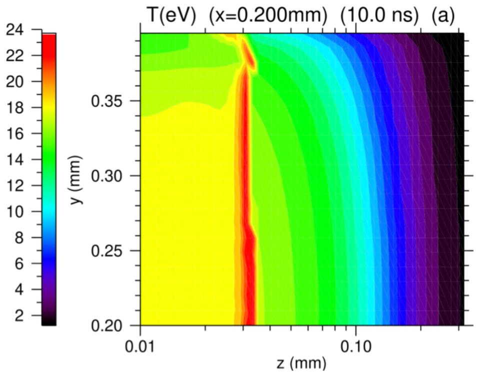
radiant intensity $(\text{erg s}^{-1}\,\text{sr}^{-1})$

$$I_{\text{ray}}(n,v,t) = \int_{S_E} I(M,\theta_E,\varphi_E,v,t)\,\cos\theta_E\,dS_E$$

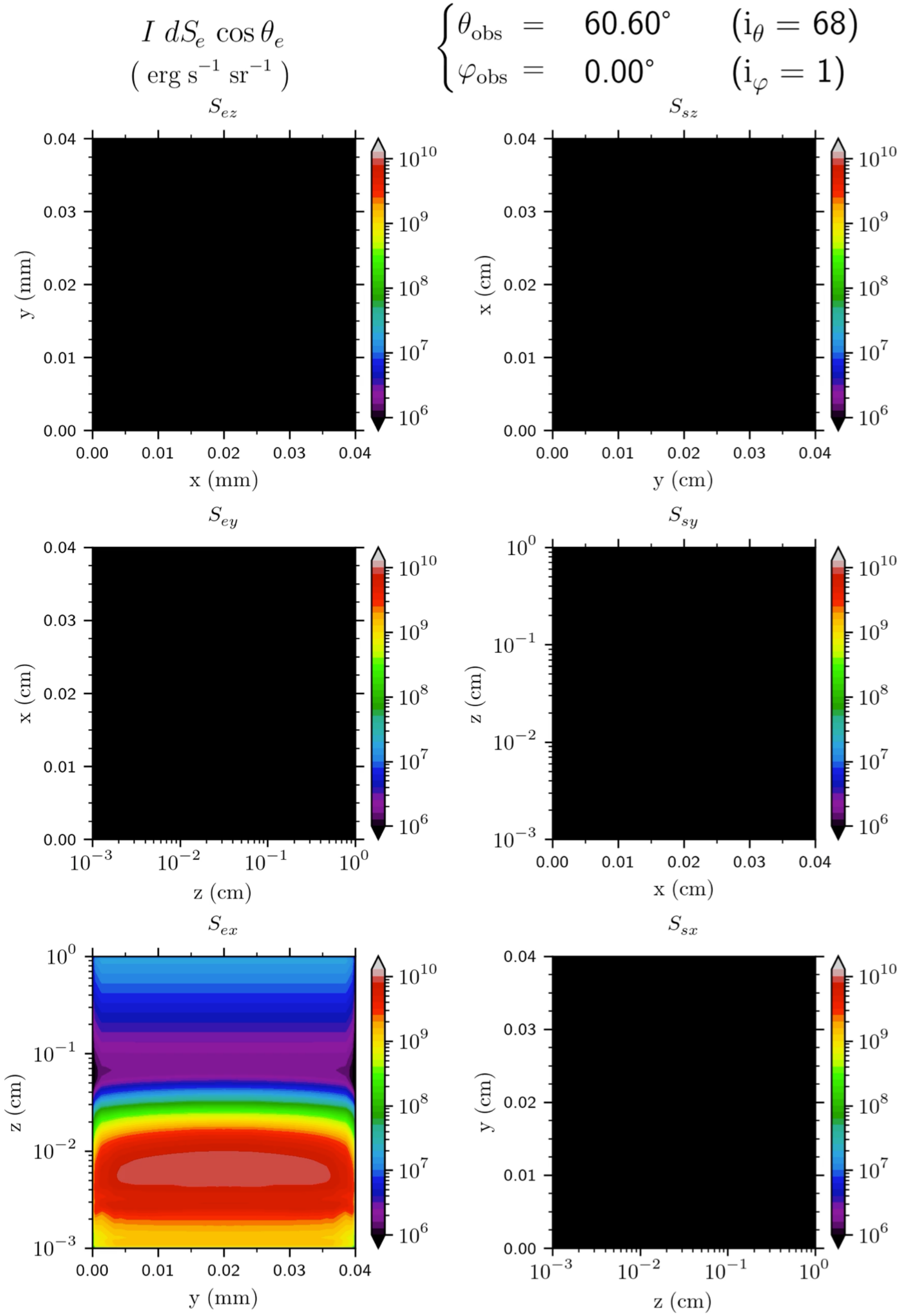
$$= \int_{S_{ez}} + \int_{S_{sz}} + \int_{S_{ey}} + \int_{S_{sy}} + \int_{S_{ex}} + \int_{S_{sx}}$$



