A Study of Steady-State Detonation Structures for Hybrid C, O, Ne White Dwarf Models

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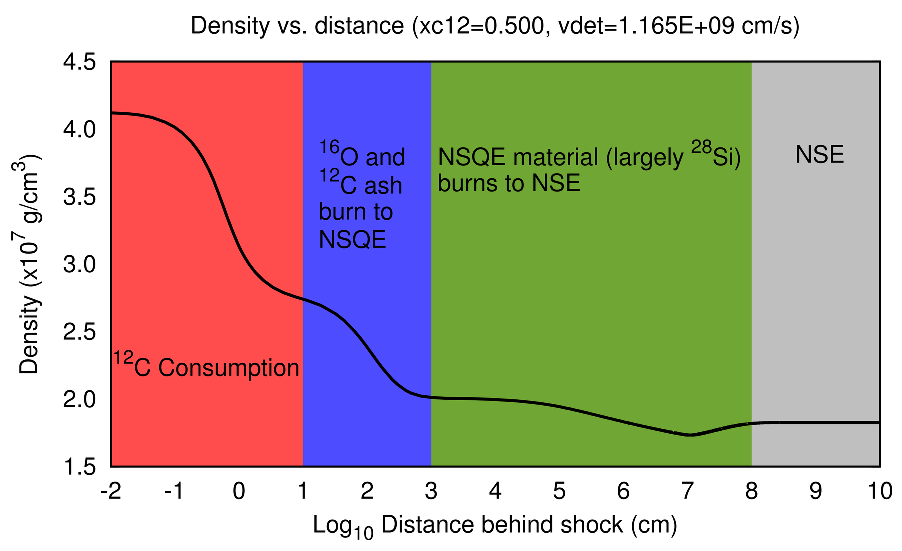
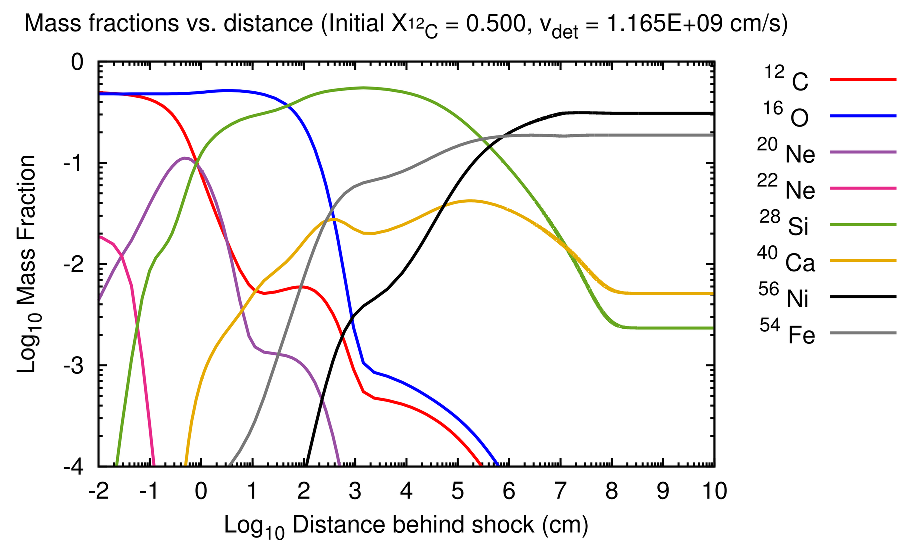
Introduction

We present a study of one-dimensional, planar detonations in white dwarf material at varying compositions of C, O, and Ne, motivated by recent stellar evolution models which predict hybrid white dwarf stars with a C, O core inside an O, Ne shell (Denissenkov et al. 2013).

Right: Density structure and primary nuclear burning regimes for a C, O WD characterized by ^{12}***C*** burning to ^{16}***O***, ^{20}***Ne***, ^{24}***Mg***, and α-particles (collectively, ^{12}***C*** ash), which then burns together with the initial ^{16}***O*** to NSQE and finally settles into NSE.

