IL NUOVO CIMENTO Vol. 32 C, N. 2 Marzo-Aprile 2009
DOI 10.1393/ncc/i2009-10397-4

Colloquia: CSFI 2008

YSO jets: MHD simulations with radiative cooling

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(ricevuto il 22 Giugno 2009; pubblicato online il 7 Settembre 2009)

Summary. — The new High Power Computing facilities available for the scientific community allowed the use of increasingly complex codes for the numerical simulation of physical processes. Recent magnetohydrodynamic (MHD) simulations of astrophysical jets could finally include non-ideal effects, such as the radiative cooling we will discuss in this work in the context of protostellar jets. This makes the simulations more reliable and, with the recent improvements in available observational data, will provide a valuable tool for model discrimination. From 2D adaptive-mesh refinement (AMR) simulations, synthetic surface brightness maps for the line emissions are computed, to be compared with observations.

PACS `98.38.Fs` – Jets, outflows, and bipolar flows.
PACS `52.65.Kj` – Magnetohydrodynamic and fluid equation.
PACS `95.30.Dr` – Atomic processes and interactions.
PACS `02.60.Cb` – Numerical simulation; solution of equations.

1. – Introduction

While undergoing dynamical transformations, the astrophysical gasses emit thermal radiation. In the case of very diluted material, as in the extragalactic medium, the typical timescales for cooling exceed by orders of magnitude the dynamical ones, so the effects of cooling can be neglected. This is not the case with intensively radiating gasses as the ones in the H II regions, planetary nebulae, supernova remnants or star-forming regions, when the cooling and ionization/recombination timescales become comparable to or even faster than the dynamical evolution of the system. For studying these regions, an adiabatic assumption is not acceptable and one has to take into consideration the effects of radiative cooling.

The propagation of shockwaves in these media puts the matter in ionization states far from equilibrium and produces powerful emissions in the post-shock regions, where gradients are extremely high and a time-dependent treatment is required. Under these conditions, the magnetohydrodynamics (MHD) equations, coupled with the equations describing the evolution of the emitting species and the radiative losses, must be solved by numerical means. The ability to work with space- and time-scales varying in wide ranges is a necessity.

We will describe in this work the application of a detailed radiative cooling treatment (MINEq, see [1]) embedded in the PLUTO MHD code [2], to high-resolution numerical simulations of radiative shocks in the jet from RW Aurigae.

2. – The MINEq cooling

The newly developed cooling module for the PLUTO MHD code (MINEq) integrates a complex ionization network of 29 ion species: H I, H II, He I, He II, C I to V, N I to V, O I to V, Ne I to V, and S I to V, and the collisionally excited line emission for these ion species in the approximation of a 5-level atom. The total line emission from these species hould give a good approximation of radiative cooling for the conditions in YSO jets [3].

The total energy E is evolved according to the standard MHD equations:

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + p_{\rm t})\vec{v} - \left(\vec{v}\cdot\vec{B}\right)\vec{B}\right] = S_E, \tag{1}$$

where S_E is a radiative loss term, and $p_{\rm t} \equiv p + |\vec{B}|^2/2$ denotes the total pressure (thermal + magnetic) of the fluid. For each ion, we solve the additional equation

$$\frac{\partial(\rho X_{\kappa,i})}{\partial t} + \nabla \cdot (\rho X_{\kappa,i}\vec{v}) = \rho S_{\kappa,i} \tag{2}$$

coupled to the original system of conservation laws. In eq. (2), the first index (κ) corresponds to the element, while the second index (i) corresponds to the ionization stage. Specifically, $X_{\kappa,i} \equiv N_{\kappa,i}/N_\kappa$ is the ion number fraction, $N_{\kappa,i}$ is the number density of the i-th ion of element κ, and N_κ is the element number density. The source term $S_{\kappa,i}$ accounts for ionization and recombination.

The system of equations for energy and ionization fractions is prone to *stiffness*—very rapid variations that ultimately lead to instability. To avoid this, a dynamically switching integration algorithm was built, to selectively use high-order explicit or even semi-implicit integration methods in the points where needed. The use of a semi-implicit method on the whole grid would have been unacceptable in terms of computational cost. The code first makes an estimation of the maximum ionization/recombination and cooling rates, and decides to proceed with semi-implicit (Rosenbrock 3-4, see [4]) or explicit methods. In this latter case, it then employs a Runge-Kutta of orders 1-2 or 2-3 with embedded error estimation, and decides either to keep the result or pass to a higher-order, Cash-Karp 4-5 integrator.

For a detailed description and testing of the cooling function we refer to [1].

3. – 2D AMR simulations of jets

Current research in the numerical study of YSO jets focuses on the creation of "synthetic observations" from the output of the MHD simulations, to compare with high-resolution observations.