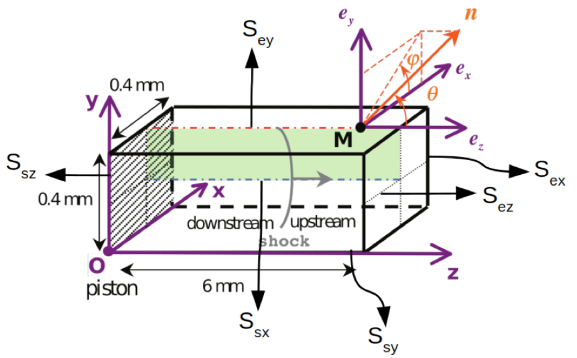


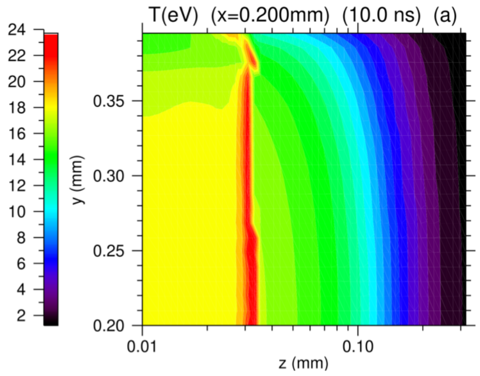


Avila Orta, June 2022



$$I\left(M,\theta_E,\varphi_E,v,t\right)\ \cos\theta_E\ dS_E$$

