Type Ia supernovae: differences due to progenitors within delayed detonation explosions

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At this moment, the use of SNIa for cosmology lies on the assumption that the SNe at high redshifts are equal to the local ones. However, some observations indicate a correlation between light curve (LC) properties and the morphological type of the host galaxy. This could indicate a dependence with the age (mass/composition) of the underlying population. In this work we have chosen the delayed detonation explosion model in CO Chandrasekhar mass WDs to explore the dependence of the SN Ia LC and nucleosynthesis with the initial mass and composition of the WD progenitor. The progenitor influences the final SNIa via the mass of the CO core formed and the C/O ratio within it (1D explosion models). We have followed the evolution of stars with masses between 1.5 and 8 M\textsubscript{☉} and metallicity, Z=0, 10\textsuperscript{-5}, 0.001 and 0.02, from the pre-main sequence to the TP-AGB phase. The differences obtained in the final C/O ratio within the explosive WD are smaller than 22%. This results in a difference at maximum of 0.03 mag and of 0.1 mag when the brightness-decline relation is applied.

1. INTRODUCTION

The increasing quality and quantity of Type Ia observations, indicate that they are not such an homogeneous class of events as it was previously thought. Moreover, several interesting correlations between observed properties are obtained (see Leibundgut this volume). These correlations could give hints about the underlying explosion mechanisms and progenitors. To understand the event and the reasons of the differences is a prerequisite to use SNIa for cosmology (at least, for us). The observations of SNIa at high redshifts have lead to the conclusion that the expansion of the Universe is accelerating \cite{13,12}. Together with the Cosmic Microwave Background observations, the mass density parameter and the cosmological constant have been estimated, \Omega_{m} \sim 0.3 and \Omega_{\Lambda} \sim 0.7.

There are some observational evidences that indicate a relation of SNIa with the morphological type of the host galaxy \cite{14,15}. In ellipticals, as compare with spirals, less events are found, they are more homogeneous (in maximum brightness and decline rate of the light curve) and in general, they are dimmer. This could mean a correlation with the progenitor population and consequently evolution in time.
Different evolutionary paths could lead to an explosive degenerate WD and several explosion mechanisms could blow up this WD (see Woosley this volume). Probably each of them contribute *up to some degree* to the SNIa population. In this work we have decided to fix both, the scenario and explosion mechanism and just change the initial mass and composition of the WD progenitor.

We have chosen the delayed detonation (1D) explosion of a Chandrasekhar mass WD because this scenario accounts for most of the observational constraints. The key parameter is the transition density, $\rho_{tr}$, the density at which the deflagration turns into a detonation. Varying $\rho_{tr}$ the optical and IR light curves and spectra evolution of normal and subluminous SNIa are reproduced. Subluminous SNIa are found to be redder, as observed. Moreover, the brightness-decline relation (LCs of brighter events decline slower) used in all the cosmological applications, is obtained \[8,9\]. Other correlations, like the CaII H+K & Si minimum velocities and mean Ni velocity with brightness are as well reproduced.

2. MODELS

We have studied the evolution of intermediate mass stars, with masses in the range, $1.5 \leq M/ M_\odot \leq 8$, and initial composition, $Z=0$, $10^{-5}$, $0.001$ ($Y=0.23$) and $Z=0.02$ ($Y=0.285$). The evolution is followed from the pre-main sequence to the thermal pulse AGB phase, including several pulses. The mass and chemical structure of the obtained degenerate CO core depends on the initial mass and composition. It is assumed that the *future* CO white dwarf has the mass and chemical structure of this CO core. Accretion of H on the WD is performed at high rates up to the central C ignition at $\rho_c=2.0 \times 10^9$ g/cm$^3$.

At that time, the mass of the CO WD is close to $1.37 M_\odot$. Note that the final amount of C and O in the accreted matter is nearly equal ($C/O \approx 1$).

For the set with $Z=0.001$, delayed detonation explosions, detailed post-processing and light curves are computed. The description of the velocity of the deflagration front is based on 3D simulations \[8\]. Explosions with several transition densities are performed, $\rho_{tr}$: 1.5, 1.8, 2.0, 2.3, 2.5 and 2.7 $10^7$ g/cm$^3$.

2.1. Numerical methods

The 1D hydrostatic evolutionary code FRANEC is used for the stellar evolution \[3\]. An extended nuclear network is employed for both, the H burning (269 reactions) and the He burning (147 reactions). A time dependent mixing is adopted and the physical and chemical evolutions are coupled.