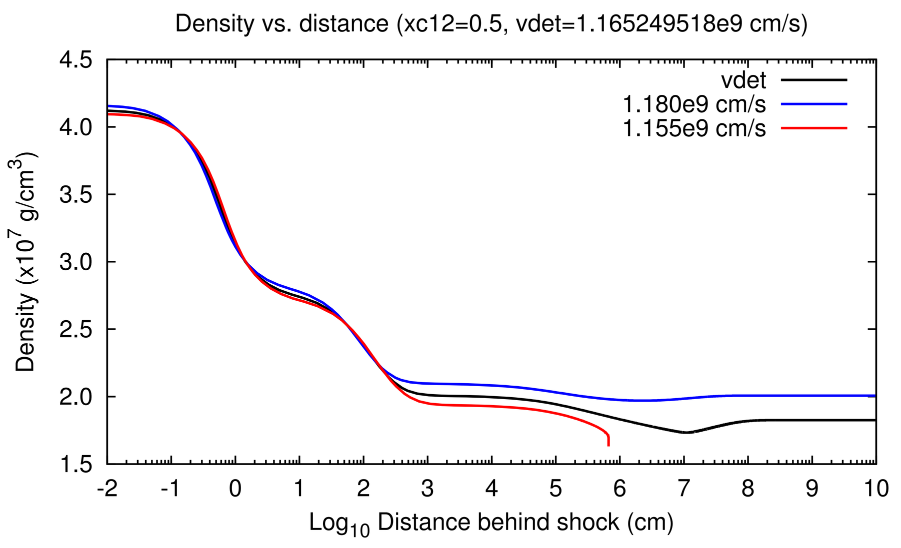
Since combustion models for SN Ia simulations of these WDs have been based on these burning stages and timescales (Townsley et al. 2009, Townsley et al., in prep), we wish to determine how the burning structure changes for WD material with less ^{12}***C*** and more ^{20}***Ne***.

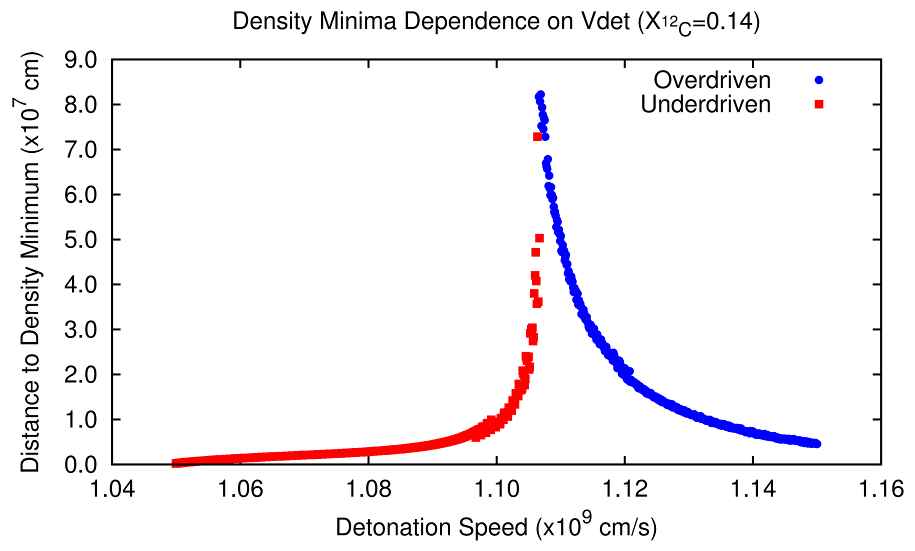




Distinguishing Minimally Overdriven Detonations

We find the minimum overdriven detonation velocity by integrating the Zel'dovich, von Neumann, During (ZND) equations at fixed density and composition with varying detonation speed.