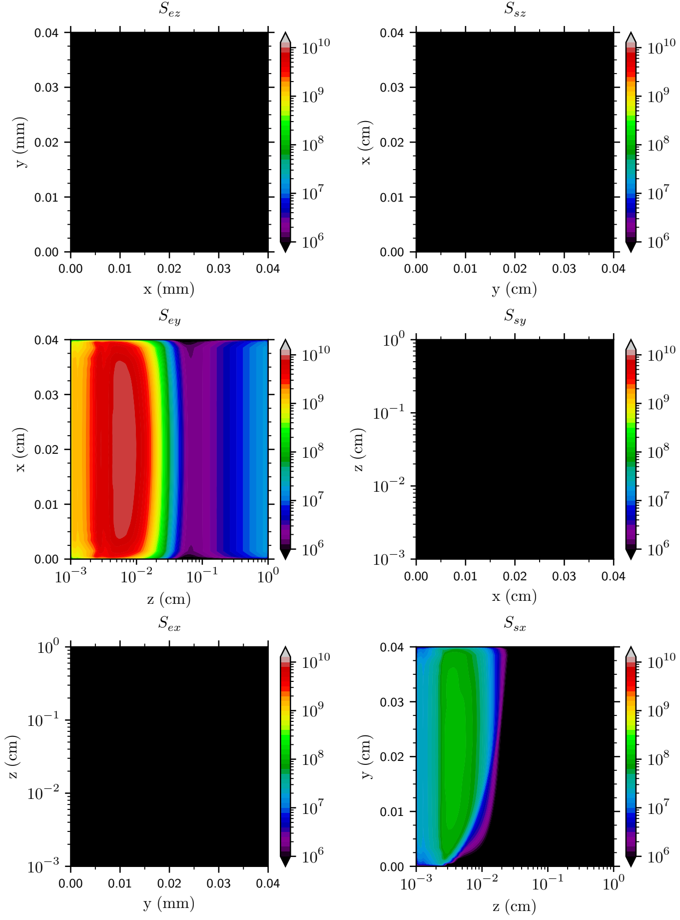




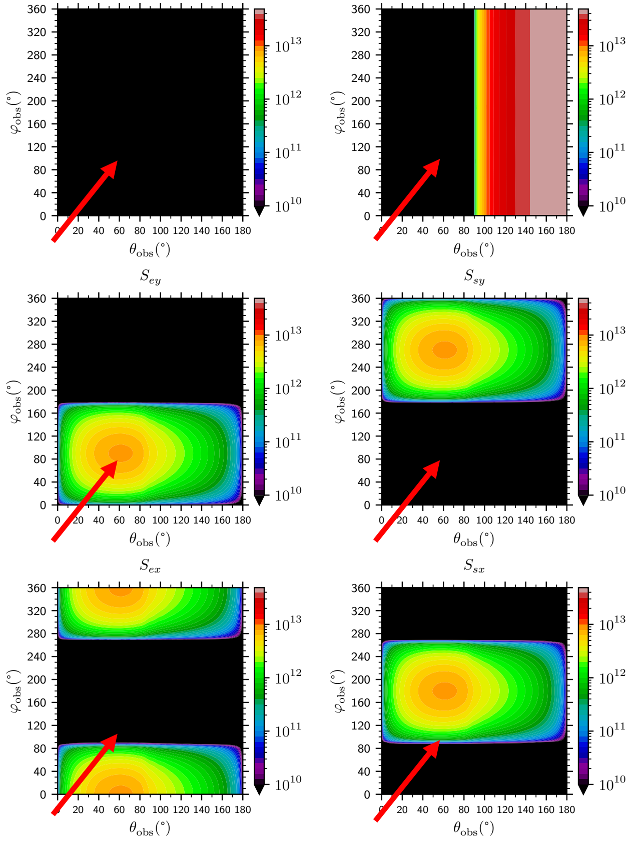
Avila Orta, June 2022

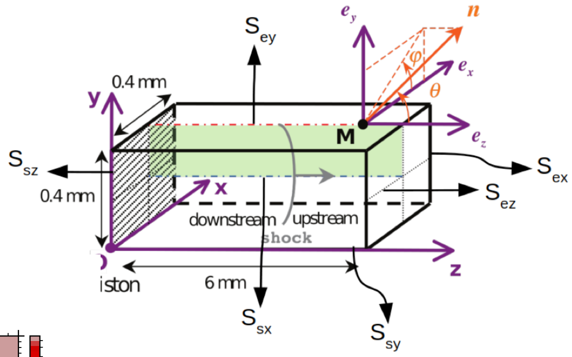
$I\ dS_e\ \cos\theta_e$
$(\,\mathrm{erg\ s^{-1}\ sr^{-1}}\,)$

