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Single point off-center helium ignitions as origin of some Type Ia supernovae

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The explosion of a helium layer accreted on top of a white dwarf, leading to the subsequent explosion of the star (while the accreting dwarf is still below the Chandrasekhar mass limit) is an alternative model for some subluminous Type Ia supernovae explosions. In this communication we present two preliminary hydrodynamical simulations concerning these so-called Sub-Chandrasekhar mass models for Type Ia supernovae, calculated in two dimensions. In the first calculation we have assumed one single detonation travelling through the helium layer which, after a while, induces the detonation of the carbon layer at the antipodes of the original ignition point. In the second case we assumed the prompt detonation of the carbon just beneath the ignition point. A comparison between these two models is presented.

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1. Introduction

The currently encouraged model for Type Ia supernovae consists of a white dwarf in a binary system which grows to the Chandrasekhar mass by accretion from its companion, and subsequently explodes. Another possibility, which was for some time considered a plausible alternative, is the explosion of the accreting white dwarf as a result of a sequence of detonations while the system is still below the Chandrasekhar mass limit (basically, a helium detonation in the accreted layer, which ends up triggering the explosion of the underlying white dwarf). Nowadays, however, it is believed that these Sub-Chandrasekhar mass models do not constitute the dominant scenario for type Ia supernovae. However, Type Ia supernovae are far from being as homogeneous as it was thought. Today it seems clear that some subluminous Type Ia supernovae explosions do not originate from a massive white dwarf (Stritzinger et al 2006). A different sort of models which could explain this fraction of the explosions are the sub-Chandrasekhar mass models. In addition, this type of scenario could have interesting features from the nucleosynthetic point of view (Goriely et al 2002). In this sense, and taking into account that very few hydrodynamical simulations for this type of models have been performed so far (Woosley & Weaver 1994 in 1D, Livne & Arnett 1995 in 2D and García-Senz et al 1999 in 3D), it is interesting to revisit these explosions in the light of models with more resolution, and explore with more detail different particular mechanisms for the outcome of the explosion.

2. Numerical methods

We use a hydrodynamical gridless lagrangian method known as smoothed particle hydrodynamics (SPH). Although this technique is ideally suited to handle 3D simulations, sometimes it is better to use a 2D axisymmetrical approximation in order to be able study problems with the desired spatial resolution. Therefore, we have performed hydrodynamical calculations using our two-dimensional axisymmetrical SPH hydrocode (Relaño et al 2006), which allows us to achieve higher resolution than precedent multi-dimensional calculations even with a moderate number of particles.

The calculations also include an accurate equation of state, and a reduced nuclear network - a 14-nuclei energy-coupled alpha chain (Cabezon et al 2004) - which allows us to follow the nuclear energy release giving at the same time an approximate idea of the resulting nucleosynthesis. Nuclear statistical equilibrim is assumed for the highest temperatures and densities reached when the burning fronts cross the innermost region of the WD.

3. Hydrodynamical evolution

The standard scenario for this kind of model consists of a white dwarf with a thick layer of accreted material on top. Provided that conditions for helium ignition are reached, a detonation will develop, burning the accreted layer and eventually causing the carbon-oxygen core to ignite too. However, differences may appear depending on the way the helium detonation manages to trigger the detonation of carbon: either after having propagated along the accreted layer or by direct prompt mechanism (which requires the helium detonation to start not exactly at the interface, but at some height). The shortcoming of the second mechanism is that in some cases the prompt ignition might not be strong enough to develop a C-detonation (see García-Senz et al 1999).

We present two models (with the same initial parameters, shown in table 1). In the first case (MODEL 1), we explore the standard mechanism of single point ignition just at the base of the accreted layer. In the second case (MODEL 2), we study the second mechanism commented above, consisting of the prompt C-detonation induced by the He-ignition above the interface.

