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The Influence of Deflagration to Detonation Transition Density on Type Ia Supernovae

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A widely accepted setting for type Ia supernovae (SNeIa) is a thermonuclear runaway occurring in a C/O white dwarf (WD) that gained mass from a companion. The peak brightness is determined by the mass of radioactive ^{56}Ni synthesized that powers the light curve. Models that best agree with observations begin with a subsonic deflagration that transitions to a supersonic detonation that rapidly incinerates the star. The condition under which the deflagration-to-detonation transition (DDT) occurs is largely uncertain and remains essentially a free parameter. We parameterize the DDT in terms of the local density because the characteristics of the burning wave depend most sensitively on density. We present a study of the role of transition density in the DDT paradigm [1]. We apply a theoretical framework for statistically studying systematic effects using two-dimensional simulations that begin with a central deflagration having randomized perturbations. The DDT 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 the DDT density depends on metallicity, we find the ^{56}Ni yield decreases $0.067 \pm 0.004 M_{\odot}$ for a 1 $Z_{\odot}$ increase in metallicity.

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1. Measuring the Outcome

We model type Ia supernovae (SNeIa) as a thermonuclear runaway occurring in a C/O white dwarf (WD) that gained mass from a companion. The burning is tracked with three progress variables representing the consumption of ^{12}C, the evolution on to Si-group material in nuclear statistical quasi-equilibrium (NSQE), and the evolution on to Fe-group material in nuclear statistical equilibrium (NSE). The NSE mass is calculated by density-weighted integration of the (third) progress variable representing the evolution of NSQE to NSE material. Tracking the state of the material including the electron fraction allows estimation of how much NSE material is in the form of stable nuclides (assumed to be an admixture of ^{54}Fe and ^{58}Ni) and how much is in the form of ^{56}Ni [2]. The ^{56}Ni mass allows assessment of the relative brightness of a simulated event.

2. Methodology

We use a progenitor white dwarf with a carbon-depleted, neutronized isentropic core and an isothermal outer layer with compositions consistent with a white dwarf that has undergone simmering prior to the birth of the flame (see Figure 1). 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 [3, 4, 5] to quietly propagate a thickened flame representing the carbon deflagration with subsequent stages of nuclear burning. The scheme takes as input a tabulated flame speed [6] and compensates for buoyancy effects of

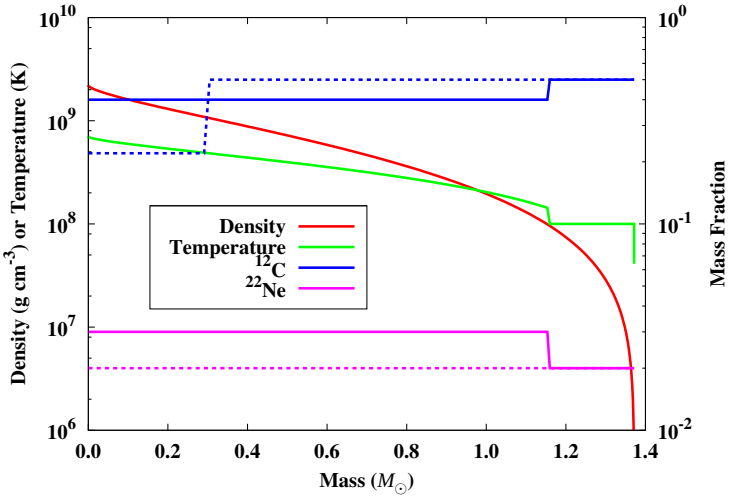

Figure 1: The thermal, density, and compositional profiles (solid lines) of the ^{12}C-^{16}O-^{22}Ne white dwarf progenitor. The dashed lines show the progenitor composition prior to carbon simmering with a 30/68 ^{12}C-^{16}O core and a 50/48 ^{12}C-^{16}O outer layer [9]. Carbon simmering neutronizes the core and expands the convection zone pulling in ^{12}C from the outer layer [10, 11]. We parameterize the neutronization in the progenitor using ^{22}Ne. From Jackson, et al. (2010) [14]. Reproduced by permission of the AAS.

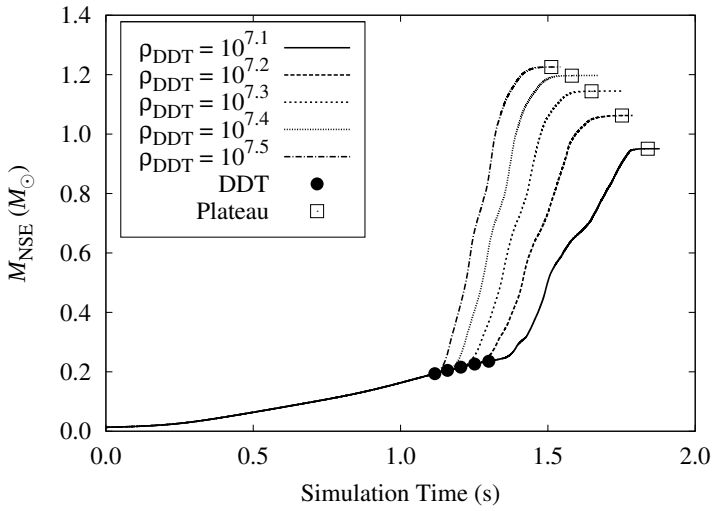

Figure 2: Plot showing the evolution of $M_{\rm NSE}$ for a particular realization for each DDT density highlighting the DDT time (closed circles) and the MNSE convergence time (open squares). The DDT time is the time any rising plume first reaches the DDT density. The $M_{\rm NSE}$ convergence time is the time the first derivative drops below $0.01 M_\odot/s$.

the Rayleigh-Taylor unstable flame front. The energetics and time-scales for the burning are taken from prior calculations and the detonation is propagated by thermally activated reactions [7, 8, 2].

