

# YSO Jets: MHD Simulations with Radiative Cooling



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## Introduction – Aims

In the frame of the JETSET network, our aim is to perform realistic numerical simulations of YSO jets. The MHD simulation code we use - PLUTO, is developed and maintained at the Turin University by A. Mignone (<http://plutocode.to.astro.it>). The newly developed cooling module (MINEq) permits a detailed treatment of non-equilibrium cooling losses and is much more accurate than the previously employed models. For the YSO jets, we are interested in the following plasma conditions:

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

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

with solar element abundances. In these conditions, the plasma is optically thin.

The cooling model accounts for the evolution of the following 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. These species should give a good approximation of the cooling for the above conditions (see also Raga & al 1997). The S, although not having an important contribution to cooling, is added especially for diagnostic purposes.

Non-equilibrium ionization fractions are computed at runtime. The ionization balance is first computed in equilibrium conditions, and used as initial condition for the MHD simulation.

The following processes are taken into consideration: collisional ionization, radiative and dielectronic recombination, charge-transfer with H, H+ and He.

## The cooling function

In order to be able to efficiently and accurately integrate the system of equations describing the ionization state of the gas (the ionization network), that is prone to stiffness, the dynamical selection of the integration algorithm became necessary.

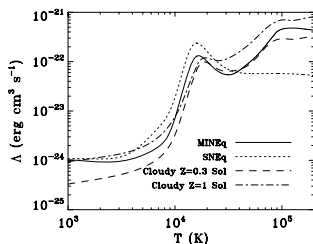
Several tests were performed with various integrators in order to compute the parameter range of applicability for each of them.

### Effective cooling

Tests and comparisons of the effective cooling rate with other models were an important step in the testing process of the newly developed cooling function,

We have compared the effective cooling rate with the previously used, simplified cooling model (SNEq) and with the much more sophisticated model employed by the Cloudy atomic network code (Ferland & al 1998).

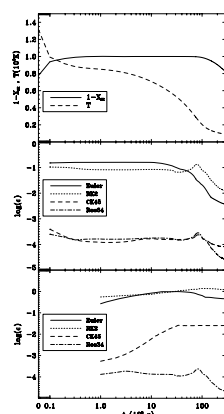
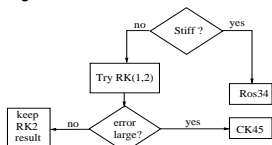
It can be seen that while the detailed cooling model accounts with good accuracy for the cooling losses up to 200,000K, the simplified one cannot follow them above above 30,000K because it lacks higher ionization stages for the atoms. Our results are situated between Cloudy's metallicities 0.3 and 1.0 due to the fact that for now, only few metals are included.



### Integration strategy and error estimation

A dynamically selected integration algorithm was employed in order to optimally balance efficiency and accuracy. Areas in the simulation far from equilibrium (stiff), for example post-shock zones, need a semi-implicit integration scheme (Rosenbrock 34), while moderately stiff cells can be integrated using a high-order explicit method (Cash-Karp). The areas close to equilibrium can be integrated using a classic second-order Runge-Kutta.

In the plots on the right the evolution in time of the error in ionization fraction for four integrators is presented, for timesteps 5 (middle) and 50 (bottom) times larger than the ionization timescale.

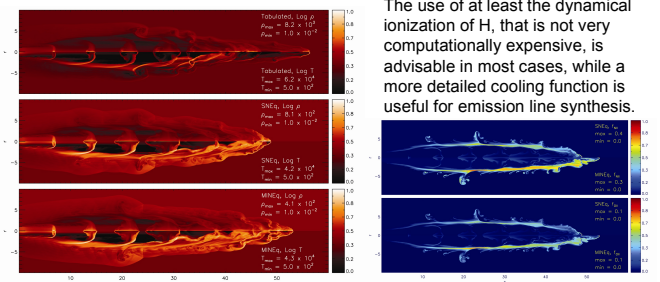


## 2D simulations of radiative jets

Several exploratory simulations were performed in order to establish the importance of the radiative cooling model on the dynamical and ionization properties of the jet.

Presented here are the results of medium-resolution simulations of jets using a tabulated cooling function (with the Cloudy Z=1 effective cooling values), the simplified cooling SNEq (integrating only the ionization fraction of H) and the detailed cooling model MINEq. Because of the non-equilibrium ionization balance, SNEq and MINEq give more similar (and reliable) results than the tabulated cooling curve.

The ionization fractions of NII and OII (presented in the lower right figure) are quite different between SNEq (where they are computed directly from H ionization balance) and MINEq (where they are dynamically computed in the ionization network). This is an important aspect for the line emission simulations.



The use of at least the dynamical ionization of H, that is not very computationally expensive, is advisable in most cases, while a more detailed cooling function is useful for emission line synthesis.

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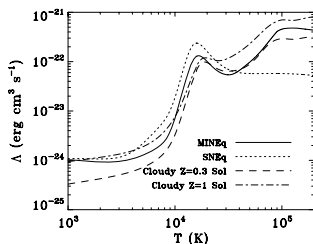
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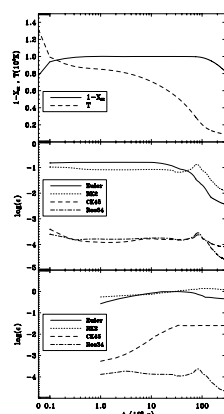
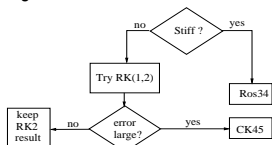
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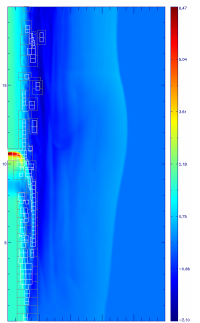
## Large scale and AMR

The post-shock zones in radiative jets need very high resolution to be resolved. This would, on normal fixed grids, limit the scale of the simulation to very small distances. Adaptive Mesh Refinement techniques permit to overcome this problem, and allow us to perform simulations on scales of several thousand A.U. with reasonable computational costs.

The Chombo library for AMR is employed by PLUTO for 2D and 3D AMR runs.

The purpose is to simulate the shocks (forming by initial perturbations) propagating along the jets and compute the line emission to compare with observations).

Shock propagating through a jet. Medium resolution simulation with AMR PLUTO, 2D cylindrical, 2 levels of refinement, density log map.



## Conclusion and perspectives

The new detailed cooling function MINEq is implemented in the PLUTO MHD code, and the post-processing routines for line emission computations are ready.

We are currently working on setting the parameter space for 2D AMR simulations on scales of 1 – 2,000 A.U., with effective equivalent resolutions of 36,000x6,000 and more. We aim to reach a resolution of around 10<sup>2</sup>A.U. in the post-shock zones in the large-scale simulations to be performed at CINECA.

## References

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