Numerical Modeling of Type Ia Supernovae Explosions

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Abstract A

better knowledge of the mechanism behind the explosion of Type Ia supernovae (SNIa) is necessary to use these events in cosmological applications such as to study the large scale geometry of the universe or to find its equation of state. We review the present status of the subject with special emphasis in the so-called pulsating models which reproduce the gross features of the explosions without using free parameters.

1 Introduction

The understanding of the physical mechanism by which a white dwarf is disrupted by a thermonuclear explosion is relevant to many topics of modern astrophysics [1]. A satisfactory model of the explosion becomes crucial to better understand type Ia supernovae, which in turn have profound implications in cosmology or in studies of the dynamics of the interstellar medium among others. What we mean with the word satisfactory model is that the outcome of the simulation should be: a) as much compatible as possible with observations and, b) free of adjustable parameters. It can be said that nowadays it does not exist a model satisfying these two items. Calculations assuming spherical symmetry were able to reproduce many of the observational features of SNIa but using tunable parameters to achieve that. On the other hand multidimensional explosion models are more self-consistent from the physical point of view but, paradoxically, they lead to worse results than spherically symmetric models. Moreover the number of models ruled out either by observations or on physical grounds is still low as compared to the

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amount of proposed models. As multidimensional calculations have introduced new categories of potential models of the explosion the degeneracy is high. In figure 1 there is shown a classification of the zoo of proposed models for SNIa with indications concerning their viability in light of the current knowledge of the subject.

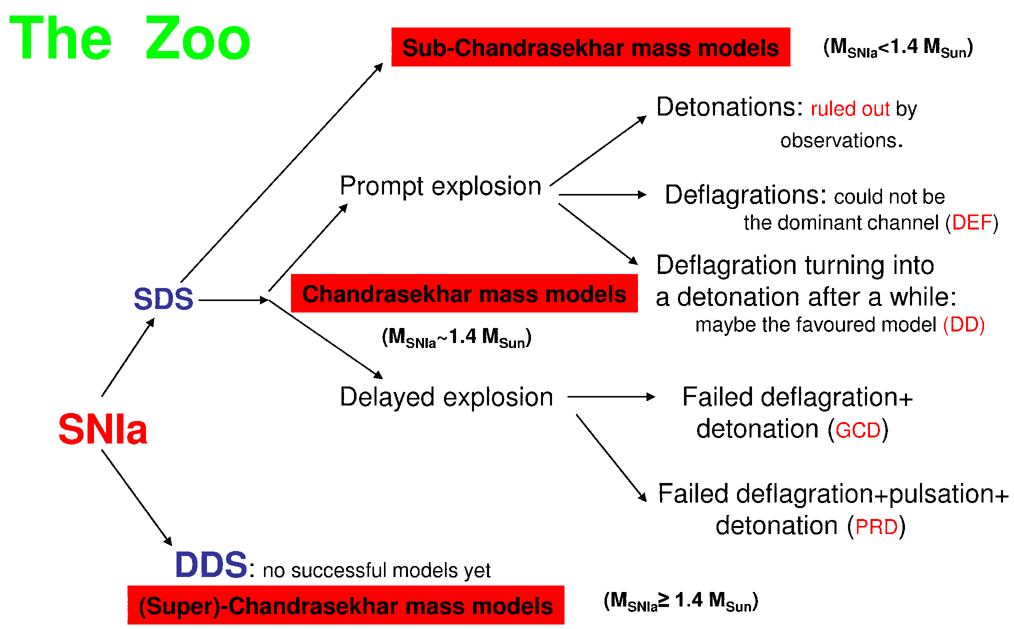

Fig. 1 Type Ia supernova models variety. The names SDS and DDS refers to the Single Degenerate Scenario (explosion of an accreting white dwarf) and Double Degenerate Scenario (merging of two white dwarves) respectively. Indications about the reliability of the model in light of the present knowledge of the subject is included. a) **Sub-Chandrasekhar mass models**: Edge lit ignition of a white dwarf with a $0.6-0.8\ M_\odot$ core composed of carbon and oxygen surrounded by a thick helium layer of $0.1-0.2\ M_\odot$. Not a favoured model because it leads to a composition inversion (nickel on top, IME underneath). b) **Chandrasekhar-mass models** (Ch-mass models): successful models would probably start as a deflagration and turn into a detonation after a while (prompt explosion scenario) or experience a pulsation followed by the detonation of the core, Pulsation Reverse Detonation (delayed explosion scenario, model PRD). When ignition takes place off-center in a single spark there is also the chance to detonate the core by the overpressure created by the collision of the nuclear ashes at the opposite side of the white dwarf, a mechanism called Gravitational Confined Detonation (delayed explosion scenario, model GCD), [2] c) **Super-Chandrasekhar mass models**: simulations of the merging process of two WD have not given any successful explosion insofar.

