JET Simulations, Experiments and Theories

# Jets from Young Stellar Objects: from MHD Simulations to Synthetic Observations


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Protostellar Jets in Context

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www.jetsets.org

# Overview

## Problem

- cooling processes are essential for the YSO jet physics – their inclusion in the MHD codes is necessary
- shock propagation through the jet creates highly non-equilibrium events, impossible to capture with a simple synthetic cooling function
- possibility of computing emission line ratios with realistic ion abundances needed

## Solution

- Multi-Ion Non-Equilibrium cooling (MINEq)
- optically-thin plasma, non-equilibrium ionization state computation
- emissions from more ion species: H, He I and II, C I to V, N I to V, O I to V, Ne I to V, S I to V (for a total of 29)
- optimizations for the conditions we are interested in:

$$n_e \in (10^{-2}, 10^{5}) cm^{-3}$$

(shocks propagating inside the YSO jets)

$$T \in (2 \cdot 10^{3}, 2 \cdot 10^{5}) K$$

## Various approaches to MHD jet simulations:

- large scale simulations: problems balancing resolution with reasonable computational power needs
- local simulations: for example single shocks propagating through jets, with algorithms to convert the resulting measurable quantities to larger scales
- Adaptive Mesh Refinement techniques – permit an optimum use of computational power for both small and large scale simulations
- Radiative cooling handling – simplified (dynamics) vs. detailed (diagnostics)

# Overview

## Aim

- **Simulation of the propagation of shocks along the stellar jet, geometrical integration along the LoS at different inclination angles and comparison with observations in various emission lines.**

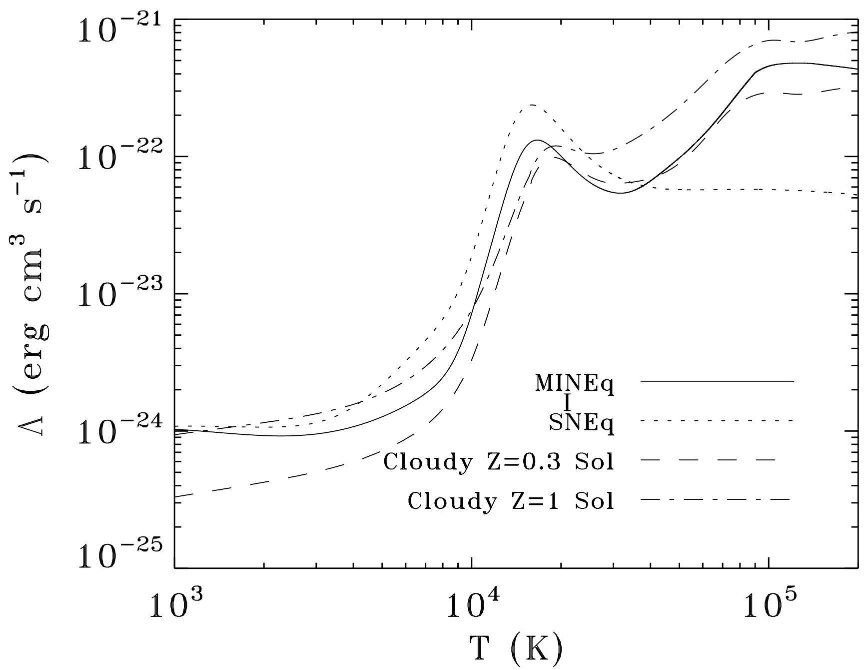
## Numerical Code

- PLUTO (Mignone & al 2007, ApJS) – http://plutocode.oato.inaf.it
- energy source term added due to radiative cooling and ionization/ recombination processes
- multiple, dynamically switching integration algorithms to handle stiff systems of equations (ionization network)
- customizable/upgradeable in terms of ion species and emission lines
- tested and compared with other cooling functions

# MINEq cooling function

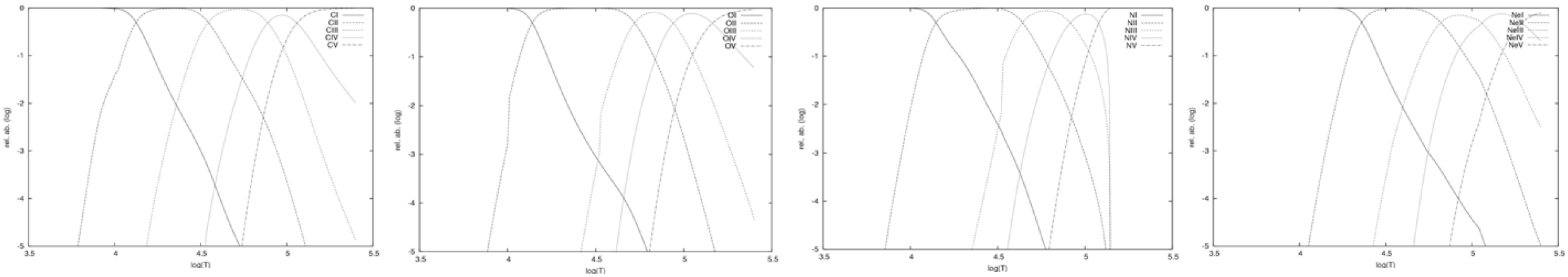
## Effective cooling comparisons

- marked differences between MINEq and SNEq (Simplified treatment) at high temperatures
- MINEq compares well with Cloudy results
- at low temperatures, important emission lines of Fe, Mg and Si were added empirically




## Equilibrium ionization balance

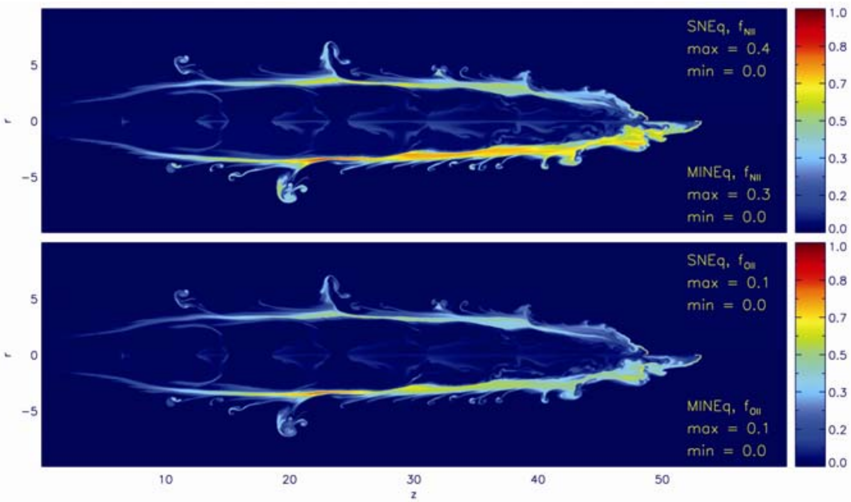
in good agreement with previous works (Sutherland & Dopita 1993, Dalgarno & McCray 1972)

