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

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Protostellar Jets in Context

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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.**

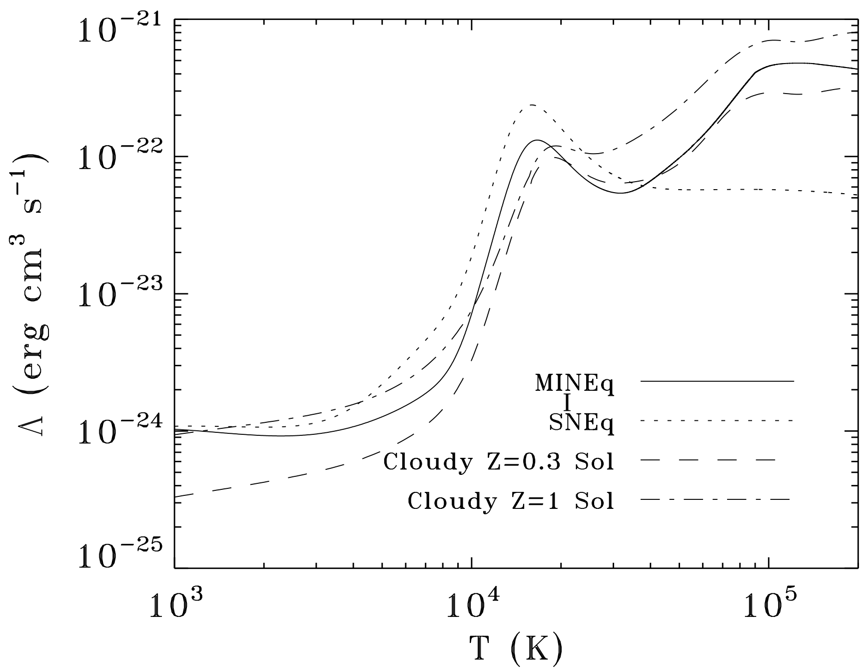
Numerical Code

- 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

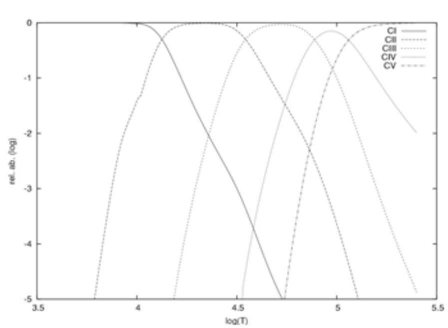
Effective cooling comparisons

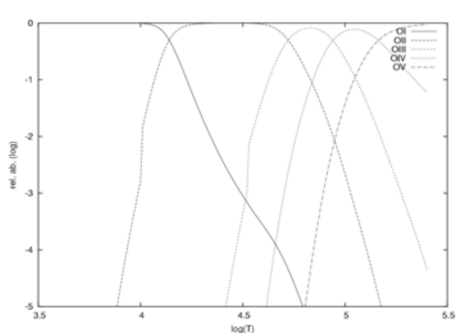
- marked differences between MINEq and SNEq (Simplified treatment) at high temperatures
- MINEq compares well with Cloudy results
- at low temperatures, important emission lines of Fe, Mg and Si were added empirically