TABLE 1: Parameters of the initial models: mass (solar masses), composition (mass fraction) and external radius ($\cdot 10^8$cm) of the WD core and the He layer respectively; density ($\cdot 10^7$ gcm^{-3}) and temperature ($\cdot 10^6$ K) of the center and interface respectively. 34875 particles were used in the simulation.

M_c	X_C	X_O	R_c	M_{He}	X_{He}	R_{He}	ρ_c	T_c	ρ_b	T_b
0.7	0.5	0.5	3.97	0.2	1	6.28	1.72	5	0.196	5

3.1.1 Model 1: Single point He-ignition

The evolution of this model can be summarized as follows (see figure 1): Helium is ignited at one point at the interface. In our case, this is done by increasing (to 10^9 K) artificially the temperature of a very small area. The helium detonation develops, and propagates across the accreted layer towards the opposite pole, where the detonation front converges approximately 1.1 s after the ignition. The hot spot resulting from this convergence is enough to trigger the detonation of carbon just below the interface, which in turn propagates causing the explosion of the underlying white dwarf core.

The results obtained, as seen in table 2, are in good agreement with other previous simulations (Woosley & Weaver 1994, Livne & Arnett 1995, García-Senz et al 1999).

It may seem, however, that the convergence conditions are somehow favoured by the axisymmetrical approximation. For example, we know that for other SNIa mechanisms which also imply convergence of burning fronts leading to a second detonation (Plewa et al 2004) it has been found in some cases that the convergence is probably not strong enough to trigger the second detonation when the simulations are performed in 3D (Röpke et al 2006). However, in these cases the subsonic propagation of the burning front takes place in an already perturbed and expanding star. In consequence the geometry of the converging burning fronts becomes complex due to instabilities, making the differences between 2D and 3D approximations quite relevant. In contrast, in our case we are dealing with a detonation, so that the explosion progresses much faster, through an unperturbed and unexpanded star. Moreover, the geometry of the burning front in a detonation is much simpler and there are not so many differences between 2D and 3D approximations. Therefore, we don't expect significant differences in the final ability of the focusing mechanism to trigger the second detonation if the simulations of these models were revised in a 3D calculation with enough resolution.

