Simulations of Radiative Shocked YSO Jets: Time-dependent Ionization and Cooling

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Introduction – Aims

Our purpose in the framework of JETSET is to perform realistic 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). We developed a new cooling function which greatly improves over the rather simplified implementation of Raymond's algorithm (1992).

We are interested in the following plasma conditions:

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

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

with solar element abundances.

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.

Ionization Equilibrium

The collisional ionization equilibrium of an optically thin plasma is a good approximation for our conditions.

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

The variation of the relative abundance coefficient of the *j*-th ion of the considered element is expressed by:

$$\frac{df_j}{dt} = n_e \{ f_{j+1} \alpha^{rec}(j+1) - f_j \left[\alpha^{ion}(j) + \alpha^{rec}(j) \right] + f_{j-1} \alpha^{ion}(j-1) \}$$

where the $\alpha^{ion}(j)$ and $\alpha^{rec}(j)$ coefficients for the *j*-th ion are:

$$\alpha^{ion}(j) = \alpha^{ion}_{coll}(j,T) + \frac{n_H}{n_e} f_{HII} \alpha^{ChTrH^+}(j,T)$$

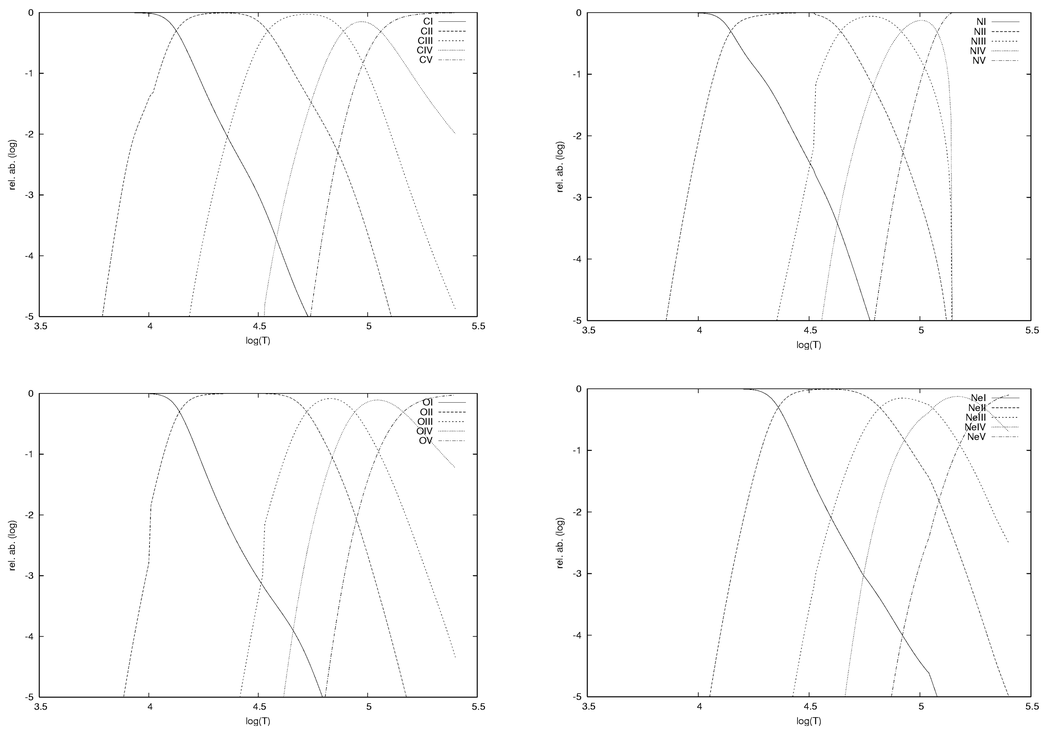
$$\alpha^{rec}(j) = \alpha^{rec}_{el}(j,T) + \frac{n_H}{n_e} f_{HI} \alpha^{ChTrH}(j,T) + \frac{n_{He}}{n_e} f_{HeI} \alpha^{ChTrHe}(j,T)$$

where f_j is the relative abundances of the ions, n_X is the number density of the X ion and n_e the electron number density. Also, $\alpha^{ion}_{coll}(j,T)$ is the collisional ionization rate, the total recombination rate (radiative plus dielectronic) is $\alpha^{rec}_{el}(j,T)$ and the α^{ChTr} coefficients represent the charge-transfer with H, p and He.