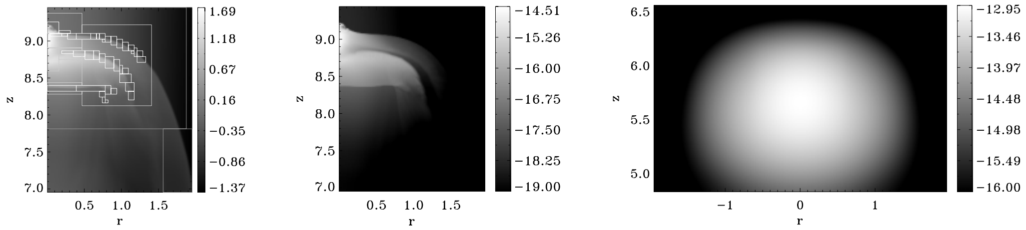

Fig. 1. – Left panel: Logarithmic map of density of the shock zone with refinement levels superimposed; Center panel: Emissivity logarithmic map in [S II]λ6731 Å, units of erg cm^{-3} s^{-1}; right panel: Logarithmic map of source surface brightness in [S II]λ6731 Å, convolved with the PSF and projected on the plane of the sky; units of erg cm^{-2} arcsec^{-2} s^{-1}.

We have employed the AMR library CHOMBO with the PLUTO code for high-resolution simulations (equivalent maximum resolution of $4\,096 \times 16\,384$ cells) of YSO jets on integration domains of 5×20 jet radii, with $r_{\rm jet} = 5 \times 10^{14}$ cm. Perturbations are created at the base of the jet, according to the algorithm described in [5], and during propagation evolve into shocks that could explain the emission knots along the observed jets. AMR permits to follow the evolution for equivalent times of 20 y with an adequate resolution for the post-shock zone (see fig. 1, left panel). The emissivity maps are computed in various emission lines, then the emission is geometrically integrated, considering an arbitrary inclination angle (in the case of RW Aur this is 44°) with respect to the line of sight, convolved with a PSF and projected on a plane perpendicular on the line of sight (see fig. 1, center and right panels for an illustration).

The PSF for the presented examples is a Gaussian function, but any PSF from real telescopes can be used. The knots in the real jet correspond, in the simulations, with a shock at various evolution moments and with various intensities of the initial perturbation. In fig. 2, the first attempt to model the RW Aurigae redshifted jet is presented. The first fours knots were simulated (due to restrictions in domain size and simulation time). The model jet had a base velocity $v_{\rm jet} = 110\,{\rm km\,s^{-1}}$, particle number density $n_0 = 5 \times 10^4\,{\rm cm^{-3}}$ and the simulation was done with an amplitude of the velocity perturbation of $33\,{\rm km\,s^{-1}}$. The choice of the simulation frames taken for the four knots was

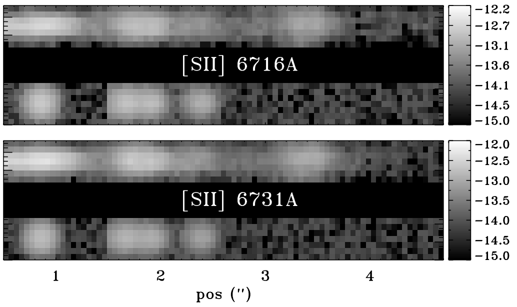

Fig. 2. – Logarithmic maps of surface brightness in the two emission lines of the [SII] doublet. Each image contains the observed (upper half) and synthetic (lower half) images of the redshifted RW Aur jet. Units of erg cm^{-3} s^{-1}.

Table I. – *Computational cost of the radiative jet simulations with cooling.*

Configuration	Ex.time (s)	Steps	Time/step (ms)
Adiabatic	17	38	436
Tabulated	19	39	475
Simplified	114	118	958
MINEq	338	109	3070

based on the estimated age of the observed knots from their proper motions. A random weak background was applied to the synthetic jet.

The simulation results are in good agreement in the SII doublet, but before considering this a good model for the jet, the comparison must be extended to the other observed emission lines. Also, it might be necessary to lower the width of the synthetic jet to better match observations.

4. – Computational cost

Table I presents the total execution times for identical simulations that reach the same evolutionary time, as well as the time per timestep, when various cooling functions are employed. The simulations are of a pulsing jet, at a resolution of 100×600 cells, and were run on a single core of a 3 GHz Pentium 4HT machine. It can be seen that the tabulated cooling (when only a source term in the energy equation is added, without any atomic specie) is the less computationally expensive, adding only a small supplementary execution time to the adiabatic setup. Next is the simplified cooling implementation (with dynamically integrated ionization state of hydrogen only), with runtime computation of the energy losses due to the 16 most important emission lines. The most accurate cooling model, MINEq, previously described, is also the most expensive from the point of view of computational cost.

In terms of total execution time, there is a difference of factor of 20 between the adiabatic simulation and the one with the most complex cooling treatment. The detailed cooling provides realistic ionization fractions in non-equilibrium conditions, important in emission line computations. The total execution time can be reduced by a factor of three by employing the simplified cooling, adequate in some dynamical studies.

5. – Conclusions

The preliminary results from 2D AMR simulations on scales of $\sim 1000\,\mathrm{AU}$, with spatial resolution of about $10^{-2}\,\mathrm{AU}$ in the post-shock zones (adequate to resolve the processes) are encouraging, further studies being aimed at simulating arrays of knots in the real observed jets in multiple emission lines.

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The present work has been supported by the European Union (contract MRTN-CT-2004-005592) within the Marie Curie RTN JETSET. OT has also received 50 000 CPU hours at CINECA Bologna for the numerical simulations of YSO jets.

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