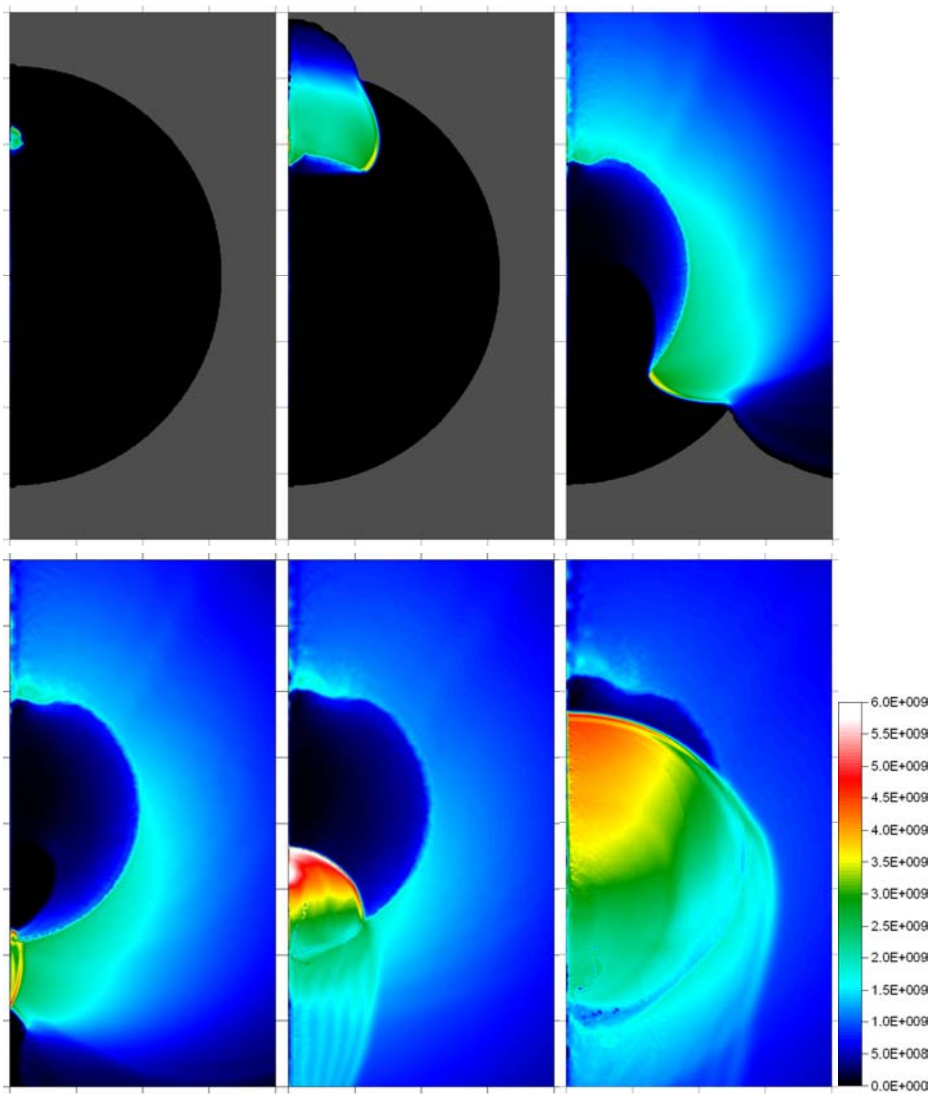

FIG 1: Model 1. Temperature plot at different times (left to right, up to down): t=0.06, 0.28, 0.89, 1.15, 1.38 and 1.71 s. Initial location of WD is plotted in black. Each box measures $8 \cdot 10^8$ *X* $16 \cdot 10^8$ *cm. Temperature scale is shown at right*