The equilibrium ionization balance of the ions of each element can be computed by considering $df_j / dt = 0$ in the equations above. Together with the normalization condition for the total ion abundances for one element: $\sum_{j=1}^{A} f_j = 1$, this procedure yields a system of equations which is weakly nonlinear in the *f's* .

The nonlinearity is introduced by the number densities which depend on H and He, and an iterative method is used to obtain the physically relevant solution.

The graphs below show our computed equilibrium ionization balance for the considered species of C, N, O and Ne.



Ionization Balance

Once the equilibrium ionization balance is assigned as the initial condition in our numerical simulation, the ions populations are evolved in time by solving 28 advection equations of the form

$$\frac{\partial f_j}{\partial t} + v \nabla f_j = S_j$$

for the ion species. S_j is the source-term calculated using the number densities of electrons and ions and the ionization / recombination rates previously discussed.

Radiative Losses

For our typical plasma conditions, radiative cooling gets its most important contribution from collisionally excited line radiation.

In additiom, we also consider free-free (bremsstrahlung) radiation from protons and ionized helium, and energy losses by ionization / recombination processes.

The cross section for the excitation to level 2 of a particular ion by electron collisions with ions in the lower level 1 can be expressed in terms of the collision strength $\Omega(1,2)$ as:

$$\sigma_{12}(v) = \frac{\pi \hbar^2}{m^2 v^2} \frac{\Omega(1,2)}{\omega_1}$$

The collision strengths must be computed quantum mechanically. In the absence of a unique source for the most recent data, we gathered the needed coefficients from literature.

In the five-level model we have used, the equilibrium equations for each of the levels *i = 1,5* become:

$$\sum_{j \neq i} N_j N_e q_{ji} + \sum_{j>i} N_j A_{ji} = \sum_{j \neq i} N_i N_e q_{ij} + \sum_{j<i} N_i A_{ij}$$

After computing the level populations, the cooling rate:

$$L_C = \sum_i N_i \sum_{j<i} A_{ij} h\nu_{ij}$$

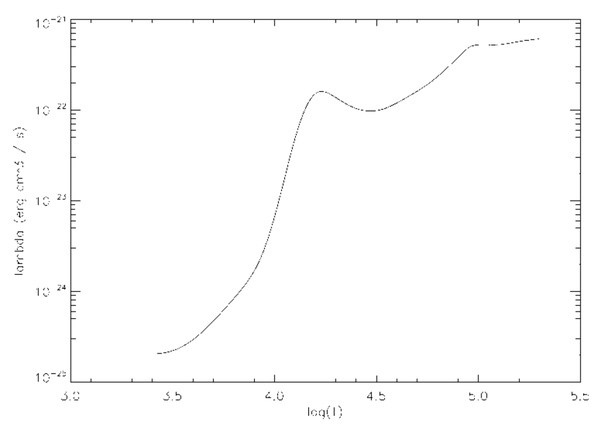
is properly tabulated for each ion.

Implementation and tests

At runtime the MHD simulation code computes the ionization balance and uses the pre-loaded tables of cooling to compute the total cooling for each computational cell:

$$L_C = \sum_{elem} \left[\sum_i N_i^{elem} \sum_{j<i} A_{ij}^{elem} h\nu_{ij}^{elem} \right]$$

The total computed cooling function for equilibrium is shown below.



Our first preliminary tests show that, in the case of 1-D MHD radiative shock models, the new cooling function yields a dynamical behavior significantly different with respect to when simpler cooling functions (e.g. Raymond) are used.

This can be explained by the far more complex cooling and non-equilibrium ionization balance calculation employed.

References

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