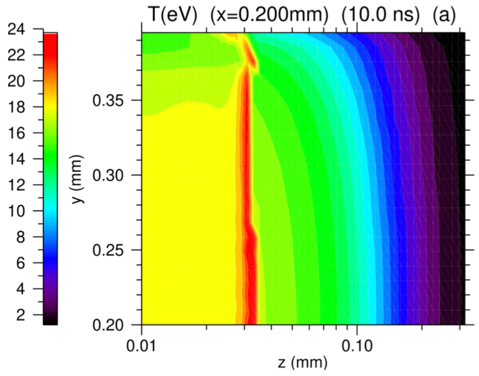
$$\begin{cases}\theta_{\mathrm{obs}} = 60.60^\circ & (i_\theta = 68)\\ \varphi_{\mathrm{obs}} = 90.91^\circ & (i_\varphi = 26)\end{cases}$$



radiant intensity $(\,\mathrm{erg\ s^{-1}\ sr^{-1}}\,)$







Test case : laboratory radiative shock

Avila Orta, June 2022

- a radiative shock can be identified for some orientations of the unresolved structure wrt observer.
- in the laboratory radiative shock case, $40^\circ < \theta_{obs} < 80^\circ$, for any φ, peak at $\theta_{obs} = 60^\circ$
- method can be readily applied to spectra with possible direct comparisons with observations
- future applications : accretion columns on T Tauri stars, any 3D radiating structure

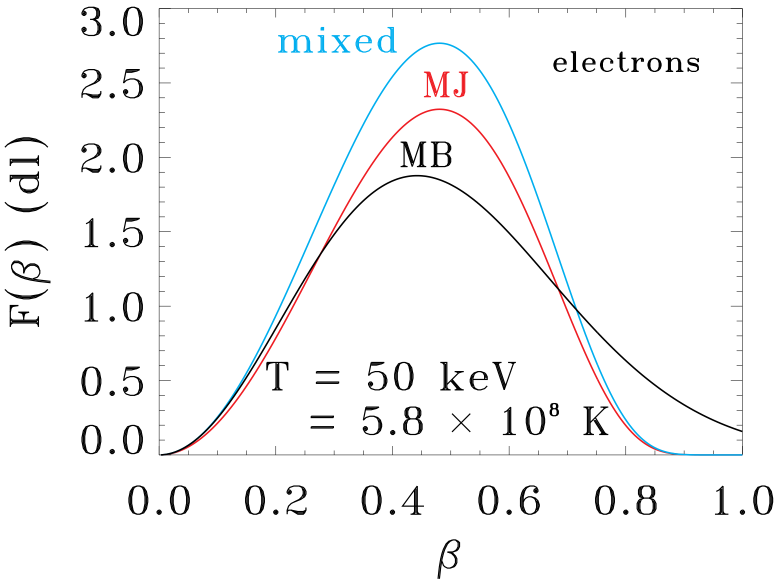
Further developments with IRIS (1)

polarized radiation with synchrotron/cyclotron radiation (magnetized accreting white dwarfs)

Andrea Ciardi (Sorbonne U.)
CEA : Emeric Falize, Jean-Marc Bonnet-Bidaud, Clotilde Busschaert, Lucile Van Box Som

T : 10 – 50 keV (116 – 580) 10^6 K. => $v_{thermal}$: 0.2 – 0.44 c

mildly relativistic electrons (Maxwell – Jüttner distribution): approximate relations