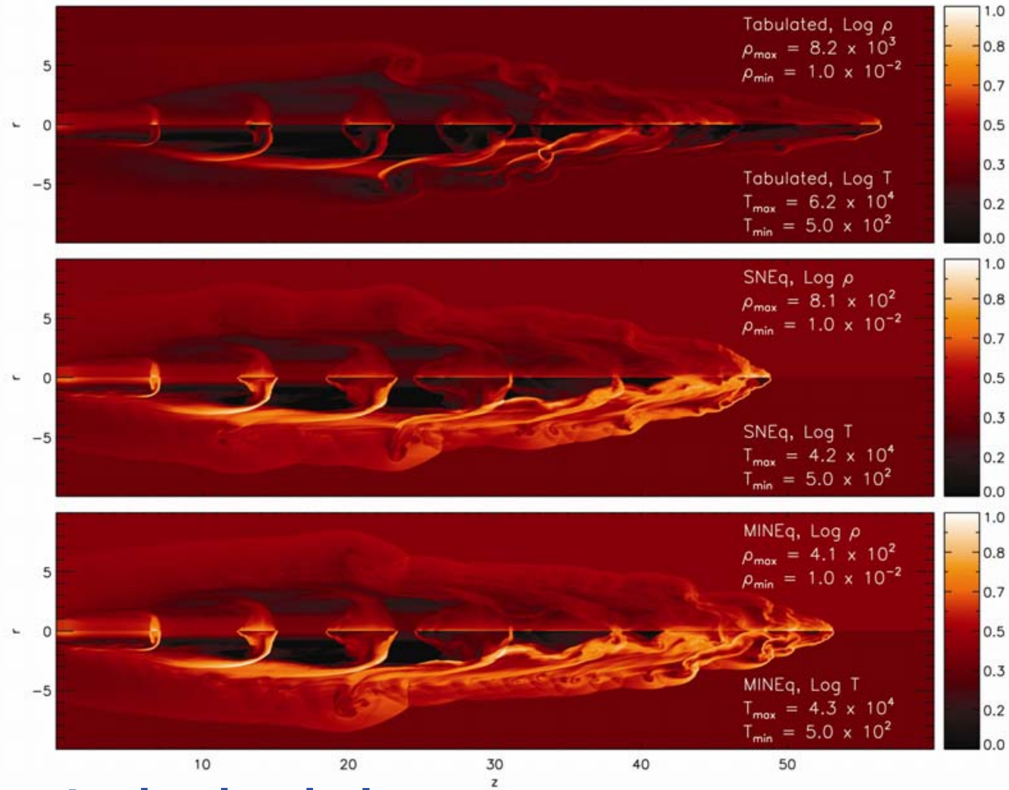


# Effects of the cooling model

## Dynamics

- important differences between adiabatic and the other two
- moderate differences at the jet head (high temperatures) between MINEq and SNEq, almost identical at the intermediate shocks




## Ionization balance

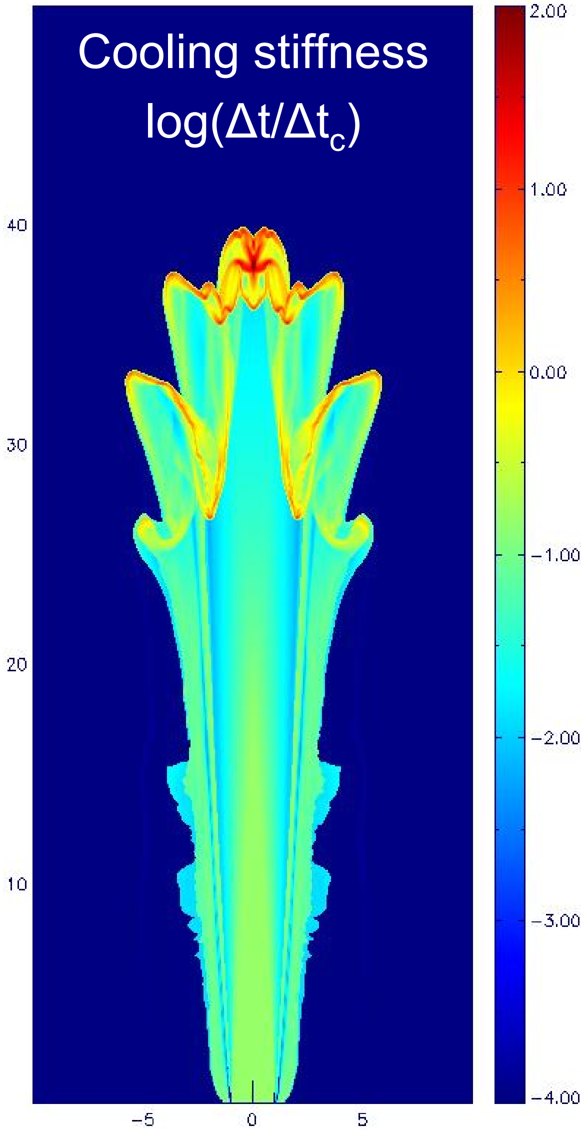
moderate differences in ion abundances, important for line emission computations

*Simulation presented: a pulsing jet with density $10^4$ cm$^{-3}$, average injection speed 150km/s, velocity oscillation amplitude 25% and period 50yrs, propagating in an uniform medium with density $10^3$ cm$^{-3}$ and temperature 1000K.*

# MINEq – Numerical Aspects

Various integration algorithms were tested:

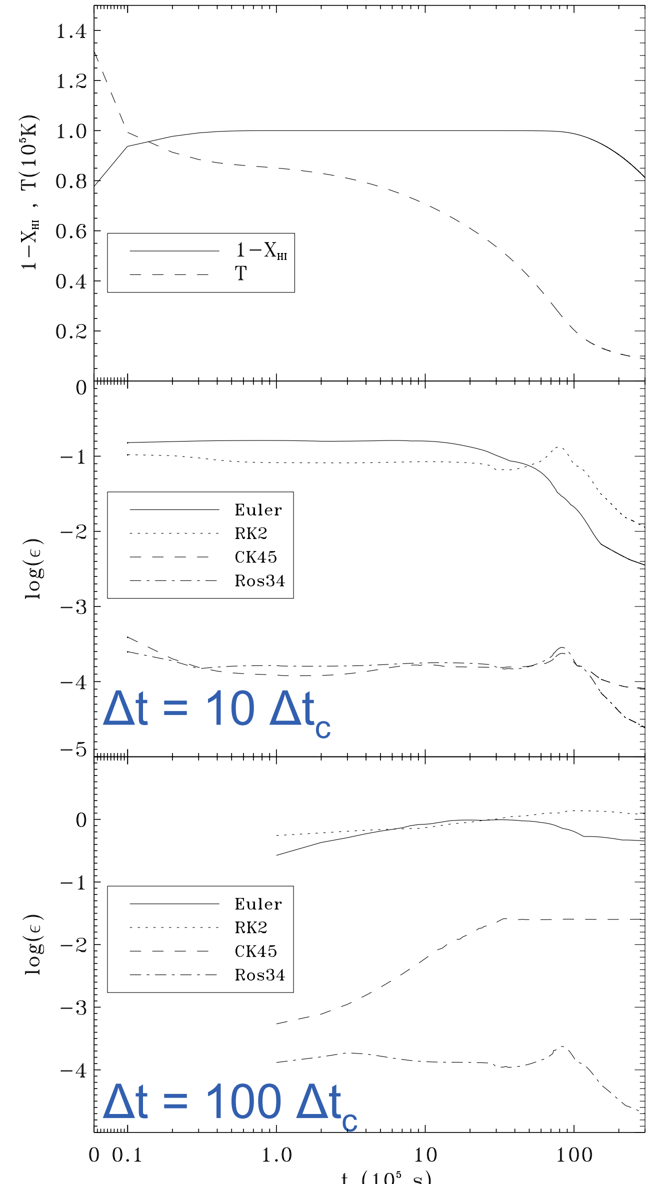
- Explicit, non-adaptive **Runge-Kutta 2nd – 3rd** order integration of the ionization fractions and energy
  - NOT suitable in stiff regions of the flow
- **Cash-Karp 4-5 (adaptive timestep)**
  - embedded 4th & 5th order explicit integration
  - error estimation and timestep adjustment
  - ... so sub-timestepping possible...
  - still low accuracy in some points of high stiffness
- **Rosenbrock 3-4 (adaptive timestep)**
  - semi-implicit, embedded 3rd & 4th order integration
  - error estimation and timestep adjustment
  - stiff cells very well handled, with sub-timestepping
  - but... there are matrix inversions required by the implicit method – computationally-expensive



# MINEq – Numerical Aspects

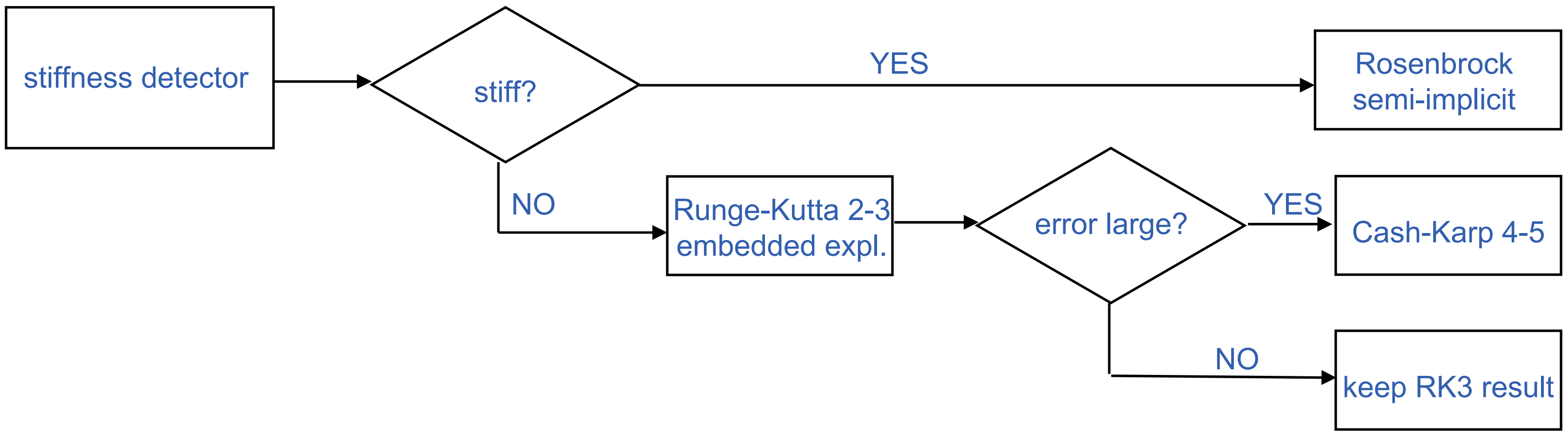
## Some error plots...

- in stiff regions the “normal” order of the integrators is not maintained – RK2 has lower accuracy than Euler
- increasing more the timestep, even CK45 ceases to offer good accuracy, while Rosenbrock maintains its position
- stiff regions + large timestep => implicit
- the only way to handle these regions with a acceptably large timestep is to use an implicit integrator
- the very high computational cost of an implicit integrator drove us to a solution of compromise...