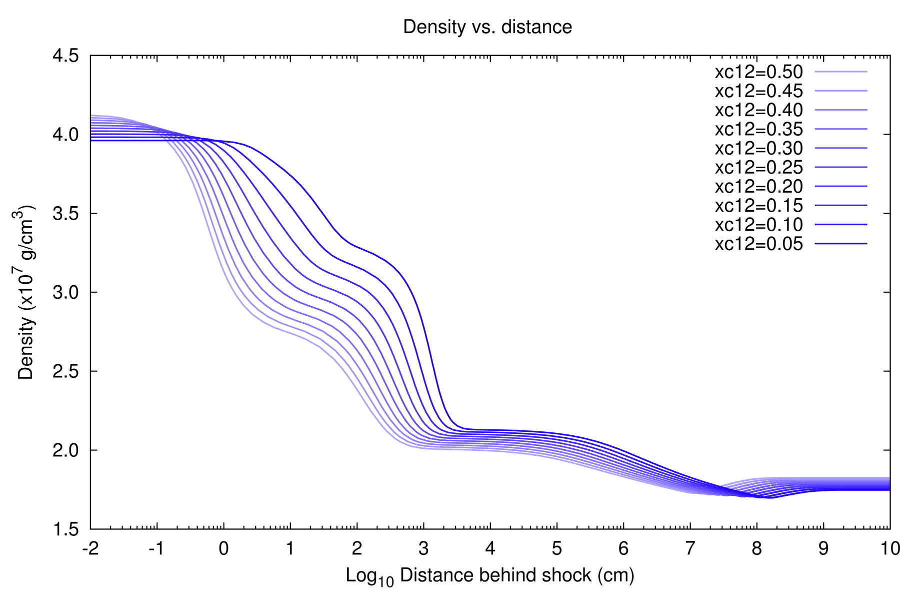


- **Far Left:** density structure of C, O white dwarf material for an overdriven detonation (blue), minimally overdriven detonation (black) and underdriven detonation (red).
- **Near Left:** location of density minimum vs. detonation speed, showing a clear transition from underdriven to overdriven detonations at the minimally overdriven velocity.
- *Overdriven Detonations:* density minima corresponds to integration to the sonic point where a ZND solution exists.
- *Underdriven Detonations:* density minima is the asymptotic drop in density beyond which there is no ZND solution.

The minimally overdriven detonation velocity corresponds to a detonation structure with the sonic point furthest behind the shock, while higher velocities give progressively more compact density structures.

Composition Table, Density Structure, and Mass Fraction Curves for C, O, Ne WD Material

$X_{^{12}C}$	$X_{^{16}O}$	$X_{^{20}Ne}$	$X_{^{22}Ne}$
0.50	0.48	0.00	0.02
0.49	0.48	0.01	0.02
0.48	0.48	0.02	0.02
…	…	…	…
0.05	0.48	0.45	0.02



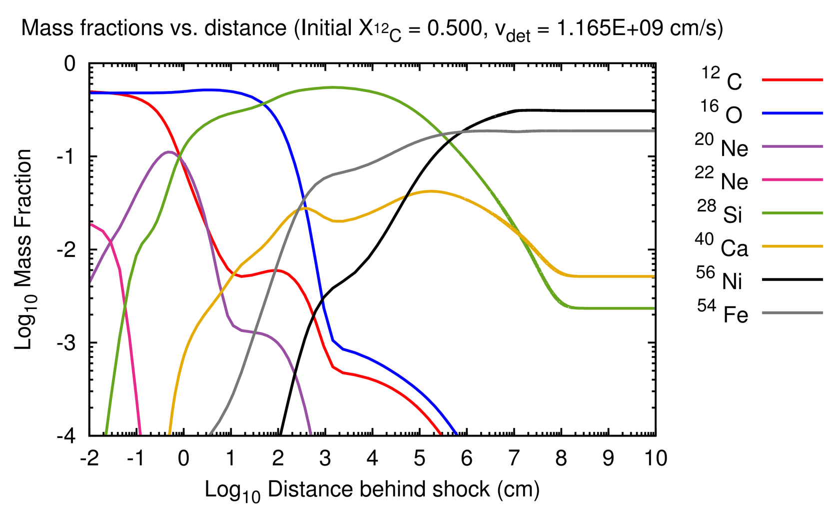
Left: Shown is the tabulated composition range we explored and a plot of minimally overdriven density structures with carbon fraction ranging from 0.5 to 0.1.

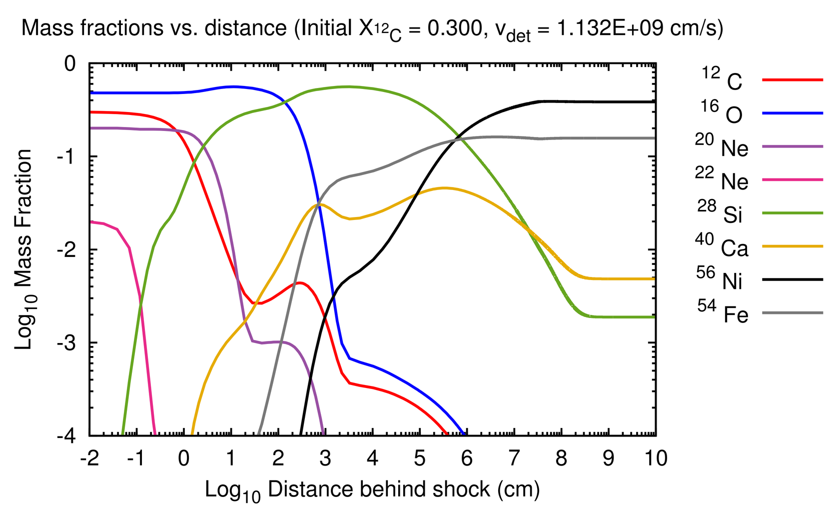
- Constant ^{16}***O*** and ^{22}***Ne*** composition.
- Equal reduction of ^{12}***C*** and increase of ^{20}***Ne***.