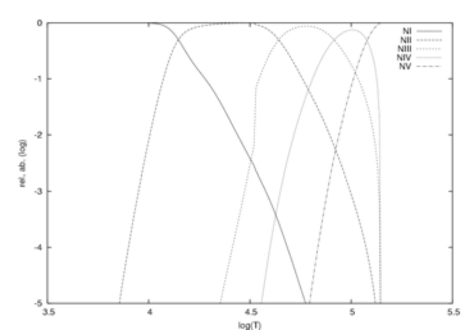


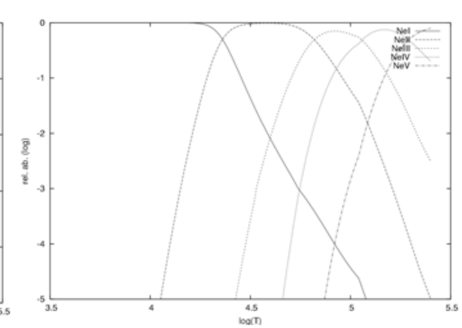
Equilibrium ionization balance

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







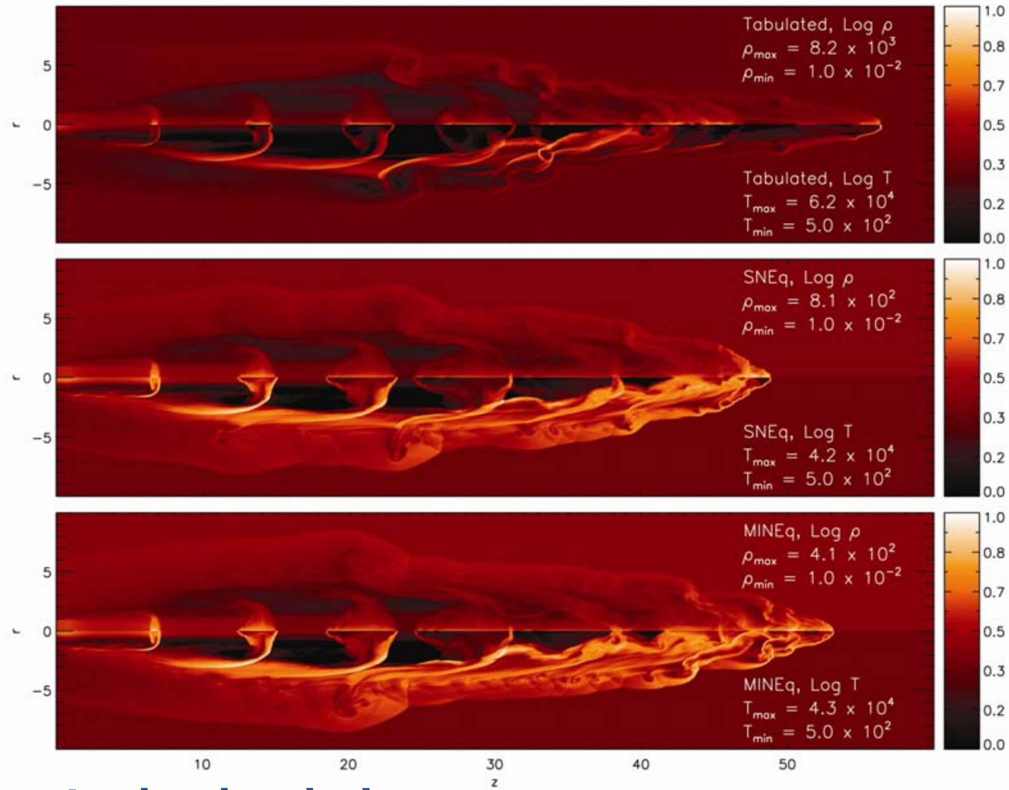


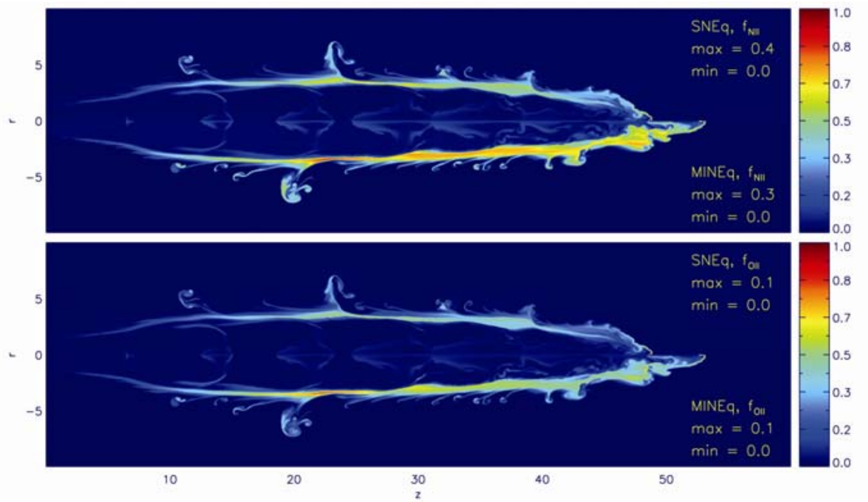
JET Simulations, Experiments and Theories

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

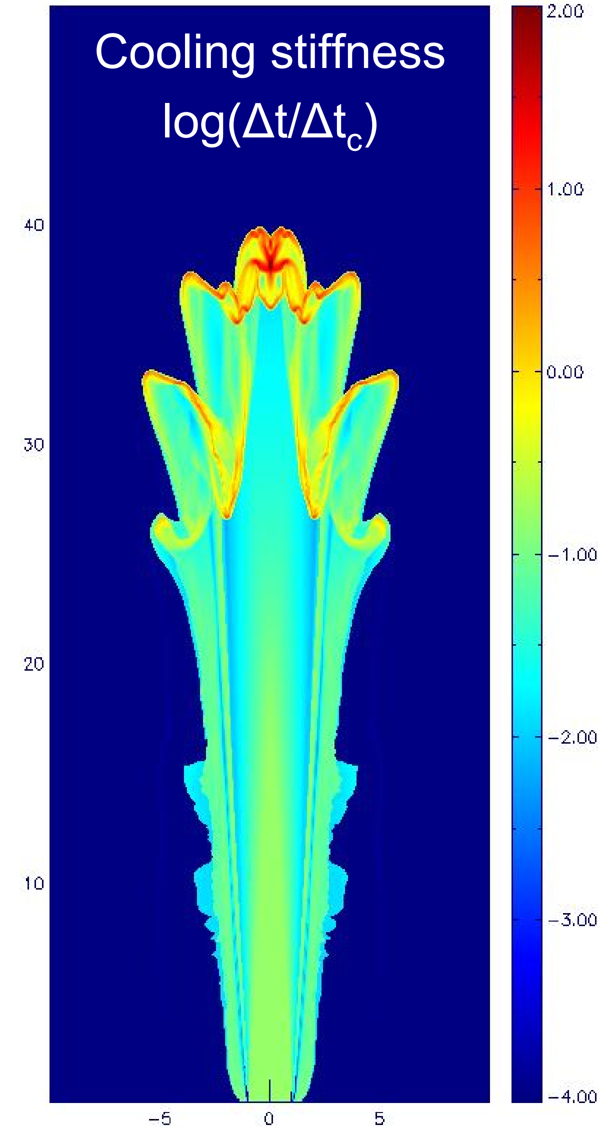
moderate differences in ion abundances, important for line emission computations

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:

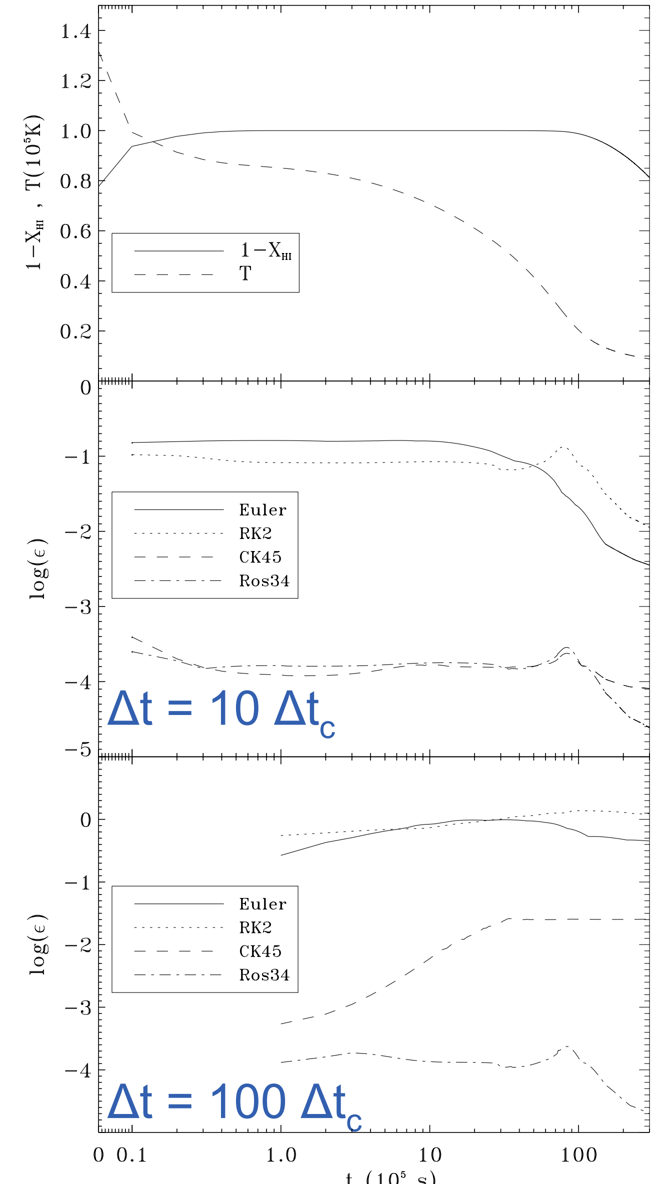
- Explicit, non-adaptive **Runge-Kutta 2nd – 3rd** order integration of the ionization fractions and energy
  - NOT suitable in stiff regions of the flow
- **Cash-Karp 4-5 (adaptive timestep)**
  - embedded 4th & 5th order explicit integration
  - error estimation and timestep adjustment
  - ... so sub-timestepping 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

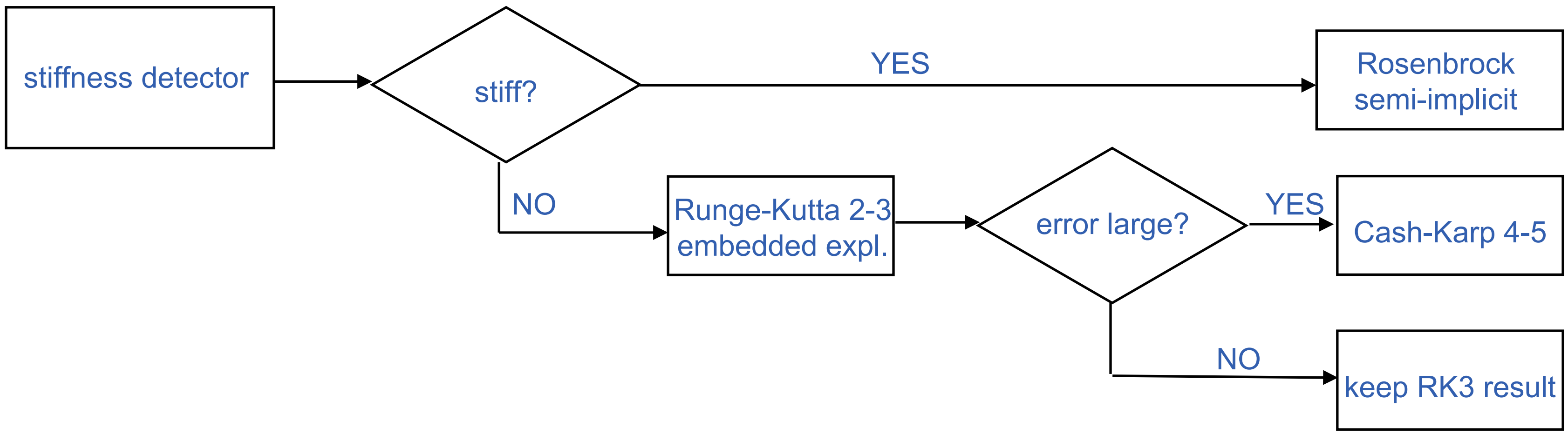
Some error plots...

- 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:

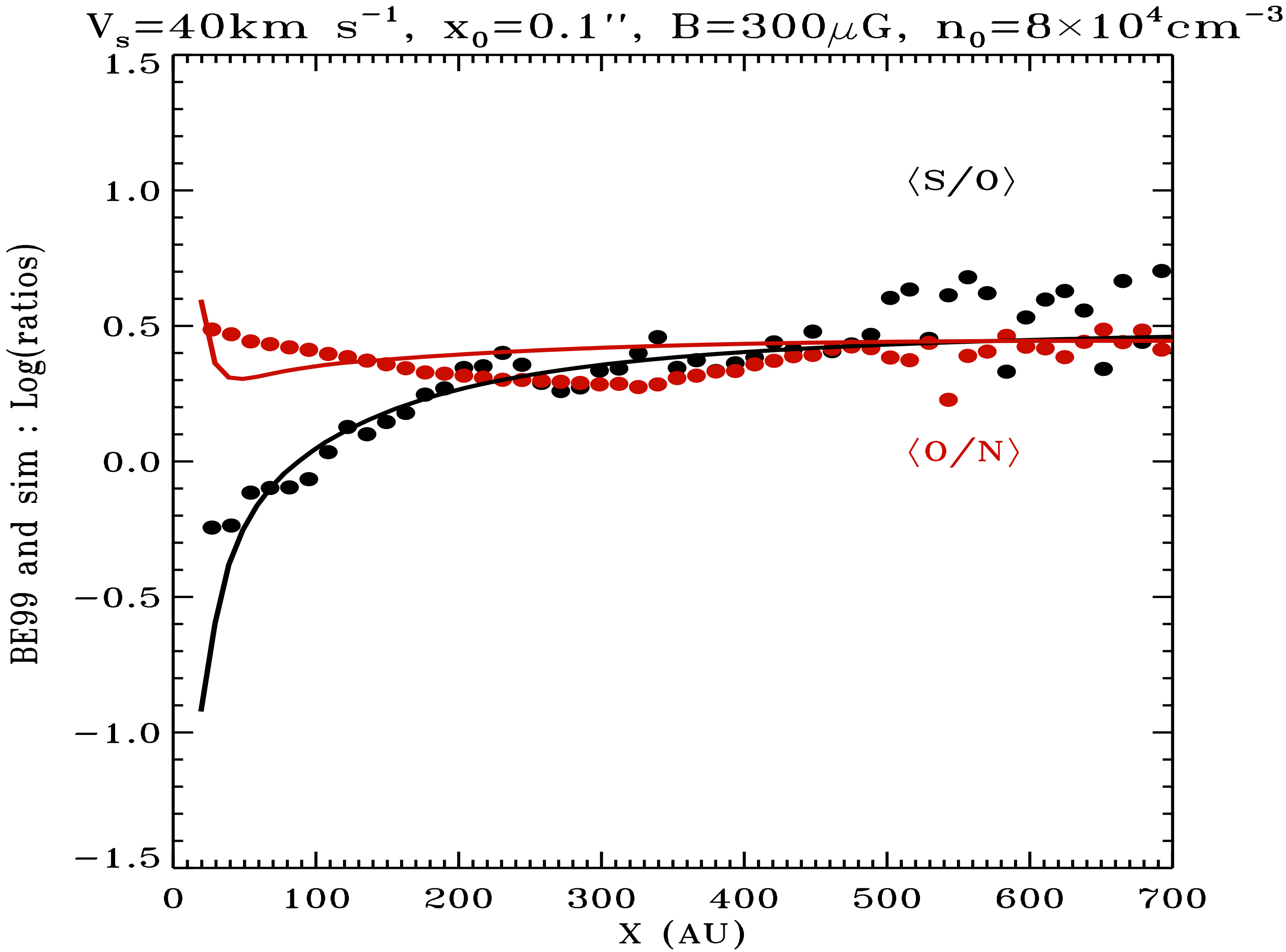


- RK23 (embedded 2nd & 3rd order) employed for the embedded error estimation
- both CK45 and Rosenbrock employed with sub-timestepping
- higher order and pass to implicit only where needed
- efficient computer power use

HH30 line ratios estimations

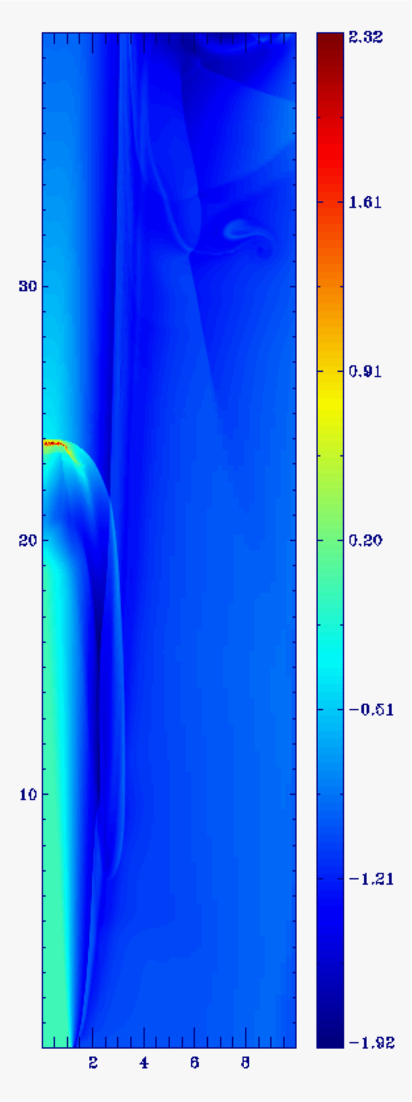
- simple 1D model, AMR employed
- MINEq cooling in the PLUTO code (29 ion species, 5-level atom model for collisionally excited emissions)
- emission generated in the post-shock zones
- 1 propagating shock simulation in the Reference Frame of the jet
- medium density distribution $\rho = \rho_0 \frac{x_0}{x + x_0}$
- 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