## Selective Integration

- Dynamically selected integration algorithm, in 3 phases:

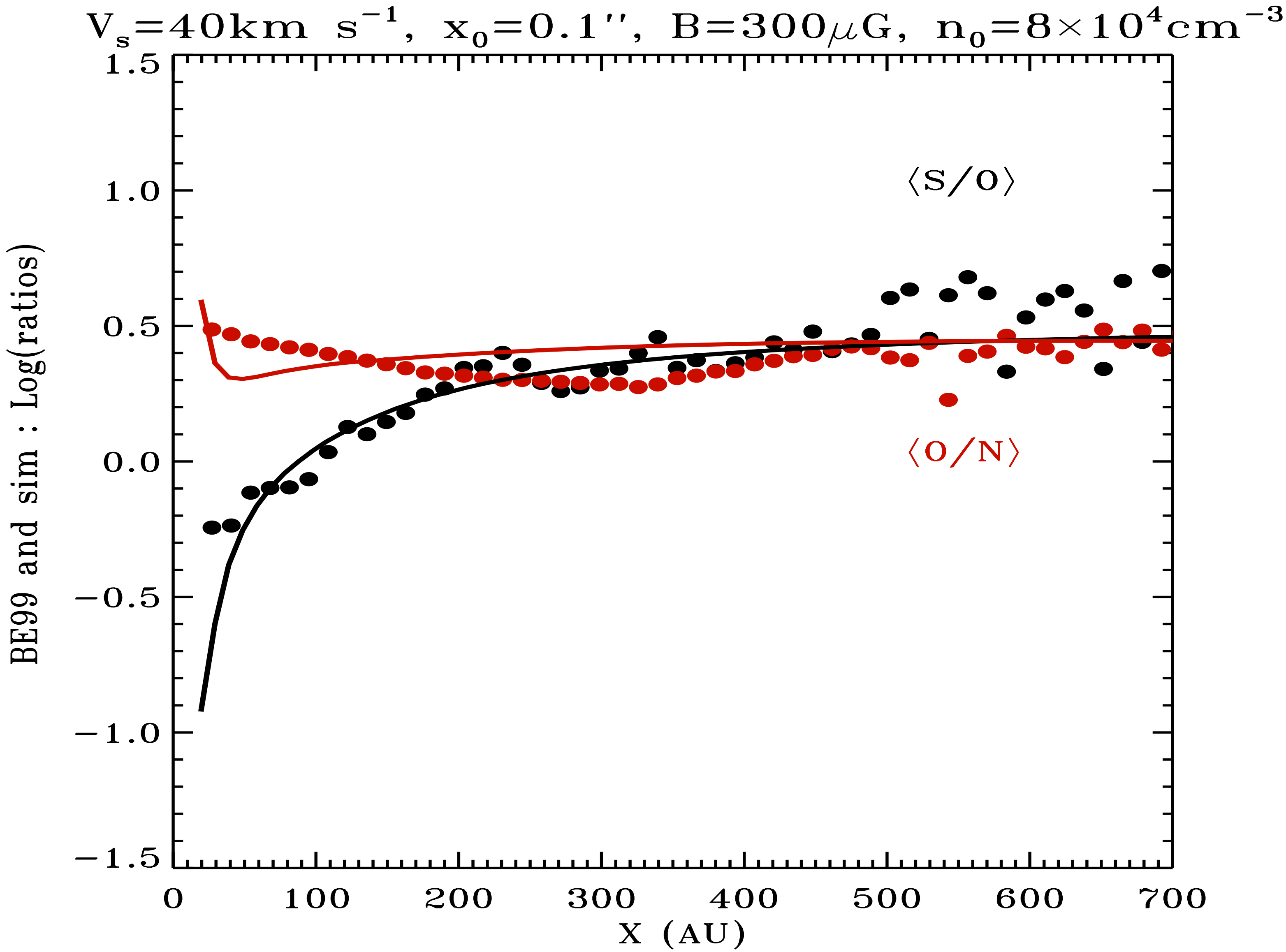



- RK23 (embedded 2nd & 3rd order) employed for the embedded error estimation
- both CK45 and Rosenbrock employed with sub-timestepping
- higher order and pass to implicit only where needed
- efficient computer power use

# HH30 line ratios estimations

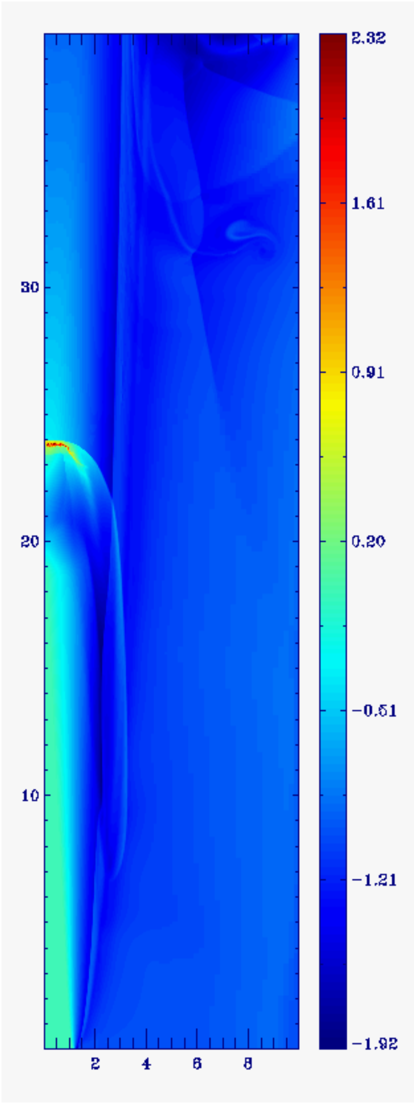
- simple 1D model, AMR employed
- MINEq cooling in the PLUTO code (29 ion species, 5-level atom model for collisionally excited emissions)
- emission generated in the post-shock zones
- 1 propagating shock simulation in the Reference Frame of the jet
- medium density distribution $\rho = \rho_0 \frac{x_0}{x + x_0}$
- emission line ratios averaged on 0.1” (~10AU at source distance)
- convolution with jet velocity 150km/s
- Presented here: line ratios between [OI] 6300+6364, [NII] 6548+6583 and [SII] 6716+6731
- good agreement with observational data (considering the simplicity of the model)