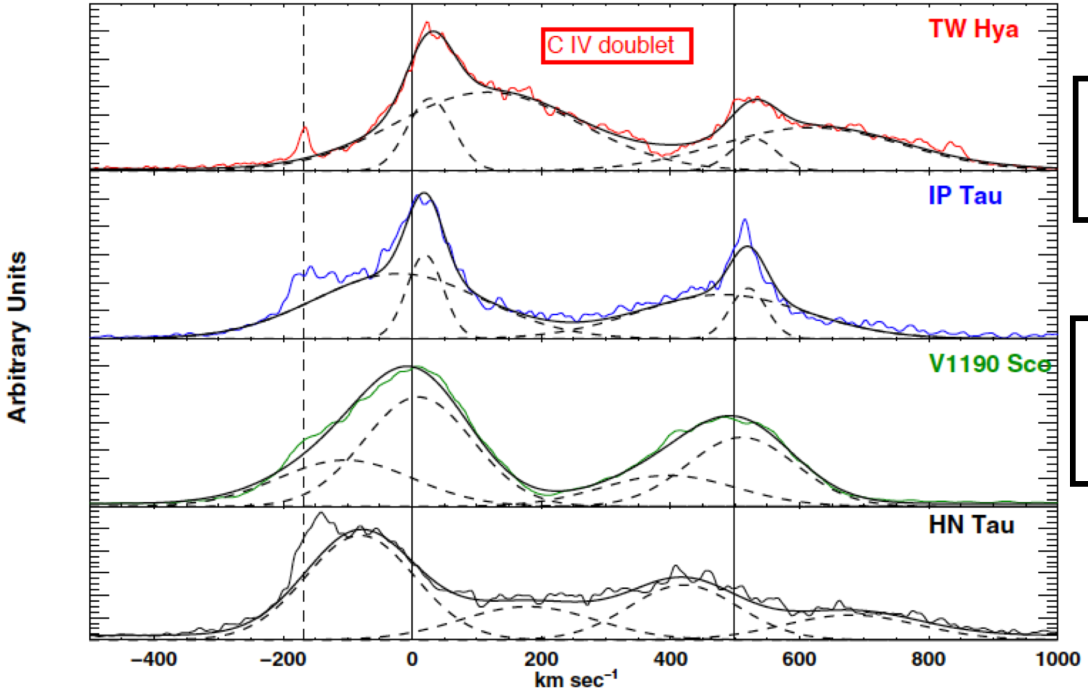
Further developments with IRIS (2)

non-LTE radiation with **ALI** method (**A**ccelerated **L**ambda **I**teration)
Ivan Hubeny (University of Arizona)
opacities: C IV 1548, N V 1240, O VI 1035, Si IV 1403 , Balmer lines, …

Applications :
CTTSs (classical T Tauri stars)
Palermo U. , INAF, Osservatorio Astronomico di Palermo:
Salvatore Orlando, Salvatore Colombo, Rosaria Bonito, Costanza Argiroffi

POLLUX (LUVOiR)

C iv 1550 Å



example of **observed** spectra

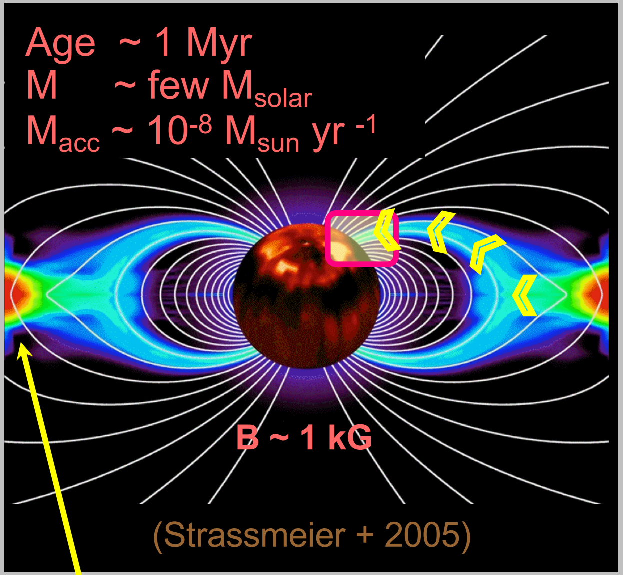
(Ardila et al. 2013)

to be calculated theoretically by IRIS, by post-processing a RMHD simulated structure

3D Radiation magnetohydrodynamic (RMHD) with PLUTO

PhD (October 2019): Colombo et al. 2019a, 2019b – Univ. and Obs. Palermo (Orlando S.)

