Nucleosynthesis as a result of multiple delayed detonations in Type Ia Supernovae

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The explosion of a white dwarf of mass 1.36 M\textsubscript{☉} has been simulated in three dimensions with the aid of a SPH code. The explosion follows the delayed detonation paradigm. In this case the deflagration-detonation transition is induced by the large corrugation of the flame front resulting from Rayleigh-Taylor instability and turbulence. The nucleosynthetic yields have been calculated, showing that some neutronized isotopes such as \textsuperscript{54}Fe or \textsuperscript{58}Ni are not overproduced with respect to the solar system ratios. The distribution of intermediate-mass elements is also compatible with the spectra of normal SNIa. The exception is, however, the abundance of carbon and oxygen, which are overproduced.

1. Introduction

The undeniable influence of Type Ia Supernovae explosions in, among others, the chemical evolution of the galaxy and cosmology makes the quest of solid theoretical models as an urgent task. Guided by the insight gained from two decades of modelization of spherically symmetric models, modern multidimensional calculations try to make a reliable picture of the explosion on physical basis, minimizing the number of free parameters. Nevertheless, even supposing that the exploding object is a CO white dwarf near to the Chandrasekhar-mass limit the subject is not firmly resolved yet. In particular, there remain uncertainties in the immediate pre-explosive stage and in the mechanism/s by which the thermonuclear flame is spreaded through the white dwarf. In this regard a difficult point is related with the acceleration of the combustion. We know that the explosion is triggered by a thermonuclear flame whose initial velocity is clearly subsonic. We also know, from parametrized calculations, that after several sound-crossing times the effective velocity of the deflagration must reach a significant fraction of of the local sound speed in order to synthesize the adequate amount of nuclear species to explain both light curve and spectra. This translates into an increase factor of thousands over the pure laminar value at maximum effective velocity. The physical mechanism behind this huge factor is currently attributed to flame surface corrugation by hydrodynamical instabilities (mainly Rayleigh-Taylor and turbulence). A branch in this scenario could be achieved if the already fast deflagration turns into a steady detonation at late times, when flame density is below $\rho \approx 4 \times 10^7$ g.cm\textsuperscript{-3}. This is the so called delayed-detonation scenario which, in
Table 1
Main features of the model$^a$

| t(s) | $\rho_c$ (g.cm$^{-3}$) | $\langle \rho_{\text{flame}} \rangle$ (g.cm$^{-3}$) | $E_{\text{kin}}$ ($10^{51}$erg) | $M_{\text{CO}}(M_\odot)$ | $M_{\text{Si}}(M_\odot)$ | $M_{\text{Ni}}(M_\odot)$ |
|------|------------------------|-----------------------------------|-----------------|----------------|----------------|----------------|
| 0    | $1.4 \times 10^9$     | $1.06 \times 10^9$                | $2.6 \times 10^{-3}$ | 1.29           | $3.4 \times 10^{-4}$ | $1.84 \times 10^{-3}$ |
| 1.54 | $5.4 \times 10^7$     | $2.04 \times 10^7$                | 0.29             | 0.65           | 0.072          | 0.272          |
| 7.92 | $3.5 \times 10^3$     | --                                | 0.75             | 0.34           | 0.16           | 0.54           |

$^a$ First column is the elapsed time since the beginning of the SPH simulation. Previously, the initial stages of the explosion were calculated with a Lagrangian one-dimensional code.

calculations carried out in spherical symmetry, have provided some of the best models for SNIa in the past [1].

In this short paper we present the results of a calculation concerning the delayed detonation model carried out in three dimensions by using a SPH code. We describe the main features of the evolution of the model with more emphasis in the nucleosynthetical side.

2. Description of the model

The initial model is a white dwarf of 1.36 $M_\odot$ in hydrostatic equilibrium. The first stages of the explosion were followed by using a 1D hydrocode until the central density declined to $\rho_c = 4 \times 10^7$ g.cm$^{-3}$. From here on the model was mapped into a 3D distribution of 250,000 particles and its evolution followed with the SPH. In addition, the velocity field around the flame front was perturbed at the beginning in order to seed the hydrodynamical instabilities. This allows us to describe the large scale deformation of the flame in a self-consistent way although a lot of surface is lost owing to the limited resolution of the code.

To take into account these hidden lengthscales a subgrid model has to be set. We assume that the main effect of the smallest lengthscales is to increase the laminar velocity of the flame, $v_l$, until a first effective value $v_b > v_l$. Afterwards the final effective velocity $v_{\text{eff}} > v_b$ is directly computed from the hydrocode [2].

During the progression of the calculation the geometrical features of the flame front were tracked by calculating the main scaling parameters of the surface such as $l_{\min}$, $l_{\max}$ and flame fractal dimension $D$ by using the method described in [3]. As discussed in [2] the local evolution of $D$ can be used as a practical criteria to turn the deflagration into a detonation. In particular, we have allowed such transition in those regions of the flame with fractal dimension higher than 2.5 once flame mean density is $\langle \rho_{\text{flame}} \rangle \simeq 2 \times 10^7$ g.cm$^{-3}$.

The relevant features of the evolution of the model are summarized in Table 1. Basically the explosion proceeded in two phases. From $t=0$ s to $t=1.54$ s the combustion propagated subsonically as a deflagration. However, a considerable acceleration of the flame was seen because the effective flame velocity passed from $v_{\text{eff}} \simeq 8 \times 10^{-3}c_s$ for $t < 0.7$ s to $v_{\text{eff}} \simeq 0.14c_s$ at $t = 1.41$ s. At the end of this phase the total energy was already positive, although too low to represent a normal supernovae explosion. At $t=1.54$ s a detonation was artificially induced in those regions of the flame surface which had a large
Information about the nucleosynthetic yields is provided in Table 1 and figures 1, 2. The ejected amount of $^{56}\text{Ni}$ is enough to power the light curve of a typical Type Ia supernovae and the amount of silicon and other intermediate-mass elements is consistent with the spectrum near maximum light. A clear difference with respect 1D calculations is that the abundance distribution in velocity space show a lot of dispersion in comparison. The isotopic composition of the ejecta, calculated by postprocessing the dynamical model, is depicted in figure 2. Although we see a large production of vanadium there is not overproduction of problematic isotopes such as $^{54}\text{Fe}$ or $^{58}\text{Ni}$. This is a feature of multidimensional models where electron captures proceed, on average, at lower density owing to the buoyancy of high entropy ashes. The ejected amount of carbon and oxygen is somewhat high, being distributed in isolated pockets within the star but not close to the center. Our results suggest that the three-dimensional version of the delayed detonation model is also able to reproduce the main observational features of Type Ia Supernovae.

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REFERENCES

1. P. Höflich and A. Khokhlov, ApJ 457 (1996) 500.
2. D. García-Senz and E. Bravo, in Proceedings of the ESO/MPA/MPE workshop "From Twilight to Highlight: The Physics of Supernovae", (2003), in Press.
3. D. García-Senz, E. Bravo and N. Serichol, ApJSS 115 (1998) 119