# HH30 line ratios estimations



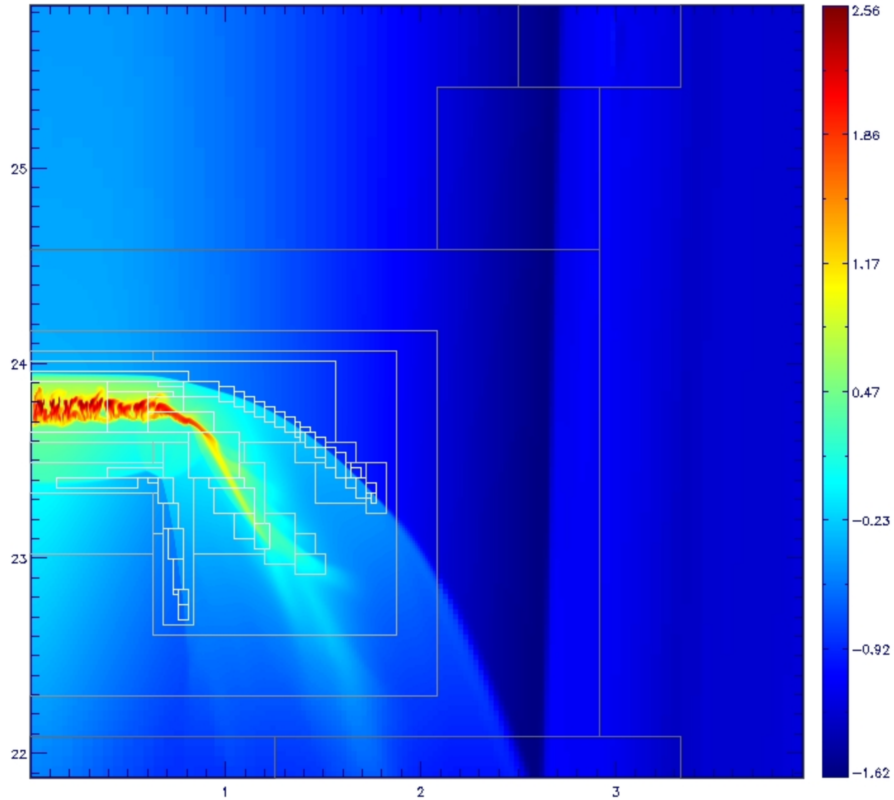
# Synthetic observations

## Input data




- 2D maps of density, pressure, velocities from the MHD simulation output
- Fraction of neutrals (for SNEq) or ion abundances (for MINEq)
- Possible input AMR HDF5 files, using HDF5PLOT routine

*Parameters: a perturbation ($\Delta v/v_{jet}$ = 25%) evolving in a shock propagating along a jet with density $10^4$ $cm^{-3}$, $T = 10^4$ K, speed 150km/s. The external medium is homogeneous, with density $2{*}10^3$ $cm^{-3}$ and temperature 2000K.*




*Detail from an AMR simulation with SNEq, 7 levels of refinement with equivalent maximum resolution 6144x24576*

*Density $\log_{10}$ map.*

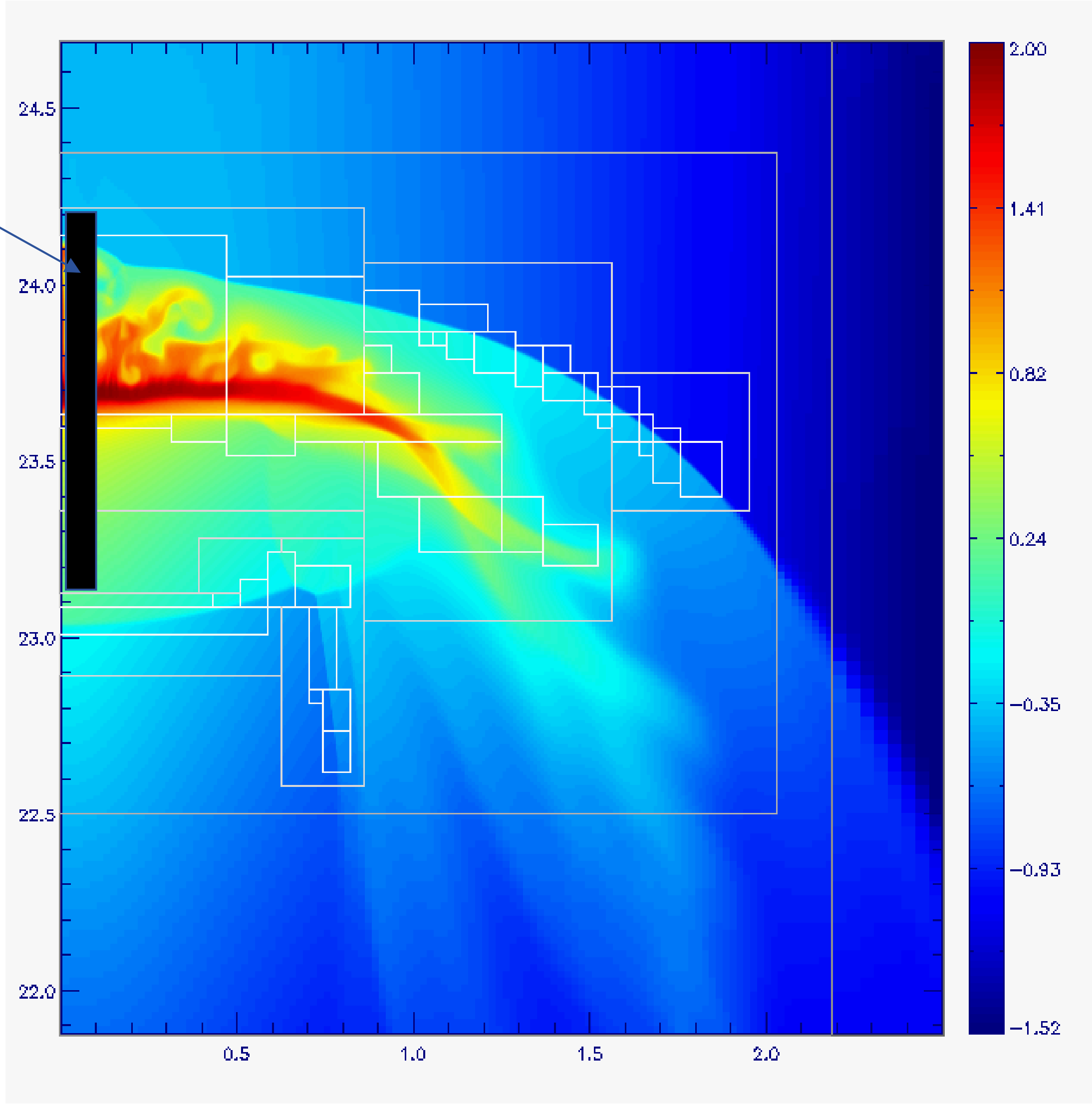
## Input data

- **MINEq cooling**

*Detail from an AMR simulation with MINEq, 7 levels of refinement with equivalent maximum resolution 6144x24576*

