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# Numerical calculation of sub-luminous Type II-plateau supernova events

M.L. Pumo[1], L. Zampieri[1], and M. Turatto[2]

[1] INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy
[2] INAF - Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95123 Catania, Italy

**Abstract.** We are developing a specifically tailored radiation hydrodynamics Lagrangian code, that enables us to simulate the evolution of the main observables in supernova events. We aim at using this numerical tool to clarify the nature of the sub-luminous Type II-plateau supernovae progenitors by comparing the properties of iron core-collapse and electron-capture events. The code features and some preliminary results are briefly discussed.

**Key words.** stars: supernovae: general - methods: numerical

## 1. Introduction

It has been suggested (e.g. Chugai & Utrobin 2000; Hendry et al. 2005; Kitaura et al. 2006) that the peculiarities of a fraction of the so-called sub-luminous Type II-plateau supernovae (type II-P SNe) — characterised by low luminosity, small amount of ejected $^{56}$Ni, extended plateaus (implying envelope mass of several $M_{\odot}$) and slow expansion velocities — can be interpreted in terms of core-collapse SNe events triggered by electron-capture reactions (so-called electron-capture SNe), involving progenitors which develop degenerate NeO cores such as the super-AGB stars (e.g. Siess & Pumo 2006; Pumo 2006, 2007).

However an alternative interpretation, in which the progenitors are massive stars with extended ($\gtrsim 15 M_{\odot}$) envelopes, has been proposed (e.g. Zampieri et al. 2003). So far, no definite picture has emerged.

With the aim of clarifying the nature of the sub-luminous Type II-P SNe progenitors, we are comparing the properties of iron core-collapse and electron-capture SNe, in order to see if they are compatible with the observations.

To this end, we are developing a specifically tailored radiation hydrodynamics Lagrangian code that enables us to simulate the evolution of the main observables in SN events.

## 2. The numerical code

The code is a new, improved version of a dedicated relativistic, radiation hydrodynamics, Lagrangian code described in Zampieri et al. (1996, 1998) and in Balberg et al. (2000), and originally developed for studying fall back in the aftermath of a SN explosion.

The code computes the evolution of the light curves, the photospheric velocity and continuum temperature of core collapse SN (CC-

*Send offprint requests to*: M.L. Pumo

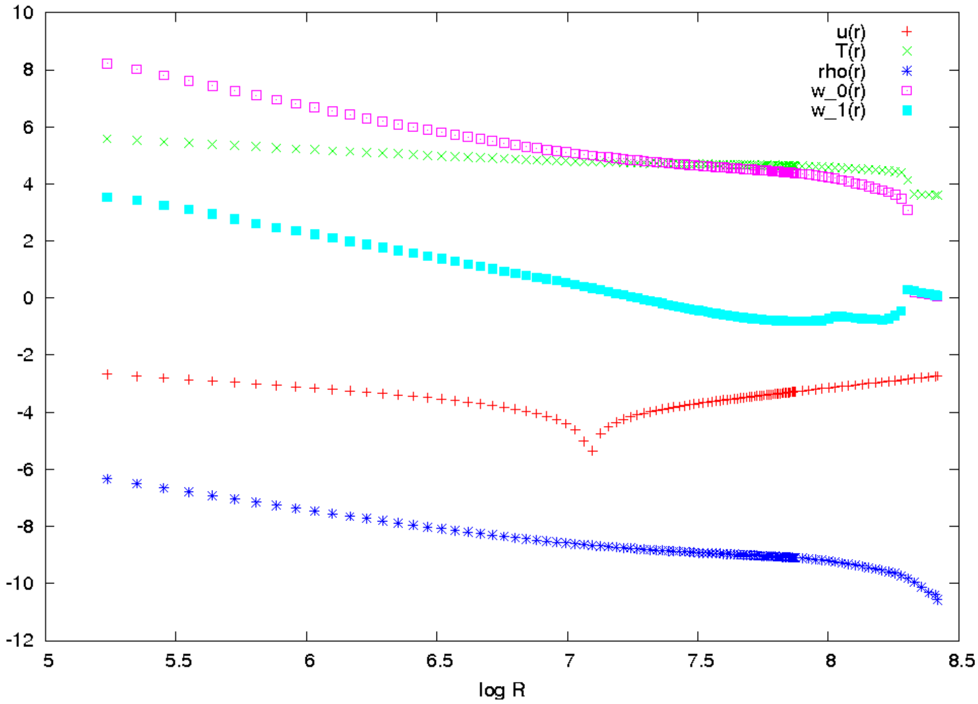


**Fig. 1.** From bottom to top, radial profiles (log scale) of the gas matter density (in units of g·cm$^{-3}$), fluid 4-velocity (in units of the velocity of light), radiative flux (in units of erg·cm$^{-3}$), gas temperature (in units of Kelvin) and radiation energy density (in units of erg·cm$^{-3}$) as a function of radius (in units of the Schwarzschild radius $R_s$ for $1.5M_\odot$). The solution was evolved for ∼ 46 days. The envelope mass and initial radius are 5.5 $M_\odot$ and $2{\cdot}10^{13}$cm, respectively. The explosion energy is ∼ $10^{49}$ erg. The innermost part of the envelope, below ∼ $10^7$ $R_s$, is accreting onto the central remnant (the 4-velocity is negative). In order to increase the accuracy, the radial mesh is equally spaced (in log scale) in mass in the internal layers and in radius in the outer ones.