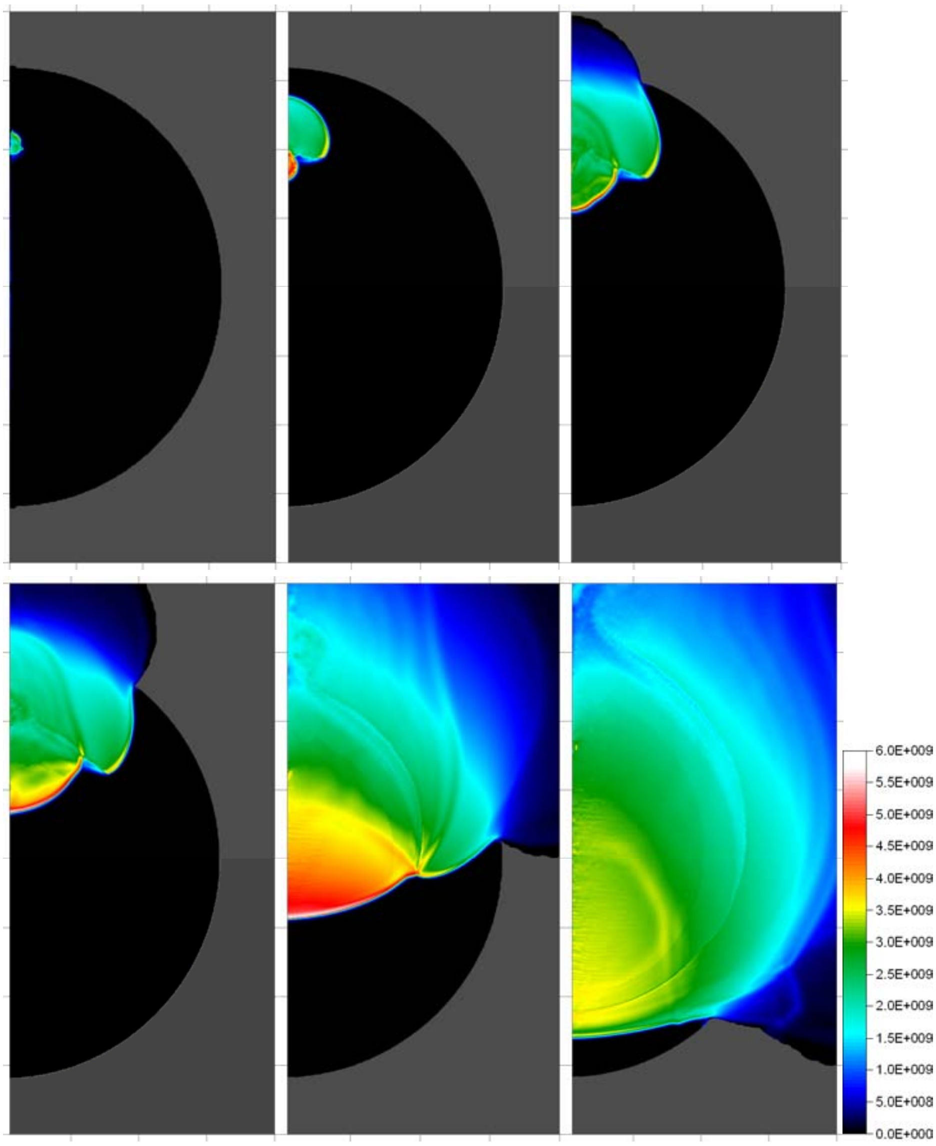

FIG 2: Same as fig 1, for Model 2: t=0.06, 0.16, 0.28, 0.37, 0.64 and 0.87 s

3.1.2 Model 2: Single point He-ignition followed by underlying C-detonation

As commented before, we also want to explore an interesting variation of the standard scenario (see figure 2) which arises from the fact that helium may detonate at some height above the interface between carbon and helium layers, triggering in some cases a prompt detonation of the carbon underneath. The evolution of the model is as follows: Helium is ignited above the interface, as done in Model 1. In this simulation it was not possible to get the detonation of carbon in a self-consistent way owing to the limited resolution. Therefore, we induced C-ignition by further increasing the temperature of the small area of carbon underneath the accreted layer, which had been already compressed as a result of the propagation of the helium detonation taking place above. As a result, carbon ignited just after the helium detonation reached the CO core, and a second detonation developed. Therefore, the white dwarf is in fact burned by the simultaneous propagation of two burning fronts (carbon in the WD core and helium in the accreted layer). At some point, the C-burning front advances the other, leaving a single burning front which ends up blowing up the star.

4. Conclusions

The final energies and nucleosynthesis yields for Models 1 and 2 are shown in Table 2. On the whole, our results match well with other previously calculated models. It is interesting to remark that, despite progressing asymmetrically, both explosions end up with a quite spherical velocity field (see figure 3), except in the small area with higher velocities observed at the bottom of the convergence zone in the case of Model 1. Therefore, no distinctive spectral features are expected from this point of view.

The energetics and yields of both models are similar, thus, if occurred, observational counterparts of both mechanisms would also display similar characteristics. Model 2, however, left less unburnt C and O, and generated slightly more nickel and intermediate mass elements. A more detailed nucleosynthetic comparison will need the postprocessing of the data using a much larger nuclear network.