*Density $log_{10}$ map*

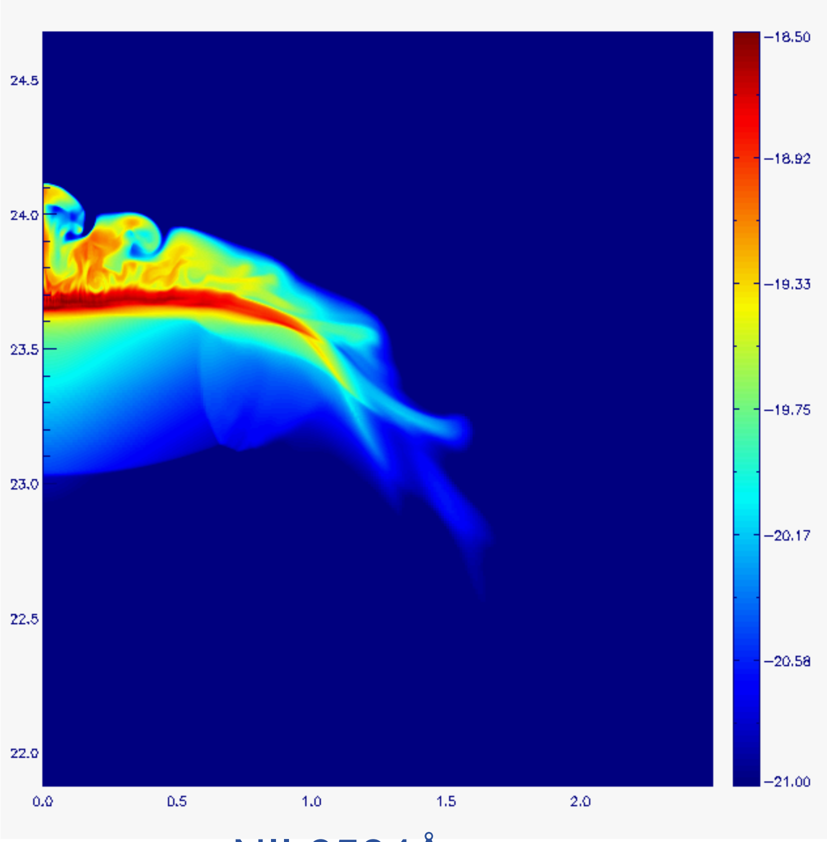
slit



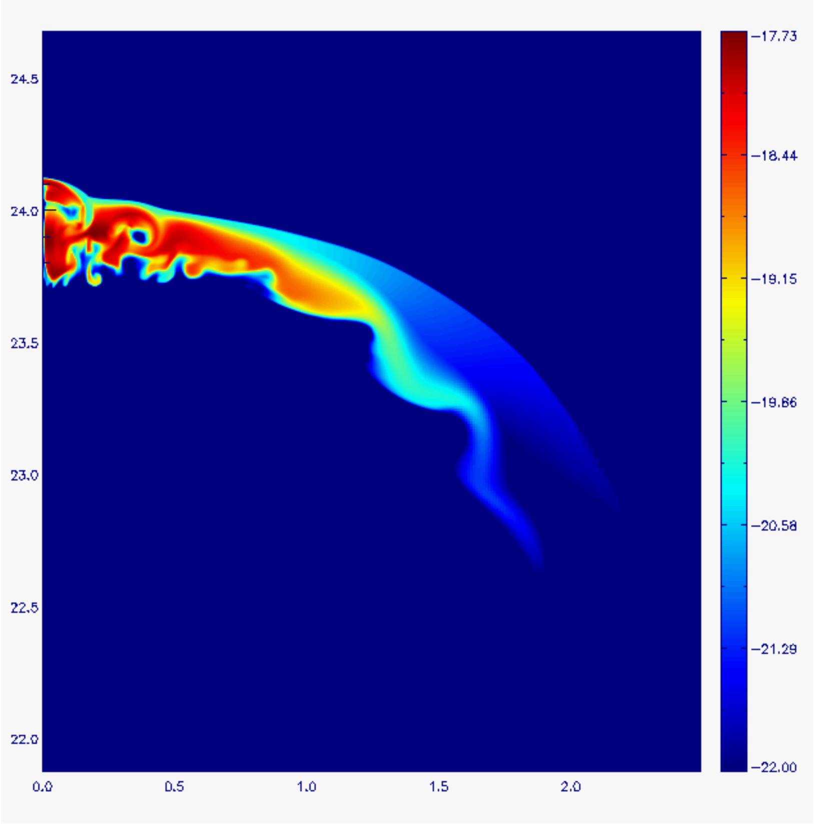
# Synthetic observations

## Phase I

- emission maps computation assuming statistical excitation/de-excitation equilibrium conditions for each cell
- output maps of emission and temperature needed for the next phase
- emission computed in erg $s^{-1}cm^{-3}$




NII 6584Å




SII 6727Å

(from MINEq data)