Classical T Tauri Stars (CTTS): magnetospheric accretion scenario

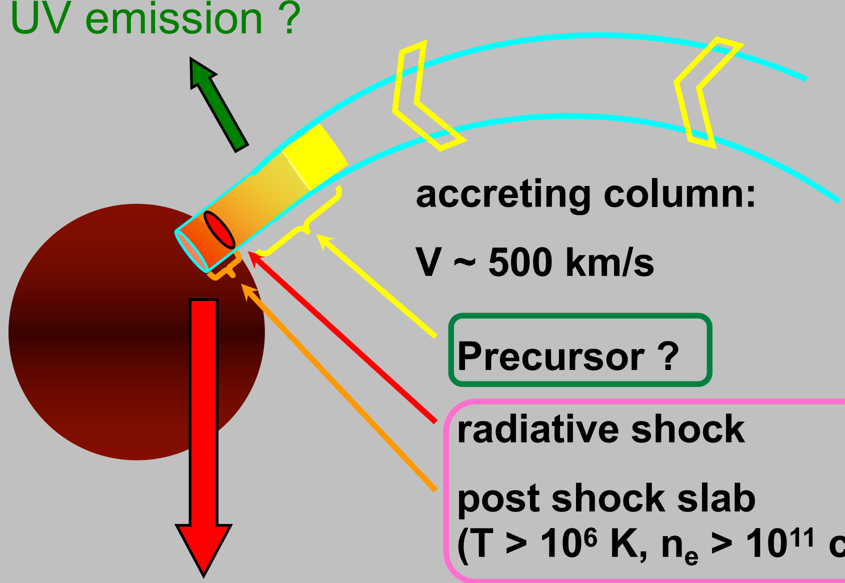


Age ~ 1 Myr
M ~ few M_{solar}
$M_{acc} \sim 10^{-8}\ M_{sun}\ yr^{-1}$

$B \sim 1$ kG

(Strassmeier + 2005)

Protoplanetary disc



UV emission ?

accreting column:

$V \sim 500$ km/s

Precursor ?

radiative shock

post shock slab
($T > 10^6$ K, $n_e > 10^{11}$ cm^{-3})

X-ray emission

3D Radiation magnetohydrodynamic (RMHD) with PLUTO

PLUTO code 3D MHD (Mignone et al. 2007, 2012) → 3D LTE RMHD (Kolb et al. 2013)
→ **3D NLTE RMHD** (Colombo et al. 2019)

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

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{u}\boldsymbol{u}) + \nabla p = \rho \boldsymbol{g} + \frac{\boldsymbol{k_R \rho}}{\boldsymbol{c}} \boldsymbol{F}$$

$$\frac{\partial \epsilon}{\partial t} + \boldsymbol{\nabla} \cdot [\,(\epsilon + p)\, \boldsymbol{u}\,] = \rho \boldsymbol{u} \cdot \boldsymbol{g} + \frac{\boldsymbol{k_R \rho}}{\boldsymbol{c}} \boldsymbol{F} \cdot \mathbf{u} + \nabla \cdot F_c \boxed{- L + k_P \rho c E}$$

$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{F} = L - k_P \rho c E$$

$$p = \rho \frac{k_B T}{\mu m_H} \qquad \boldsymbol{F} = -\lambda \frac{c}{k_R \rho} \nabla E$$

$$\epsilon = e + \frac{1}{2} \rho \boldsymbol{u}^2 \qquad e = \rho c_V T$$

- Gravity
- Thermal conduction
- Non-LTE radiation effects:
  - Gain of radiation energy by matter
  - Loss of radiation energy by matter

  $\boldsymbol{k_P}, \boldsymbol{k_R},$ and $\boldsymbol{L}$ databases are calculated in a **non-LTE** regime (Rodriguez, R. et al. 2018)