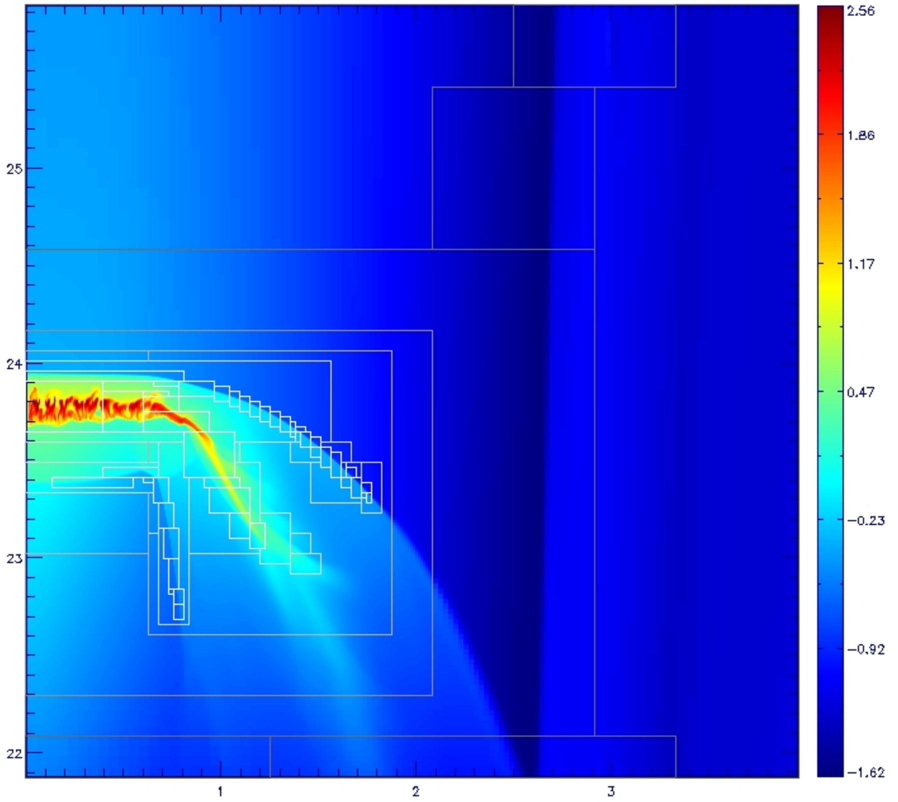
Synthetic observations

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.



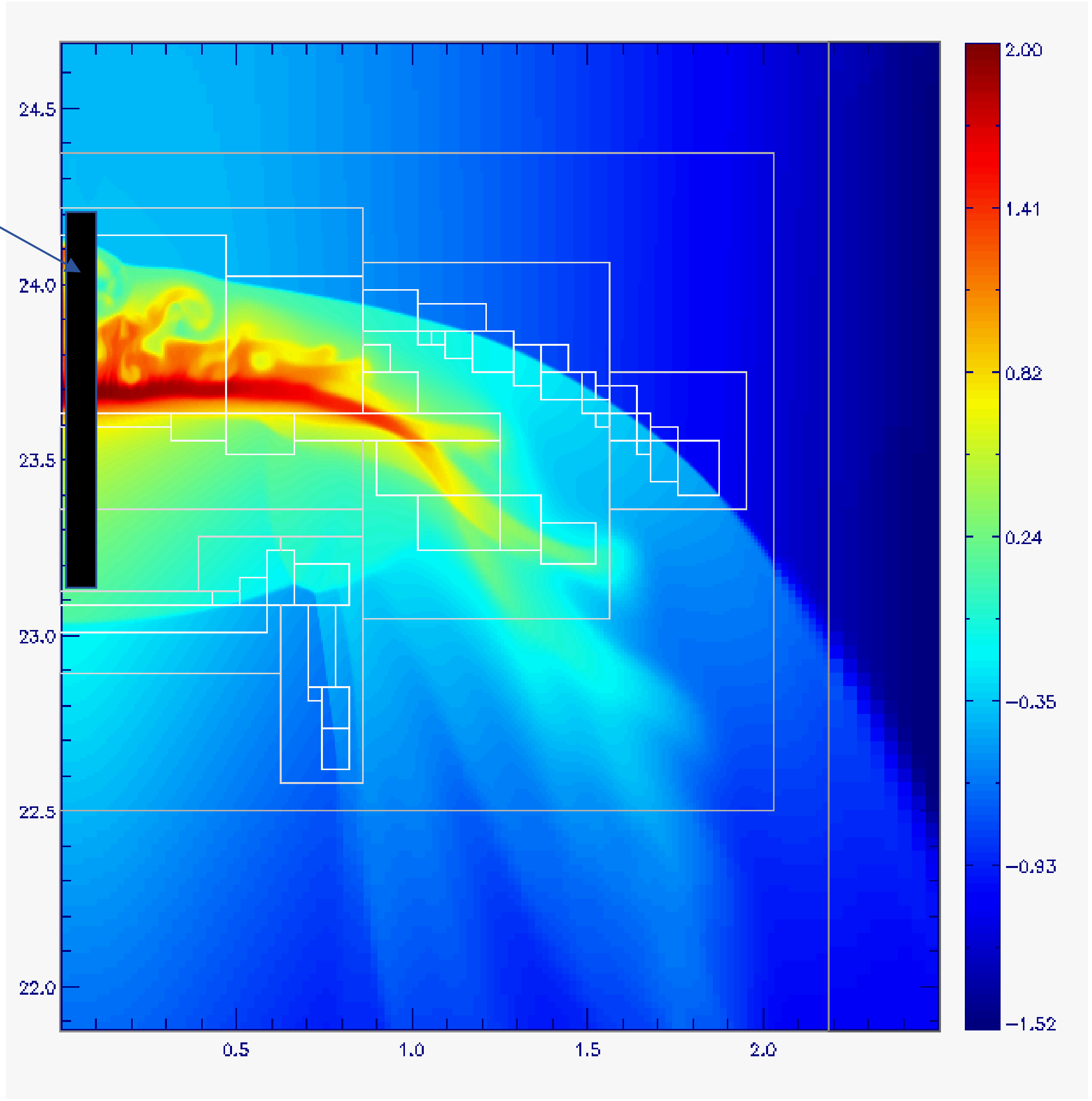
Detail from an AMR simulation with SNEq, 7 levels of refinement with equivalent maximum resolution 6144x24576

Density $\log_{10}$ map.