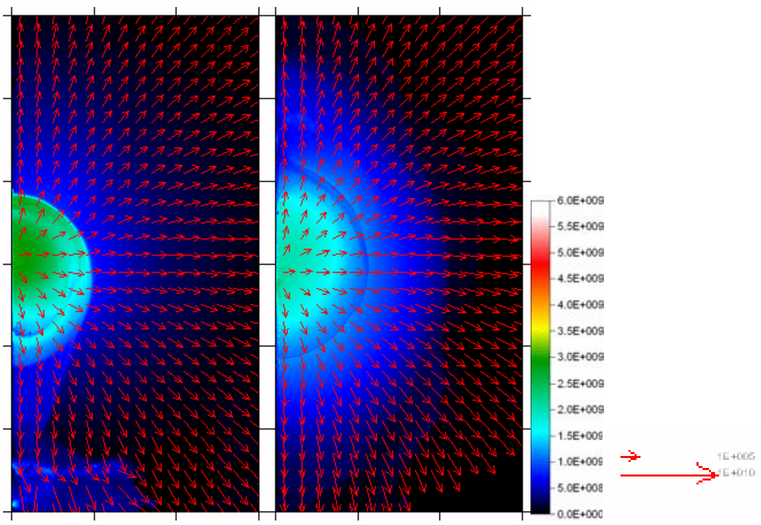

FIG 3: Temperature and velocity after the explosion has progressed through the star, for model 1 (left, at 1.98s) and model 2 (right, at 1.54s). Each box measures $3 \cdot 10^9$x $6 \cdot 10^9$ cm. Temperature (K) and reference velocity vectors(cm s^{-1}) are shown at right

TABLE 2: Final kinetic energy (erg) and ejected masses (in solar mass) (in parentheses, results of model 4 by Livne & Arnett 1995 for the most abundant nuclei)

	Model 1 (this work)	Model 2 (this work)	*Livne & Arnett 1995*
K_∞ (erg)	$1.15{\cdot}10^{51}$	$9.38{\cdot}10^{50}$	*($1.18{\cdot}10^{51}$)*
^{4}He	$5.68{\cdot}10^{-2}$	$5.42{\cdot}10^{-2}$	*($6.58{\cdot}10^{-2}$)*
^{12}C	$1.26{\cdot}10^{-3}$	$7.91{\cdot}10^{-4}$	
^{16}O	$3.29{\cdot}10^{-2}$	$2.97{\cdot}10^{-3}$	
^{20}Ne	$1.18{\cdot}10^{-4}$	$1.63{\cdot}10^{-6}$	
^{24}Mg	$1.29{\cdot}10^{-2}$	$9.92{\cdot}10^{-4}$	
^{28}Si	$9.93{\cdot}10^{-2}$	$9.96{\cdot}10^{-2}$	*($1.35{\cdot}10^{-1}$)*
^{32}S	$4.74{\cdot}10^{-2}$	$6.97{\cdot}10^{-2}$	*($6.24{\cdot}10^{-2}$)*
^{36}Ar	$1.39{\cdot}10^{-2}$	$2.08{\cdot}10^{-2}$	
^{40}Ca	$1.20{\cdot}10^{-2}$	$2.21{\cdot}10^{-2}$	
^{44}Ti	$3.32{\cdot}10^{-2}$	$2.82{\cdot}10^{-2}$	
^{48}Cr	$5.05{\cdot}10^{-2}$	$4.01{\cdot}10^{-2}$	
^{52}Fe	$4.97{\cdot}10^{-2}$	$4.13{\cdot}10^{-2}$	
^{56}Ni	0.479	0.511	*(0.466)*
^{60}Zn	$1.22{\cdot}10^{-3}$	$1.81{\cdot}10^{-2}$	

References

[1] M.Stritzinger et al ,2006, *A&A,* **450,** 241-251

[2] S.Goriely, J. José, M. Hernanz, M. Rayet, M. Arnould, 2002, *A&A,* **383,** L27-L30

[3] R. M.Cabezón , D. García-Senz, E. Bravo, 2004, *ApJ Suppl.* **151**, 345

[4] S.E.Woosley, T.A.Weaver, 1994, *ApJ*, **423**, 371

[5] E.Livne, D.Arnett ,1995, *ApJ*, **452**, 62

[6] D.García-Senz, E.Bravo, S.E.Woosley, 1999, *Astron & Astrophys*. **349**,177

[7] A.Relaño, D.García-Senz, E.Bravo, 2006 in proceedings of *29th European Conference on Laser Interaction with Matter*. In press.

[8] T.Plewa,A.C.Calder,D.Q.Lamb,2004, *ApJ*, **612**, L37

[9] F.K.Röpke,S.E.Woosley,W.Hillebrandt ,2006, [astro-ph/0609088]