Type Ia Supernova Diversity from 3-dimensional Models

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Abstract. We present results from a systematic study of the effects of initial parameters on three-dimensional thermonuclear supernova models.

One major challenge to numerical models of thermonuclear supernova explosions is to reproduce the diversity observed among Type Ia supernovae (SNe Ia). With the rapid advancement of three-dimensional models over the past years, systematic studies have become possible testing the effect of changes in the initial parameters of simulations on the explosion process. The ultimate goal is, of course, to explain the correlation between the peak luminosity and the light curve shape used to calibrate cosmological distance measurements.

We present the first systematic study on this issue based on three-dimensional deflagration models. Here, a Chandrasekhar-mass white dwarf (WD) star ignites nuclear reactions in the center which finally form a flame. In the deflagration model this flame burns outward with a subsonic velocity, which quickly becomes dominated by the effects of interaction with a turbulent velocity field. Caused by buoyancy (Rayleigh-Taylor) and secondary shear (Kelvin-Helmholtz) instabilities inherent in the scenario, turbulence wrinkles the surface of the flame effectively boosting its propagation speed. For a comprehensive review of SN Ia models we refer to Hillebrandt & Niemeyer (2000).

For the three-dimensional simulations of the explosion process we apply the scheme developed by Reinecke et al. (1999) and Reinecke et al. (2002). The final composition of the ejecta in our models is obtained via a nucleosynthetic post-processing procedure on the basis of tracer particles advected in the explosion simulation (for details see Travaglio et al. 2004).

There is a number of possible parameters of the deflagration model that have the potential to explain the SN Ia diversity. The progenitor’s carbon-to-oxygen (C/O) ratio, its metallicity, and the central density at ignition are commonly suggested, but other effects like rotation and flame ignition could also play a role. In our survey we concentrate on the former three parameters. These are varied independently. Of course, this is an oversimplification since in reality they are interrelated by stellar evolution of the progenitor WD star. Nevertheless, in this first study our goal is to infer the trends of effects of each individual parameter on the explosion.

In the setup of the explosion models we apply three different carbon mass fractions of the WD material, $X(\text{^{12}C}) = 0.30, 0.46, 0.62$, and three different central densities at ignition, $\rho_c = [1.0, 2.6, 4.2] \times 10^9 \text{g cm}^{-3}$. Three different metallicities of the WD, $Z = [0.3, 1.0, 3.0] Z_\odot$, are represented by the $\text{^{22}Ne}$ mass fractions (see Timmes et al. 2003). This defines the 27 models of our survey.
A change in the carbon mass fraction does not alter the flame evolution in our models significantly. This is due to a larger amount of $\alpha$-particles in the nuclear statistical equilibrium in the ashes for carbon-rich fuel, which act as an energy buffer (see Röpke & Hillebrandt 2004). This effect delays the flame propagation at explosion stages where iron group nuclei are synthesized and therefore the changes in the resulting $^{56}$Ni masses are little. Since the radioactive decay of this isotope powers the lightcurve, according to Arnett’s rule the peak luminosity is nearly unaffected by the C/O ratio of the progenitor. However, in the later evolution the carbon-rich fuel models release more energy (amounting to a $\sim$12\% variation) which possibly affects the light curve shape.

A lower central density leads to a lower energy release and delays the evolution of the model. The reason for this effect is the reduced gravitational acceleration experienced the flame front which leads to a slower formation of the nonlinear Rayleigh-Taylor instabilities. We find a $\sim$40\% variation in the energy releases of our models. The amount of produced $^{56}$Ni is largest for the intermediate central density. At lower densities the delayed flame propagation leads to a decreased production of iron group elements. In models with higher central densities electron captures favor neutron rich nuclei instead of $^{56}$Ni. This effect is accounted for in the nucleosynthetic postprocessing but not consistently modeled in the explosion simulation. Thus the results are preliminary for the highest central density value. The change in the produced $^{56}$Ni is $\sim$10\%. A variation in the central density prior to ignition is likely to affect both the peak luminosity and the light curve shape.

Changing the metallicity (i.e. the $^{22}$Ne mass fraction) we find a $\sim$20\% change in the resulting $^{56}$Ni masses and hence the peak luminosity of the event consistent with the analytic prediction of Timmes et al. (2003). The explosion dynamics, however, is not affected by the metallicity and thus the light curve shape will not differ significantly.

Concluding we note that the variations in the peak luminosities obtained by changing the initial parameters can partially account for of the observed scatter in SNe Ia. However, we could not identify a single parameter that reproduces the empirically established peak luminosity–light curve shape relation. A combination of initial parameters chosen according to stellar evolution could possibly explain such a relation, but initial parameters ignored in this first survey have to be explored as well in future studies. The final decision on the effect of the initial parameters on the light curve shape can only be made on the basis of synthetic light curve calculations.

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