Input data

- **MINEq cooling**

slit



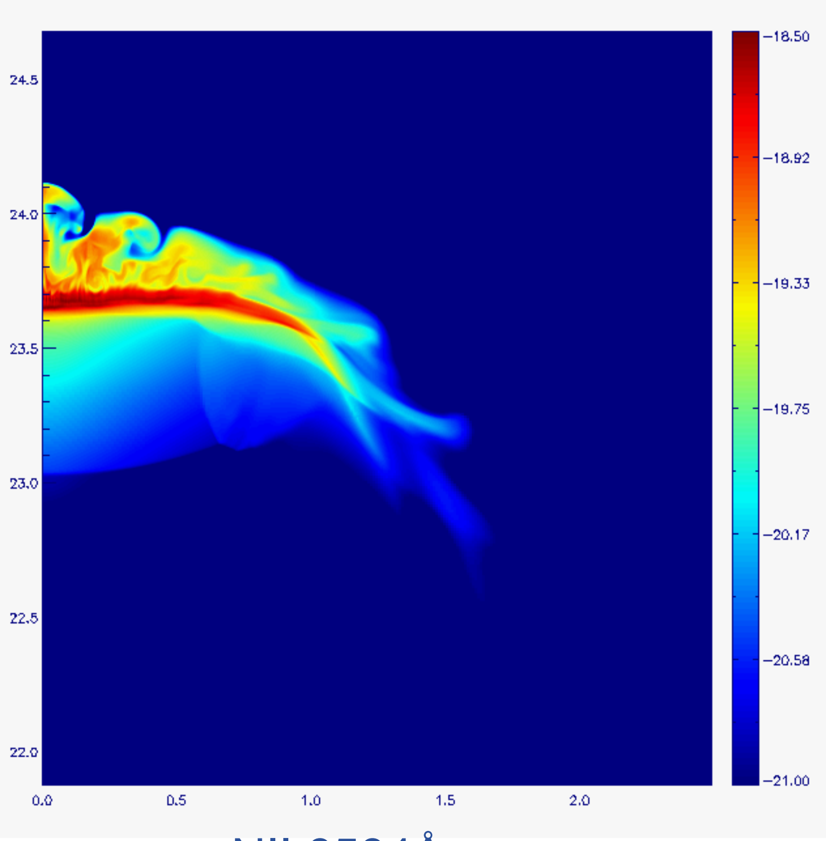
Detail from an AMR simulation with MINEq, 7 levels of refinement with equivalent maximum resolution 6144x24576