SN) events, starting from the breakout of the shock wave at the stellar surface up to the nebular stage (when the energy budget is dominated by the radioactive decays of the heavy elements synthesised in the explosion). A detailed treatment of radiative transfer is incorporated (see Zampieri et al. 1998; Balberg et al. 2000, for details).

In the old version, the evolution of the ejecta and the emitted luminosity are computed solving the equations of relativistic, radiation hydrodynamics for a self-gravitating matter fluid interacting with radiation. The code adopts a semi-implicit Lagrangian finite difference scheme where the time step is controlled by the Courant condition and the requirement that the fractional variation of the variables in one time-step be smaller than 10%.

In the new version, under development, we have modified the numerical structure by implementing a fully implicit Lagrangian finite difference scheme. This allows for a major improvement in the numerical stability and overall computational efficiency of the code, especially during those phases when fast motions of steep gradients occur (e.g. the radiative recombination phase).

In particular, the main feature of this new version is the coupling in a fully implicit scheme of the gas energy equation and the zero-th moment of the energy transfer equation with the first moment equation (see re-

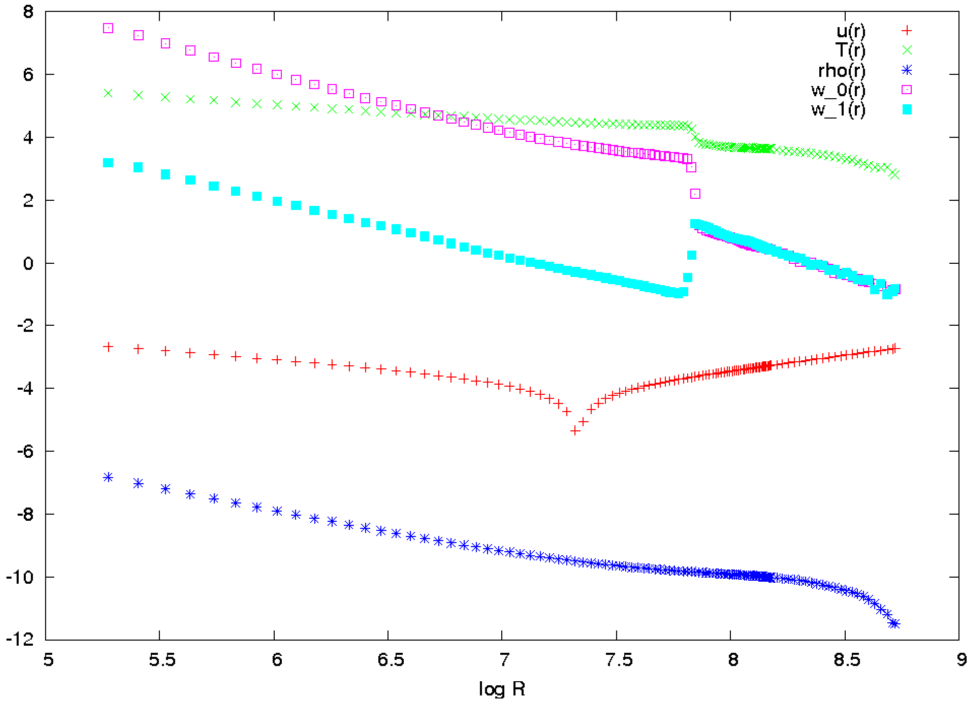


**Fig. 2.** As in Figure 1. The plot refers to the solution evolved for ~ 95 days.

spectively equations (25), (26) and (24) in Zampieri et al. 1998). This leads to a highly non linear system of coupled equations that is solved through a Newton-Raphson iterative method and a matrix inversion package that minimise the CPU time and the required storage space.

## 3. Preliminary results

A few tests have been performed evolving the solution from a simplified set of initial conditions. We varied several input parameters (number of points, location of the inner boundary, mass of the ejecta, initial radius and thermal energy) to check the stability and accuracy of the code.

We have also performed a few long-run simulations, evolving the solution from a more realistic set of initial conditions (details will be provided in a forthcoming paper). Here we show the results for one of these simulations, evolved up to ~ 150 days, so as to follow the radiative recombination phase in detail. This simulation was performed considering an envelope mass of 5.5 $M_{\odot}$, an initial radius of $2{\cdot}10^{13}$cm and an explosion energy of ~ $10^{49}$ erg. Although the explosion energy is still too low to be considered representative of a real sub-luminous event (~ $10^{50}$ erg), this allowed us to test the long-term stability of the code during some key evolutionary stages.

The radial profiles of gas matter density, fluid velocity, radiative flux, gas temperature and radiation energy density at the beginning and at the end of the Hydrogen recombination phase are shown in Figures 1 and 2, respectively. The sharp boundary that marks the position of the recombination front (at ~ $6 \times 10^7 R_s$ in Figure 1 and ~ $2 \times 10^8 R_s$ in Figure 2) where also the photosphere is located, is very well traced by the code. More detailed model computations will be presented in a forthcoming paper.

## 4. Future developments

At present we are working at improving the performances of the code. The aim is to computed fine grids of models evolved from post-explosion configurations and carry out detailed investigations of the evolution of iron core-collapse and electron-capture SNe.

Our long term goal is the development of a sort of "CC-SNe Laboratory" in order to describe in a self-consistent way CC-SN events, starting from the formation of the progenitor up to the explosion.

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