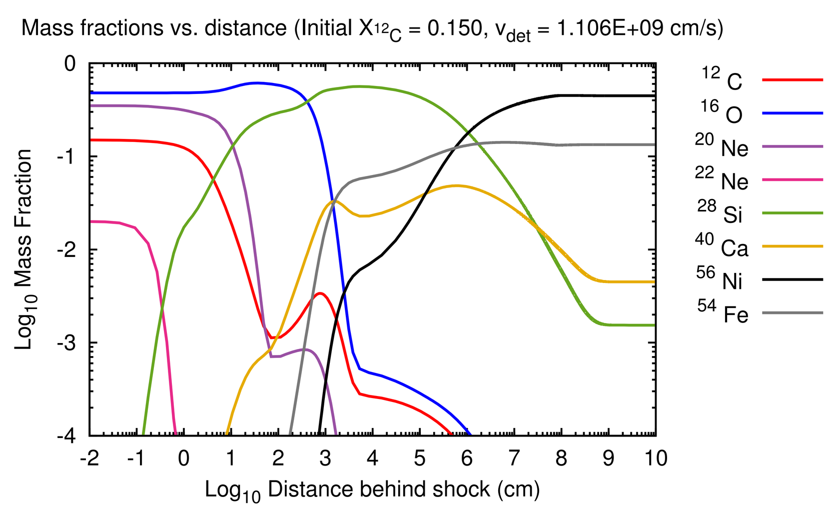
The density curves demonstrate that higher initial ^{20}***Ne*** content lengthens the timescales of the existing step features in the density structure in all burning regimes, though no qualitatively new features arise.

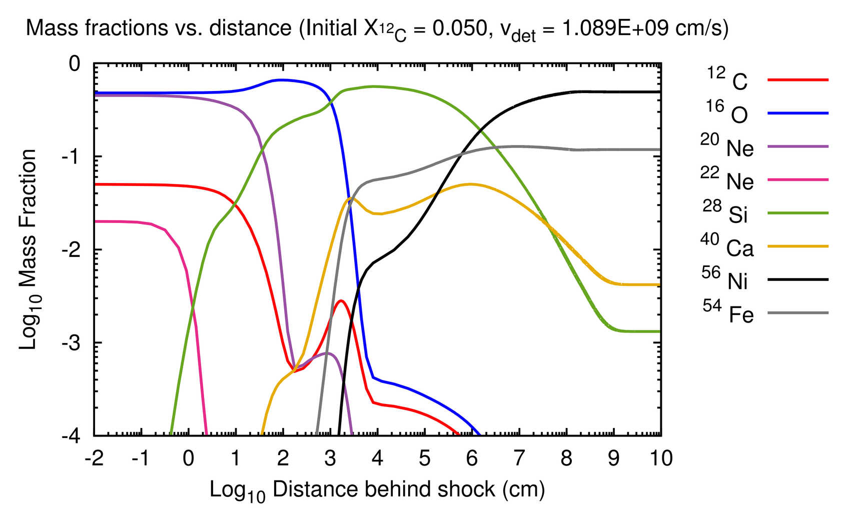
Below: Plotted are selected mass fraction curves with carbon fraction decreasing from left (0.5) to right (0.05).

- Lower carbon fractions correspond to a later burning of ^{20}***Ne*** and ^{12}***C*** ash to NSQE and a higher peak ^{16}***O*** content prior to burning to NSQE as well.
- A lower carbon fraction also corresponds to later burning from NSQE to NSE.
- Later burning is in agreement with the shift of density features further behind the shock front as carbon is reduced.