# Synthetic observations

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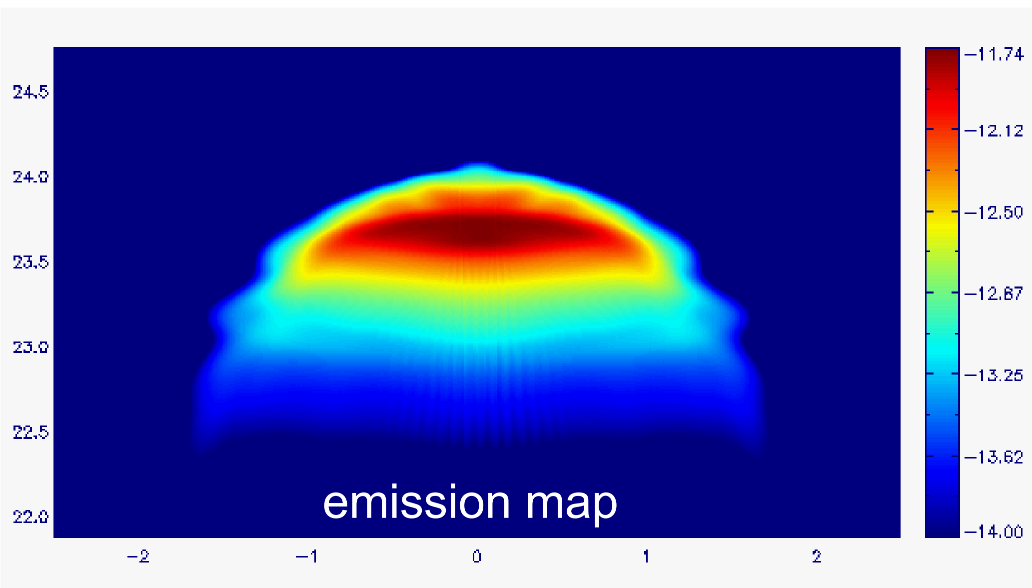
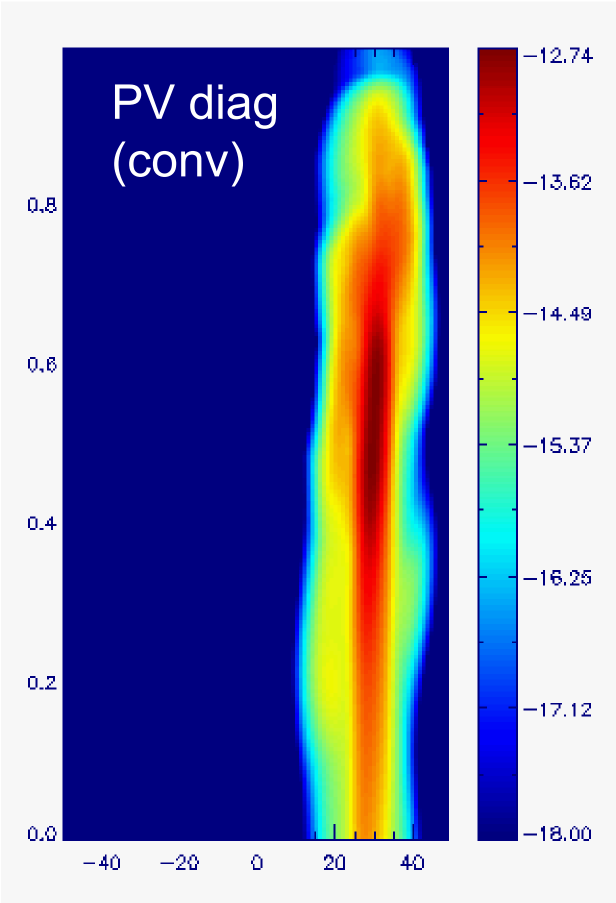
## Phase II

- Volume integrated emission maps generated as they would be observed (including instrument resolution and PSF and declination with respect to LoS)
- User-defined slit (dimensions, orientation, position)
- Emission maps in units of erg $s^{-1}$ $cm^{-2}$ $arcsec^{-2}$
- PV diagrams generated for the defined slit, at the initial map resolution for positions and with customizable velocity resolution/ranges



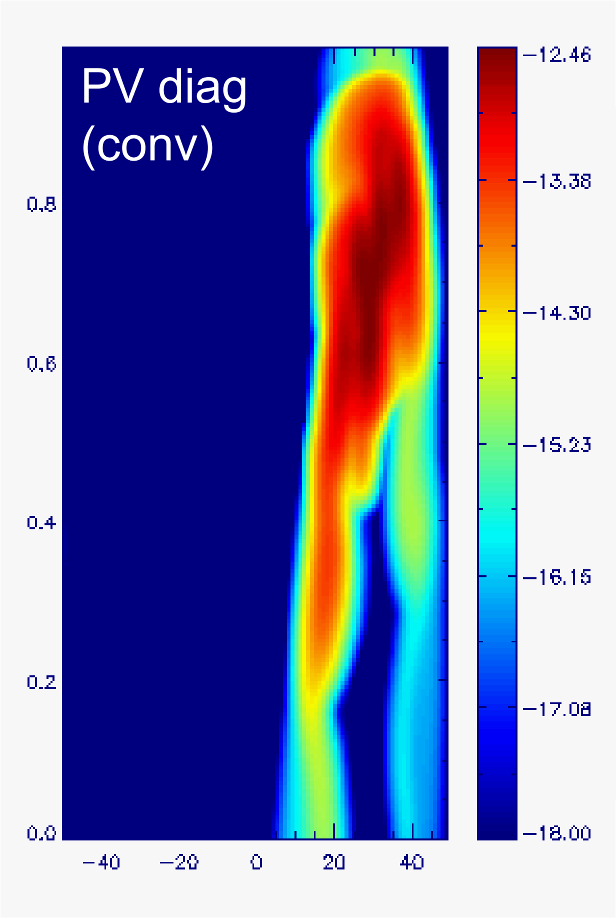




$\log_{10}$ maps
**NII 6584Å**

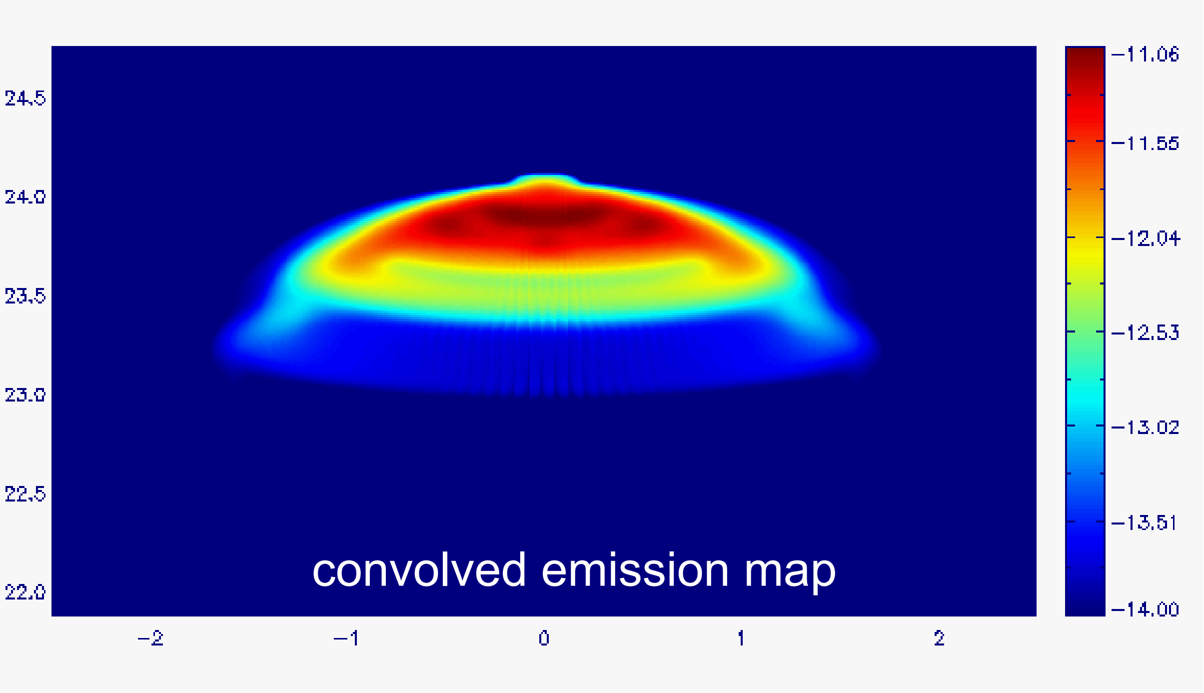
*(the 3D shock axis forms a 80° angle with the LoS)*