Density $\log_{10}$ map

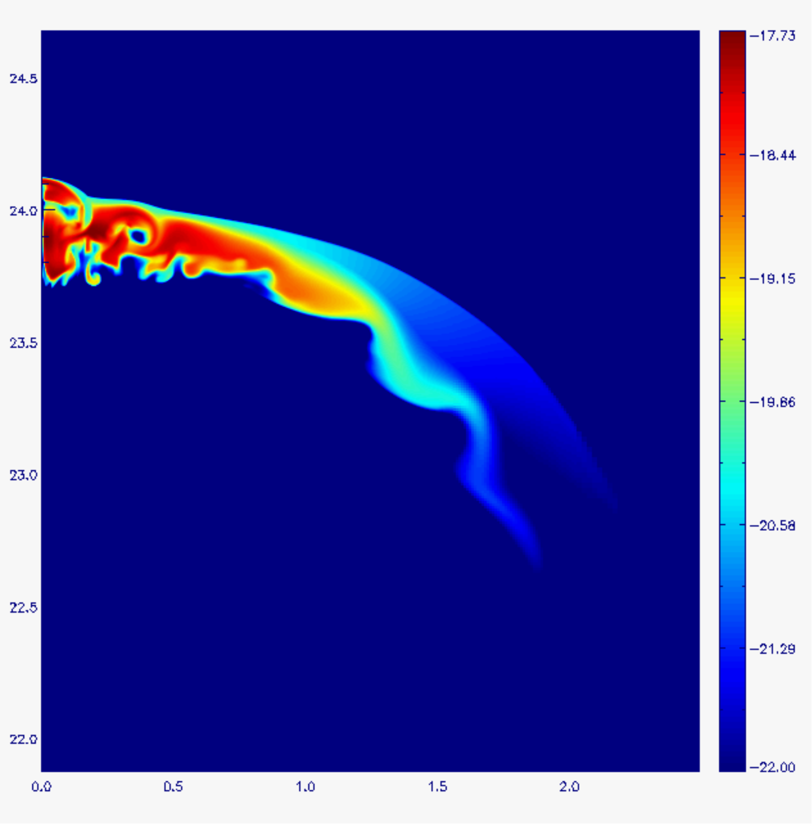
Synthetic observations

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



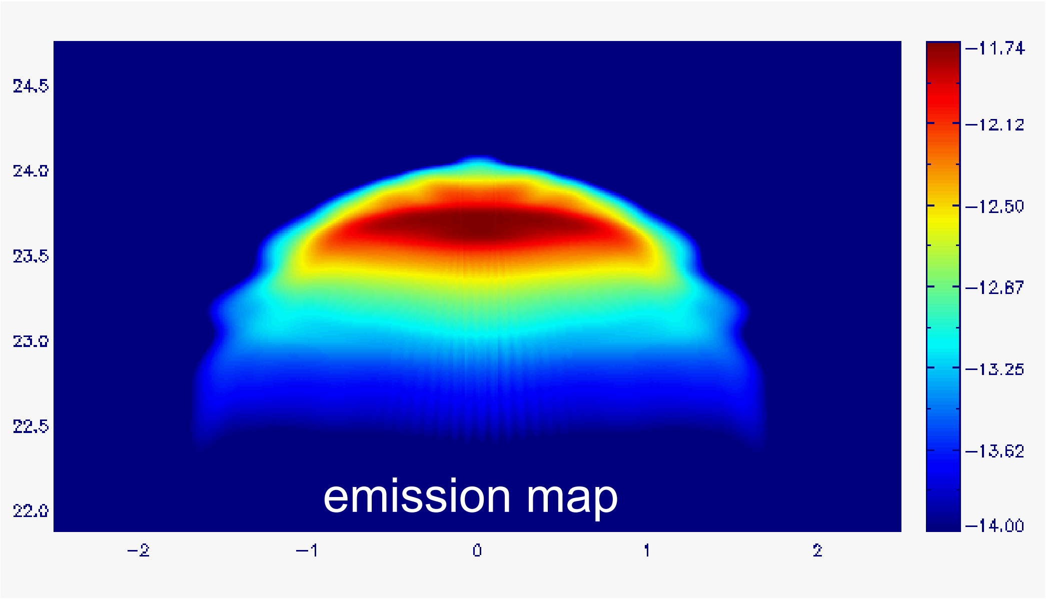
SII 6727Å

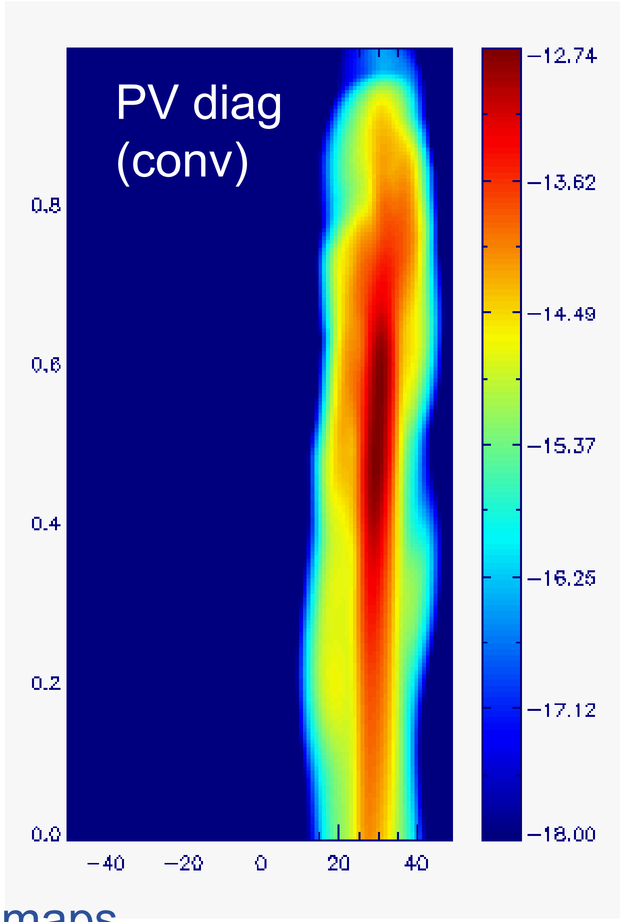
(from MINEq data)

Synthetic observations

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



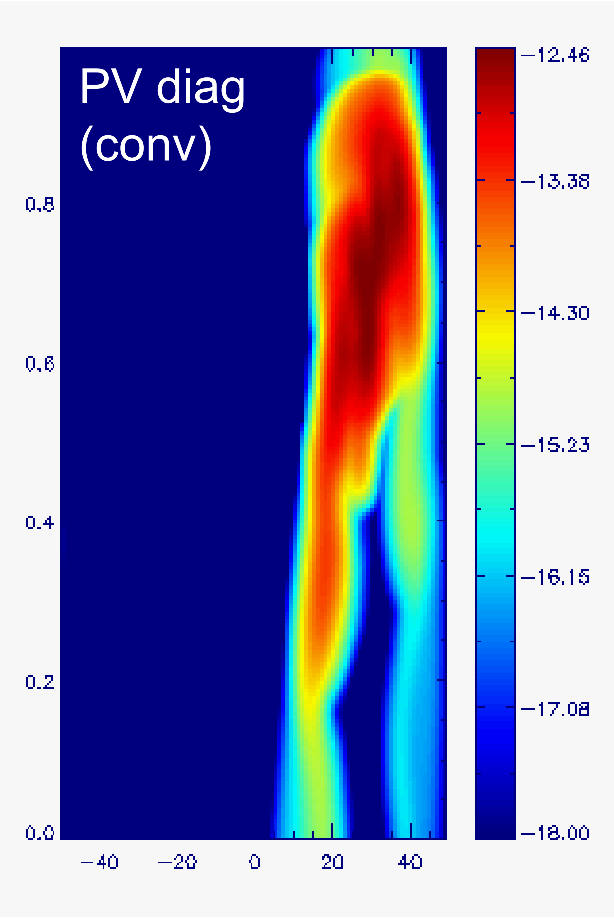


log_{10} maps
NII 6584Å

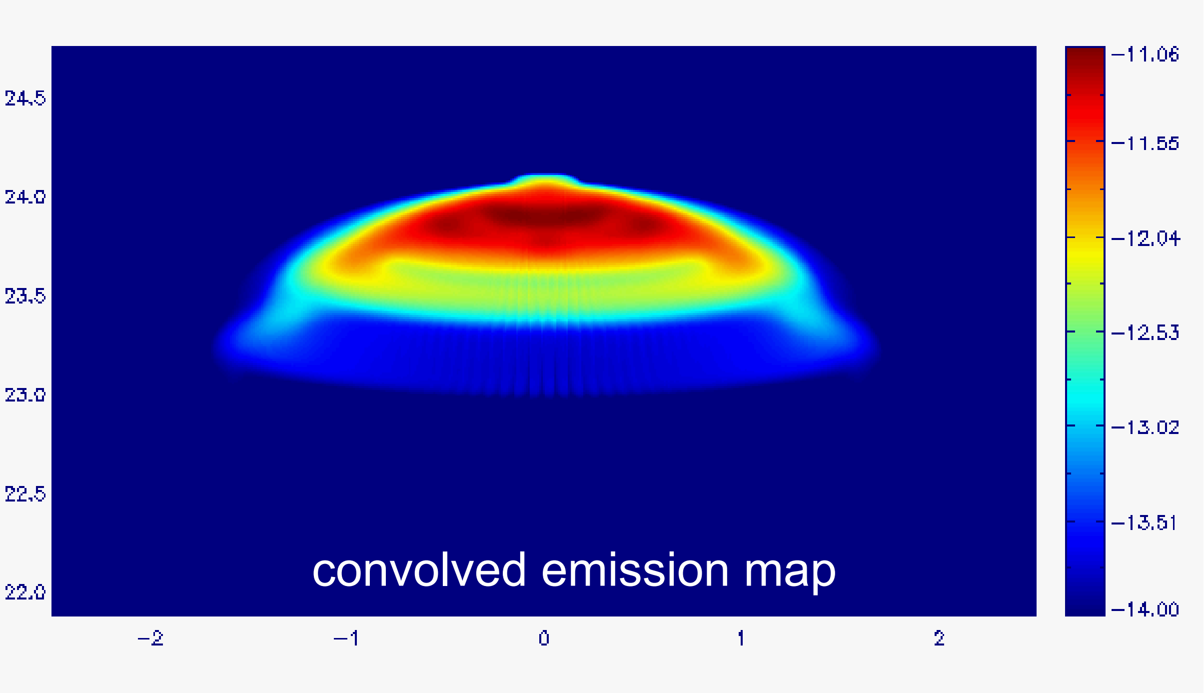
(the 3D shock axis forms a 80° angle with the LoS)