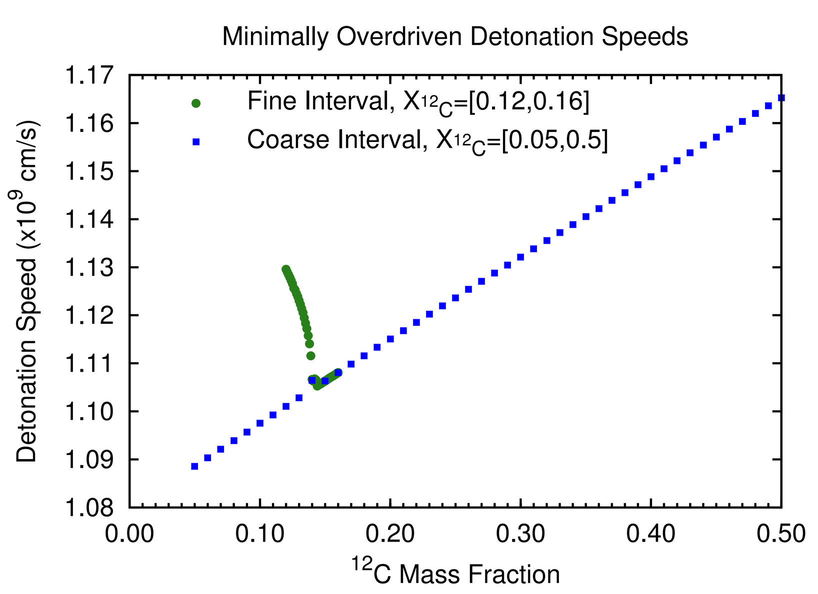








Detonation Velocity Dependence on Carbon Fraction

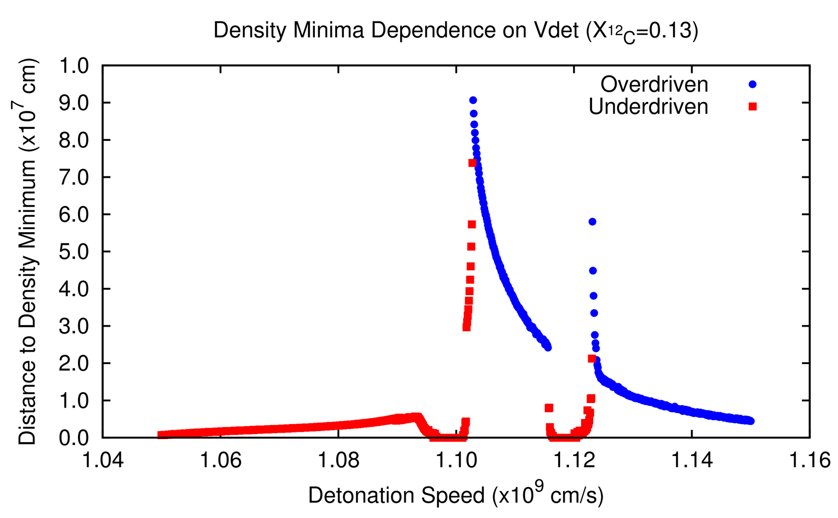


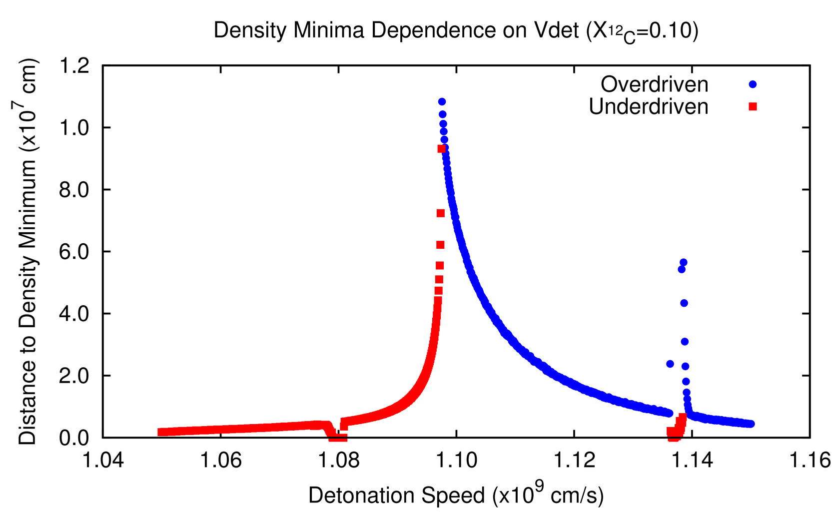
Left: Shown is the minimally overdriven detonation velocity found for each carbon fraction, complementary to the burning timescales above.