2 Method of calculation and models

The thermonuclear explosion of a white dwarf is driven by hydrodynamic instabilities that accelerates the propagation of a subsonic nuclear flame to almost sonic values. Therefore any attempt to simulate the explosion in a self-consistent manner must be undertaken in more than one dimension. We have adapted the smoothed-particle hydrodynamics technique to the peculiarities of the problem of the explosion of a white dwarf, [3]. The laminar nuclear flame is treated with a reaction-diffusion scheme that artificially enlarges the width of the flame to the resolution of the hydrocode. To save computing time an α-chain of 14 nuclei was used to obtain the release of nuclear energy. The detailed nucleosynthesis was calculated by postprocessing the outcome of the hydrodynamic evolution. Different simulations whithin the Ch-mass models paradigm (see figure 1) were carried out. The mass of the white dwarf was taken the same, 1.36 M$\odot$ in all simulations to make meaningful comparisons among the models. Three cases were considered, encompassing most of the variety found in figure 1 related to Ch-mass models: pure deflagrations (Def), combined deflagration-detonation (DefDet) and a delayed explosion driven by a pulsation (PRD). The main features of these models can be found in Table 1 which shows the final kinetic energy as well as the gross nucleosynthetic production. As we can see the amount of ^{56}Ni is a sensible function of the explosion model. In model DefDet the transition to supersonic detonation was artificially triggered in a single point at a density $\rho_t = 3.7\ 10^7$ g.cm^{-3} while the central density of the white dwarf still was relatively high, $\rho_c = 2.2\ 10^8$ g.cm^{-3}. Therefore in this particular model the detonation phase added a lot of nickel but only a moderate amount of intermediate-mass elements. As models Def and DefDet in Table 1 shared exactly the same initial conditions a direct comparison between rows 1 and 2 of Table 1 measures the effect of subsonic to supersonic transition in the effective flame velocity. On the whole model DefDet behaves much better than Def: it produces more iron-peak nuclei, more IME and larger kinetic energies while the amount of undesirable unburnt C-O material is low. In addition, the chemical distribution in velocity space is more stratified in model DefDet than in Def, [4] [5], in better agreement to observations. As a summary we can say that the artificial transition to a detonation regime cure many of the deficiencies shown by pure deflagrative models. Still a drawback of the model is the large amount of unburnt (and unseen) C-O, more than 0.4 M$_\odot$, some of it close to the center of the white dwarf and moving at low velocity.

2.0.1 The Pulsating Reverse Detonation model

In recent years a new branch of models called pulsational models have emerged (see figure 1). They are characterized by an initial deflagration phase which is unable to incinerate enough mass to unbind the star. The failed

Table 1 Results of the hydrodynamic simulations for three representative Chandrasekhar-mass models of Type Ia supernovae.

Model	Ignition	E_{kin} (10^{51} ergs)	^{56}Ni ($M_\odot$)	IME ($M_\odot$)	^{12}C-^{16}O ($M_\odot$)
Def	30 sparks	0.43	0.48	0.10	0.67
DefDet	30 sparks	0.81	0.68	0.11	0.45
PRD	6 sparks	1.05	0.7	0.33	0.21

prompt explosion is followed by a large expansion and further recontraction of most of the outer layers of the white dwarf. During the recontraction the infalling matter collides with the quasi-hydrostatic core made of unburnt carbon and oxygen. An accretion shock forms and confines the compressed fuel that ignites in degenerate conditions, giving rise to a detonation. Because the fuel is confined by the accretion shock it can no longer expand to quench the burning, that propagates all the way incinerating the core [6]. In the third row of Table 1 there are shown several interesting magnitudes relative to this model. The kinetic energy is larger than 10^{51} ergs and the amount of radioactive nickel is around 0.7 $M_\odot$ in good agreement to normal events in the SNIa sample. Encouraging features are also the large amount of intermediate-mass elements synthesized during the detonation phase and the lower amount of unburnt C-O ejected in the explosion. The distribution of species in both the normal space, depicted in figure 2, and in velocity space points to a higher stratification of elements than in others Ch-mass models, with nuclear-statistical equilibrium elements settled at the center of the configuration and IME and unburnt C-O residing in the outermost layers. However around a tenth of solar masses of iron produced during the initial deflagration are found scattered around the envelope. According to calculations of [7] such amount of Fe-peak elements could lead to a synthetic spectra redder than observed, a shortcoming which is shared by all hydrodynamic models starting from a deflagration. Therefore this class of models look promising because they do not involve any free parameter other than the initial distribution of igniting sparks and leads to similar or even better results than models relying in the deflagration-detonation transition paradigma.

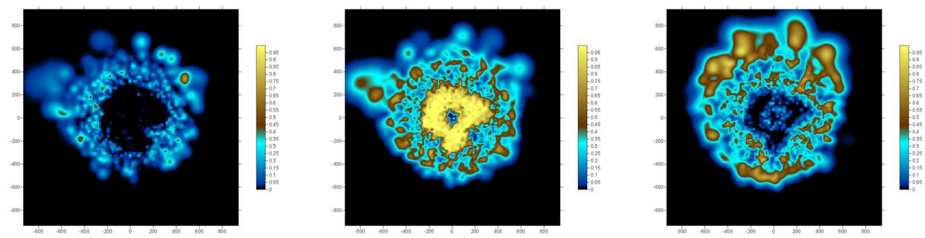

Fig. 2 Colour map of chemical mass fractions in a slice of model PRD showing the distribution of stable Fe-peak elements (left), radioactive nickel (center) and silicon (right).

3 Conclusions

Much theoretical work needs to be done to understand the explosion mechanism leading to Type Ia supernovae and to narrow the number of candidates to become standard model. Observations and numerical simulations may soon discriminate between Single and Double Degenerate scenarios. In the case of Ch-mass models a good knowledge of the evolution of the white dwarf prior explosion is necessary to break he degeneracy between prompt and delayed (pulsational) models.

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