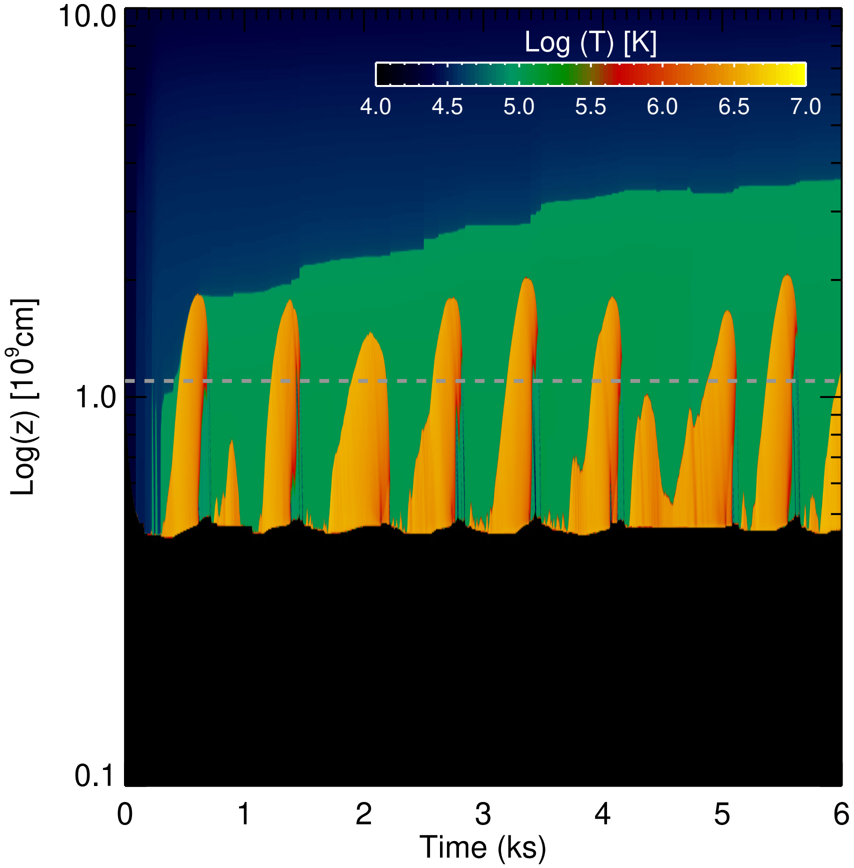
3D Radiation magnetohydrodynamic (RMHD) with PLUTO