# Synthetic observations

## Phase II



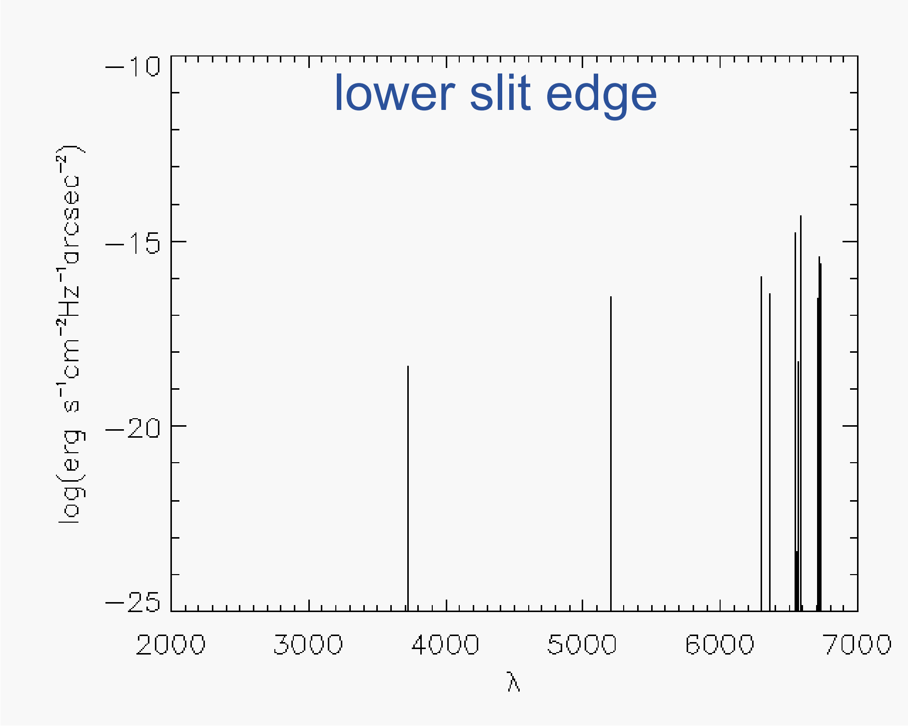

**SII 6727Å**

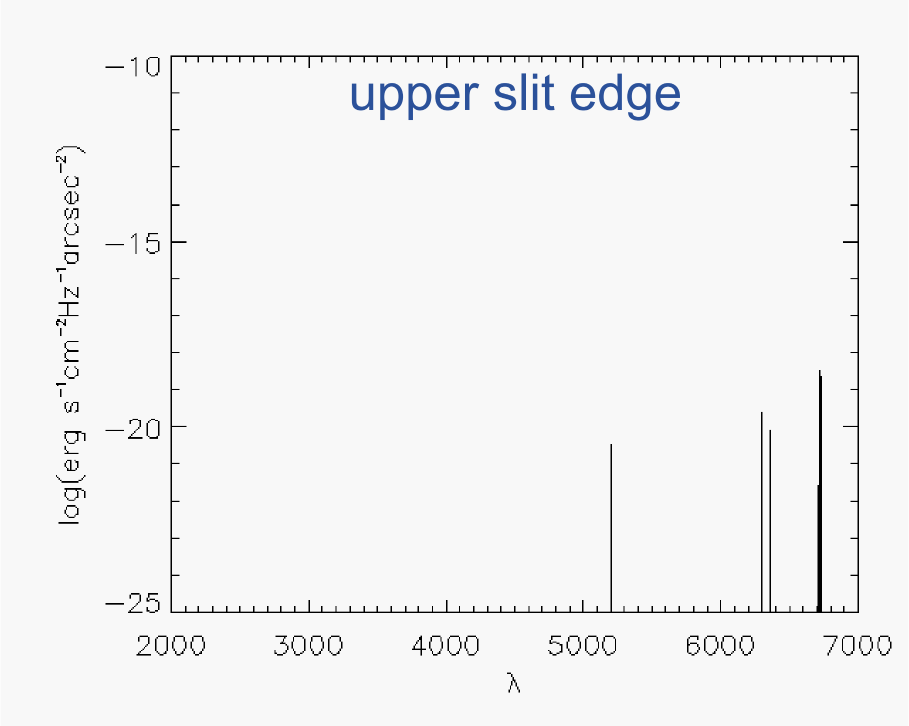



$\log_{10}$ maps

## Phase III

- **Synthetic spectra generation**
- Uses as input the line spectrum files generated in Phase II
- Spectrum generated for each pixel along the slit (output filesize will be *wavelength range / resolution * n_points*)
- Doppler shift + line broadening
- erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ arcsec$^{-2}$



# Conclusions

- detailed cooling with non-equilibrium ionization balance computation proves useful for “synthetic observations”
- AMR methods allow the post-shock zones to be satisfactory resolved with the currently available parallel computers
- selective integration solved efficiently the problems posed by the chemical network and its short timescales
- numerical implementation of the cooling function complete, PLUTO with radiation (beta version 3) available for the community
- simulations underway at the CINECA Bologna supercomputing centre (30,000 CPU hours allocated, more 30,000 requested)
- 1D and 2D simulations of emission line ratios to be compared with observations of real jets – the first candidates: HH30 and DG Tau

***Thank you***

***for your attention!***