3. Results

We find our carbon-depleted progenitor model produces less ^{56}Ni than a uniform 50/48/2 ^{12}C-^{16}O-^{22}Ne progenitor. Carbon depletion produces a slower flame, and the white dwarf has expands more by the time the flame reaches the transition density. The detonation then synthesizes less ^{56}Ni, creating a dimmer supernova. A statistical study is being performed to confirm this result.

Our results in Figures 2 and 3 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-rate and rate of expansion. As the star expands, material with density $> 2 \times 10^7$ g cm^{-3}, which provides an estimate of the NSE yield, falls off quadratically with simulation time, and faster expansion leads to a sharper decline of material at high density. The plume rise-rate determines the "sampling rate" of the estimated NSE yield via the mass at high density. Faster plumes result in frequent sampling, leading to a shallower trend with DDT density.

We extrapolate a dependence of DDT density on ^{22}Ne content from [6] and construct a function describing the ^{56}Ni yield that depends on DDT density and metallicity (through the ^{22}Ne). We evaluate this function for the fiducial DDT density 6.76×10^6 g cm^{-3} in Figure 4. The first derivative evaluated at $Z_\odot$ is $-0.067 \pm 0.004 M_\odot$, slightly steeper than Timmes, Brown, and Truran (2003) [12]. Complete details of this study may be found in Jackson, et al. (2010) [14].

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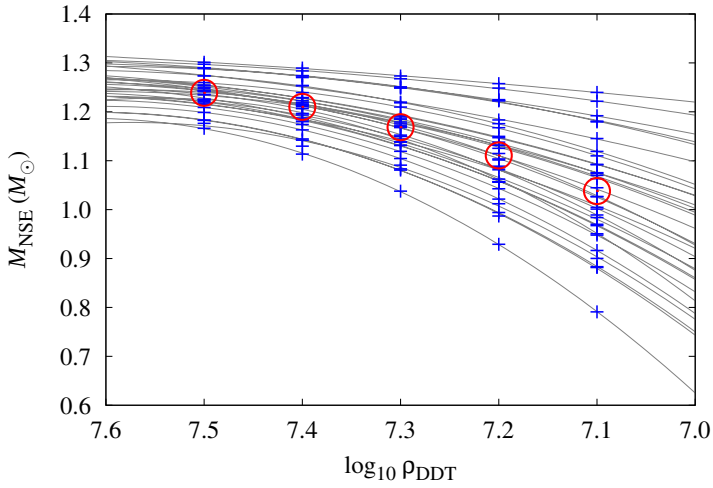

Figure 3: Quadratic fits to NSE yield for each realization at each DDT density (blue crosses) and the average NSE yield at each DDT density (red circles). The error bars on the average NSE yield represents the standard deviation of the sample. The curvature correlates well with the overall yield evaluated at any DDT density, with higher yielding realizations tending to have a flatter dependency on DDT density. From Jackson, et al. (2010) [14]. Reproduced by permission of the AAS.

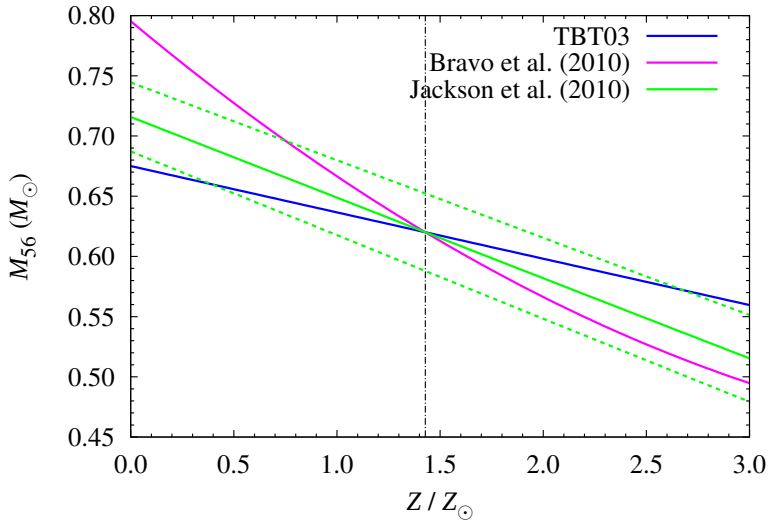

Figure 4: The solution of M_{56} (green) computed as a function of metallicity as compared to the ^{56}Ni relations from Timmes, Brown, and Truran (2003) [12] (blue) and Bravo et al. (2010) [13] (magenta) normalized to the average ^{56}Ni yield from our simulations. The dashed lines show the propagated standard deviation of the mean. The vertical dot-dashed line indicates the parameter space in which this study was performed. These results were evaluated with a fiducial transition density of 6.76×10^6 g cm^{-3} at $Z = 1.4 Z_\odot$. The derivative of M_{56} with respect to metallicity evaluated at $Z_\odot$ is $-0.067 \pm 0.004 M_\odot$, slightly steeper than Timmes, Brown, and Truran [12]. The steeper slope is a result of the NSE yield also depending on metallicity as shown in the previous figure.

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