Synthetic observations

Phase II



SII 6727Å

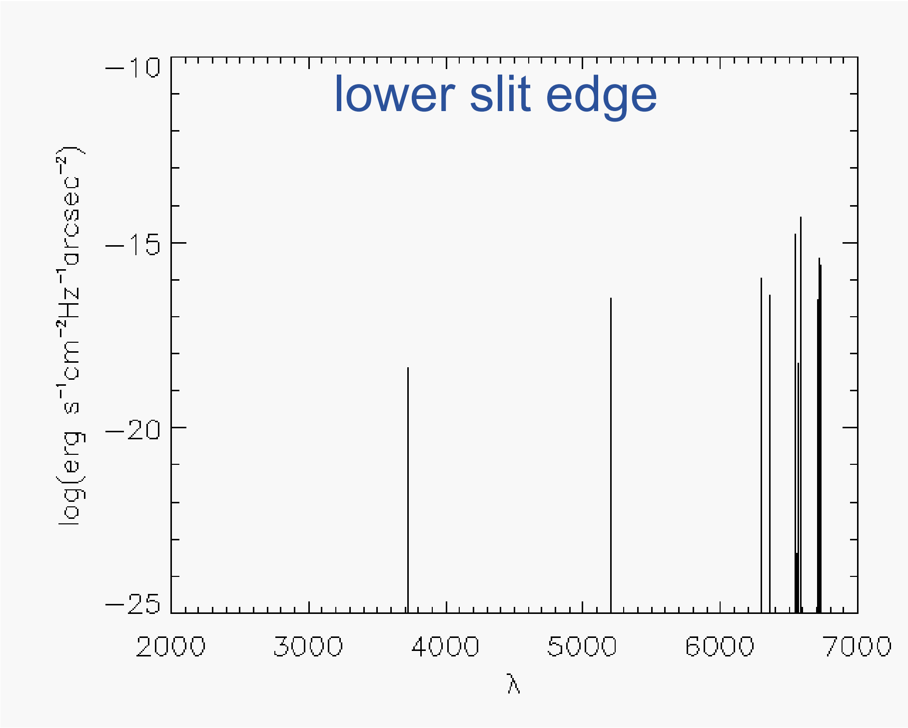


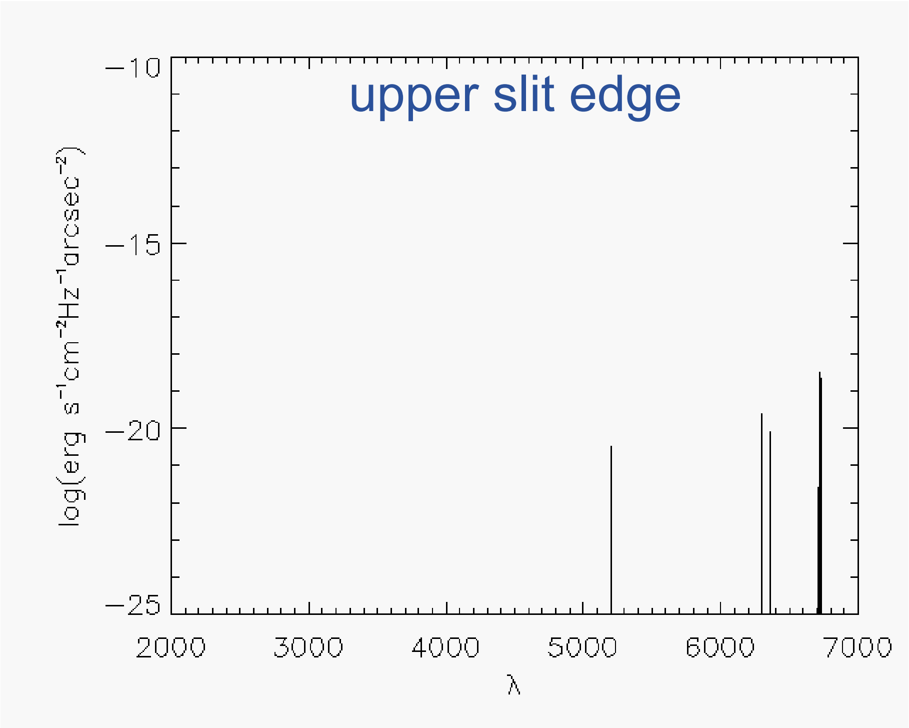
$\log_{10}$ maps

Synthetic observations

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!