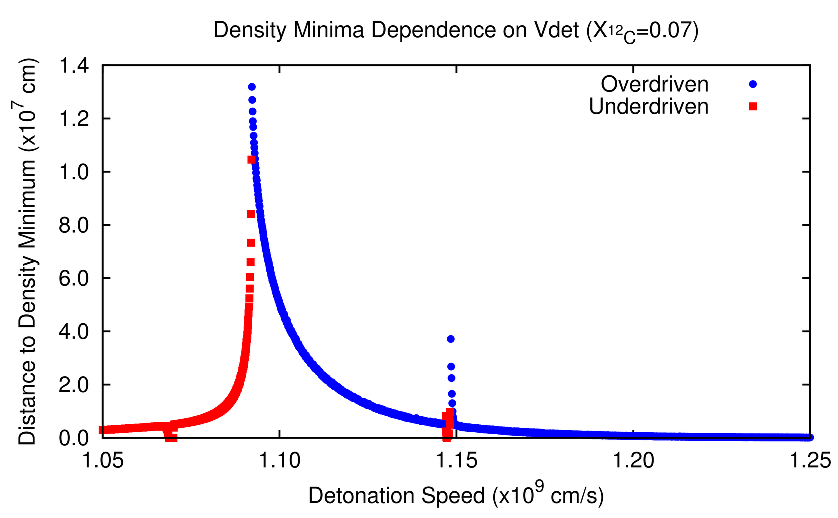
- Monotonic, approximately linear decrease in velocity above $X_{^{12}C} \approx 0.15$
- Bifurcation near $X_{^{12}C} \approx 0.15$ gives diverging minimally overdriven detonation velocities.
- The upper branch (green) has detonation velocity increasing with lower carbon fraction.
- The lower branch of the velocity curve for $X_{^{12}C} < 0.15$ follows the same decreasing trend as for $X_{^{12}C} > 0.15$. We take the lowest branch to be the stable physical solution.

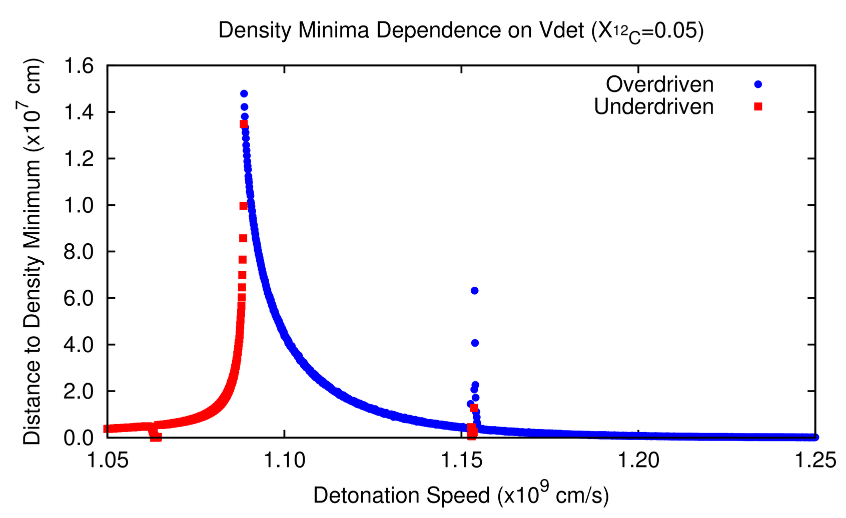
Below: From left to right we explore the detonation velocity branches as the carbon fraction decreases from 0.13 to 0.05. Note the rightmost two figures show a wider range in velocity than the leftmost.

- Overdriven detonation regimes are separated in velocity by a narrow range for which detonations are underdriven.
- Lowering the carbon fraction results in the minimally overdriven solutions moving apart and the underdriven regime shrinking.









Outlook

The detonation structure and composition evolution in the region behind the shock front for a barely overdriven detonation for mixed C, O, Ne white dwarf material provides time scales that will be used to calibrate a combustion model for simulations of thermonuclear supernovae. This calibration will enable a future study of hybrid C, O, Ne white dwarf stars as possible progenitors for some Type Ia supernovae.

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References

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Computations used F.X. Timmes' nuclear network code TORCH (http://cococubed.asu.edu/) as modified by D.M. Townsley for computing SN Ia yields (http://astronomy.ua.edu/townsley/code/).