The explosions and light curves are computed with a 1D radiation-hydrodynamic code including nuclear networks \[4\]. The hydrodynamics equations are solved explicitly by the piecewise parabolic method \[4\], the frequency averaged radiation transport equations are solved implicitly via moment equations and expansion opacities and a detailed equation of state are included. The nuclear burning (post-processing) includes 218 to 606 isotopes \[14\]. The same code is used for the subsequent expansion and bolometric and monochromatic light curves calculations. In this phase nuclear burning is neglected and gamma ray transport is taken into account using a Monte Carlo scheme. The scattering, photon redistribution and thermalization terms used in the light curve opacity calculation are calibrated with NLTE calculations \[8\].
3. RESULTS

We do not expect variations beyond a few tenths of a magnitude by changing the initial mass and composition of the progenitor. Previous studies were based on parameterized C/O ratios \([10]\) or a progenitor with \(7M_\odot\) \([11]\) indicating a change of 0.3\(m\) for a 40 \% change in the C/O or 0.1\(m\) for a change in the metallicity from 0.02 to 0.001, respectively. In our calculations, the maximum difference obtained in C/O is \(\leq 22\%\). Note that the amount of accreted matter (bigger for the smaller cores) acts as a uniform factor. This means that in the case of pure mergers (two cores) the final difference would be slightly bigger.

C/O is more sensitive to the initial mass than to the initial composition. For \(Z=0.001\), we have followed the explosion and we have computed the LCs. Varying the initial mass from 3 to 5 \(M_\odot\), changes C/O from 0.78 to 0.73 \(M_\odot\), Ni mass from 0.51 to 0.48 \(M_\odot\) (6\% !) and kinetic energy from 1.18 to 1.17 \(10^{51}\) erg (for \(\rho_{tr} = 2.0 \times 10^7 \text{ g/cm}^3\)). In Figure 1, we show the B and V light curves for the 3\(M_\odot\) and 5\(M_\odot\) models.

In summary, \(M_{MAX}\) is found to change from 0 to 0.03 mag when the initial mass and composition of the WD progenitor vary. The application of the brightness-decline relation results in \(\Delta M_{MAX} \leq 0.1\) mag.

Greater differences in the LCs are likely produce by the burning conditions, as \(\rho_{tr}\) \([8]\). For example, for the 3\(M_\odot\), \(Z=0.001\) models, a change in \(\rho_{tr}\) from 1.5 to 2.7 \(10^7\) g/cm\(^3\) leads to a change in the Ni mass from 0.17 to 0.72 \(M_\odot\). We like to stress that we treat progenitors and burning conditions completely uncoupled and this is probably not the case. In 3D calculations the composition gradients would influence the velocity of the front. Other effects like mixing and rising blobs could be relevant. On the other hand, different
scenarios, rotation and crystallization could strongly modified pre-explosive conditions.

Other important constraints obtained from the observations are the velocity range in which the different elements are found and the isotopic abundances as compare with the solar abundances. For the same transition density, differences in the global kinetic energy as function of mass and composition of the progenitor are small and the velocity range for the different elements does not vary in more than few hundreds km/s. $^{68}$Zn, $^{48}$V and $^4$He change by more than a factor of 5 when initial mass is changed. While a change greater than a factor 2 is found for $^{14}$N, $^{17}$O, $^{18}$O, $^{19}$F, $^{20}$Ne, $^{21}$Ne, $^{23}$Na, $^{25}$Mg, $^{26}$Mg, $^{42}$Ca, $^{43}$Ca, $^{46}$Ti, $^{60}$Ni, $^{61}$Ni, $^{64}$Zn, $^{66}$Zn, $^{67}$Zn, $^{63}$Cu and $^{65}$Cu.

As a final remark, we like to stress that the final CO core mass and C/O ratio depend on the treatment of turbulent convection and on the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate \[5\] (see Imbriani et al., this volume). Changing this reaction rate from the high to the low rate given by \[2\], remarkable differences in C/O and consequently in Ni mass and kinetic energy are obtained. For the 3 M$_\odot$, Z=0.001 C/O changes from 0.74 to 1.53; Ni mass from 0.50 to 0.63 M$_\odot$ and the kinetic energy from 1.15 to 1.37 $10^{51}$ erg ($\rho_{tr}$=2.0 $10^7$ g/cm$^3$).

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