Evaluating Systematic Dependencies of Type Ia Supernovae: The Influence of Detonation to Deflagration Transition Density

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The most widely accepted setting for a Type Ia supernova explosion is a thermonuclear runaway occurring in a C/O white dwarf that has gained mass from a stellar companion. In this "single degenerate" scenario, the peak brightness of the event is determined by the amount of radioactive $^{56}$Ni synthesized in the explosion that powers the light curve. Accordingly, modeling efforts investigate the $^{56}$Ni yield and distribution from an event, and the models that best agree with observations begin with a subsonic deflagration born in the interior of the white dwarf that transitions to a supernova detonation wave that rapidly incinerates the star. Within this picture, the conditions under which the transition occurs are largely uncertain and within the models remains an essentially free parameter. We choose to parameterize the deflagration-to-detonation transition in terms of the local density because the characteristics of the burning wave depend sensitively on density. We present results from an investigation of the role of transition density in the deflagration-to-detonation (DDT) paradigm (Khokhlov 1991). We apply a theoretical framework for statistically studying systematic effects (Townsley et al. 2009) using two-dimensional simulations performed with a modified version of the Flash code (Fryxell et al. 2000, Calder et al. 2002, 2007, Townsley et al. 2007). The simulations begin with a central deflagration having randomized perturbations, and the transition to a detonation occurs when any rising plumes reach a specified density. We find a quadratic dependence of Fe-group yield on the log of DDT density. Assuming a dependence of DDT density on metallicity, we find the $^{56}$Ni yield decreases 0.09 M$_\odot$ for a 1 Z$_\odot$ increase in metallicity.

III. Results

We find our more realistic progenitor model produces less $^{56}$Ni than a uniform 50/46/2 $^{12}$C-$^{14}$N-$^{56}$Ni progenitor. Carbon detonation produces a slower flame, and as a result the white dwarf has more time to expand before the time the flame reaches the transition density. The detonation then synthesizes less $^{56}$Ni, creating a dimmer supernova.

Results from our investigation given in Figures 3 and 4 show a clear dependence on DDT density, which may in turn depend on metallicity. We find that the $^{56}$Ni yield depends quadratically on the log of DDT density because of two effects: plume rise and rate of expansion. As the star expands, contours of the DDT densities fall inward and spread apart from one another as the power-law density profile becomes flatter. Therefore, the time a rising plume must spend propagating increases linearly with decreasing DDT density. The extra time feeds back into allowing more expansion, letting the star expand quadratically with DDT density. The transition density determines the duration for the deflagration phase, which controls the amount of expansion and thus the average density of the star.

We extrapolate a dependence of DDT density on $^{56}$Ni content from Chamulak et al. (2007) and investigate the relationship between the DDT density and metallicity (the $^{56}$Ni yield). We evaluate this function for the fiducial DDT density of $10^{4}$ g cm$^{-2}$ in Figure 5. The first derivative evaluated at $Z_\odot$ is -0.09 M$_\odot$, about twice that found by Timmes, Brown, and Truran (2003).

Fig. 1: Images from a thermonuclear supernova simulation. The left panel shows the development of fluid instabilities during the deflagration phase, the center panel shows the configuration just prior to the first detonation, and the right panel shows the configuration with two distinct detonations consuming the star. Shown are the reaction progress variables representing deflagration depletion (red), NSQE (green), and NSE (black). Contours of the transition density $\rho = 1.26 \times 10^{10}$ cm$^{-3}$ (red) and initial $X_\text{c,N}$ = 0.49 (blue) are also shown. The latter indicates the boundary between the neutralized core and the surface layers. Note that the scale on the rightmost panel is twice that of the first two.

Fig. 2: Plot (right) showing the thermal, density, and compositional profiles (red lines) of the $^{12}$C-$^{14}$N-$^{56}$Ni white dwarf progenitor star used for this study just prior to the birth of the flame. The dashed lines show the progenitor composition prior to carbon burning with a 30/48 $^{12}$C-$^{14}$N core and a 50/48 $^{12}$C-$^{14}$O outer layer (Dominguez, Hoff% & Straniero 2001). Carbon burning neutralizes the core and expands the convection zone pulling in $^{12}$C from the outer layer (Piro & Bloemen 2008, Chamulak et al. 2008). We parameterize the neutralization in the progenitor using $^{56}$Ni.

II. Methodology

We use a progenitor white dwarf with a carbon-depleted, neutralized inner core and an isothermal outer layer with compositions consistent with a white dwarf that has undergone simmering prior to the birth of the flame. We initialize the flame with a match-head of burned material perturbed using high-order spherical harmonic l-modes with random coefficients. This method creates unique realizations of representative supernovae and allows statistical analysis of an ensemble of simulations. We use an advection-diffusion-reaction scheme within the Flash code (Fryxell et al. 2000, Calder et al. 2002) to quickly propagate a thickened flame representing the carbon deflagration with subsequent stages of nuclear burning. The scheme takes as input a tabulated flame speed (Chamulak, Brown, & Timmes 2007) and compensates for buoyancy effects of the Rayleigh-Taylor unstable flame front. The consistent with a time-scales for the burning are taken from prior calculations and the detonation is propagated by thermally activated reactions (Calder et al. 2007, Townsley, et al. 2007, 2009).

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