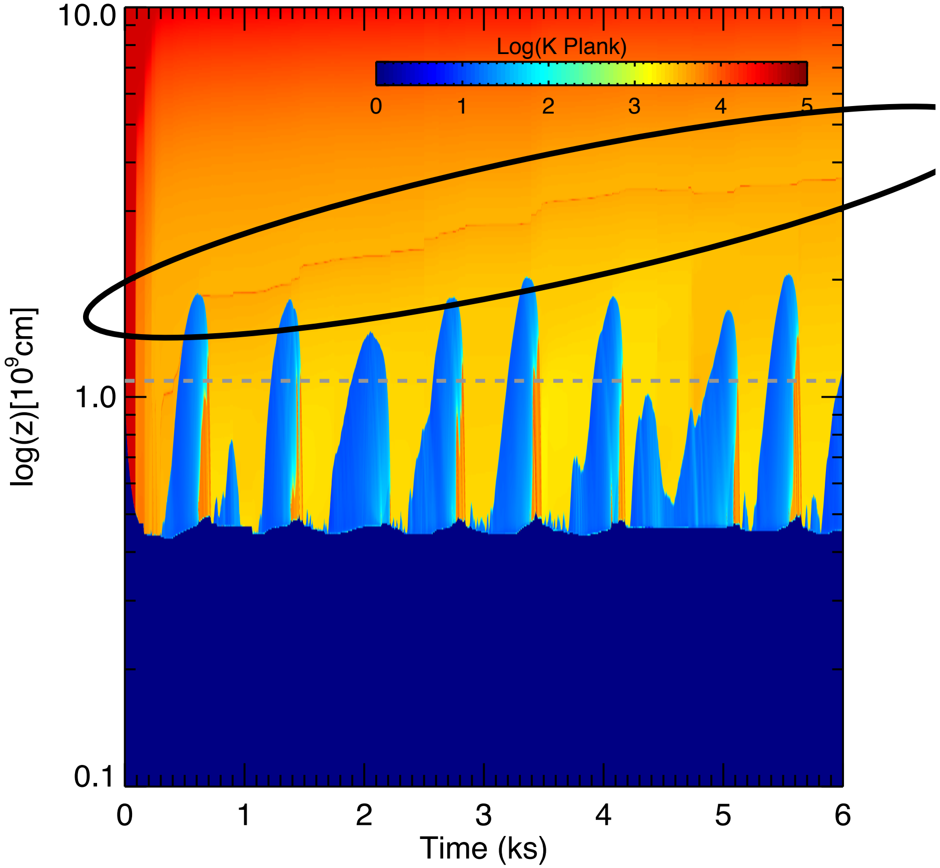
Helium effects

$\mathbf{Gain} = k_p\, \rho\, c\, E$

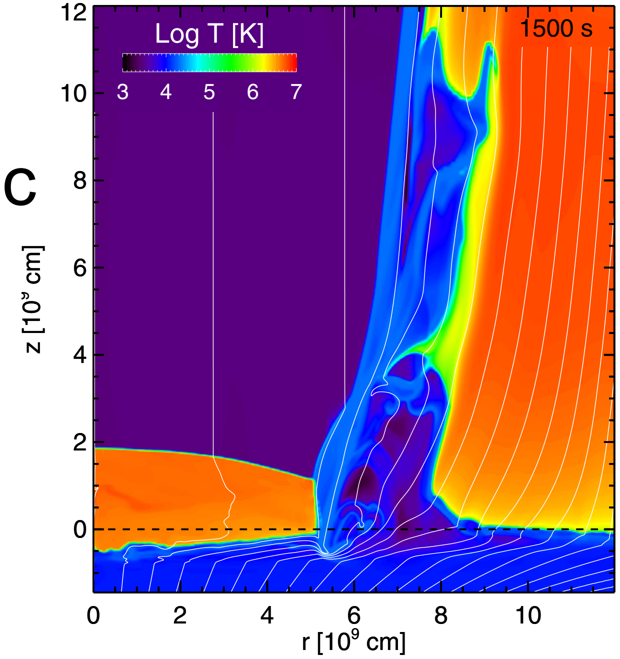
Planck opacity (cm^2 g^{-1})

Temperature (K)





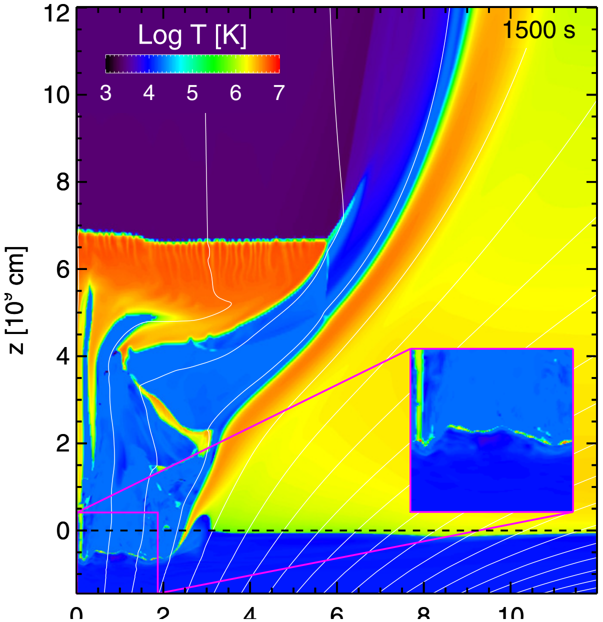
3D Radiation magnetohydrodynamic (RMHD) with PLUTO



Exploring the role of radiation and magnetic field, with multi-D RMHD simulations.

Comparison with observations (IRIS)

(Synthetic Spectra)



Orlando et al. 2013
A&A 559, A127