Low Mach Number Simulations of the Convective Urca Process

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Introduction

Type Ia Supernova Progenitor

Type Ia Supernovae (SNe Ia) are thermonuclear explosions of roughly a solar mass of white dwarf (WD) material. The exact progenitor system that leads to SNe Ia is not well understood. Proposed ideas include a WD accreting material from a companion star to the point of carbon ignition in the core. This begins the simmering phase where carbon burning drives core convection for about 1,000 to 10,000 years before the thermonuclear explosion. The carbon burning alters the composition of the core region which in turn impacts the nucleosynthesis of the SNe Ia we observe.

Convective Urca Process

The Urca process is the combination of a beta-decay and electron-capture which connects a pair of nuclei, called an Urca pair. A relevant Urca pair to simmering WDs that we explore in these simulations is the A=23 pair:

$$\begin{aligned} {}^{23}\mathrm{Ne} &\rightarrow {}^{23}\mathrm{Na} + e^- + \bar{\nu}_e \\ {}^{23}\mathrm{Na} + e^- &\rightarrow {}^{23}\mathrm{Ne} + \nu_e \end{aligned} \tag{1}$$

The convective Urca process links the Urca reactions with convection creating a cyclical process. Convection transports material above and below the **Urca Shell, the region where the Urca reactions are in local equilibrium**. Material mixed below the shell will electron-capture while that mixed above will beta-decay. Since convective Urca can continue continuously without additional fuel, even small fractions of Urca nuclei are needed to impact the WD's evolution. Convective Urca results in local cooling (from emitted neutrinos), compositional changes (particularly to $\mathrm{Y_e}$), and a potential impact on convection itself [2, 4]. We present full 3D simulations to properly model the convective flow and nuclear reactions.

Low-Mach Hydrodynamics: MAESTROeX

The convection in a simmering WD is slow compared to the sound speed (Mach Number $\sim 10^{-3}$). To efficiently model this slow moving regime, we use the MAESTROeX low-Mach hydrodynamic code [1], which is specifically designed to model stellar interiors and atmospheres. MAESTROeX effectively filters out the sound waves while still accurately modeling the the convection. Our simulations are full 3D and resolve the convective core to 2.5 km. We incorporate a reaction network with simple carbon burning and the A=23 reactions (see Eq. 1).

Initial Model

We set the initial state to represent a 40% - 60% Carbon-Oxygen WD with $\rho_c = 4.5 \times 10^9\ \mathrm{g/cm^3}$ and $\mathrm{T_c} = 5.5 \times 10^8$ K. We start in hydrostatic equilibrium with an isentropic core and isothermal envelope (see blue lines in Fig. 1). The Urca pair are initialized in local equilibrium around the Urca Shell. This setup was motivated by 1D stellar evolution models [3] and was developed by Don Wilcox for his dissertation [5].

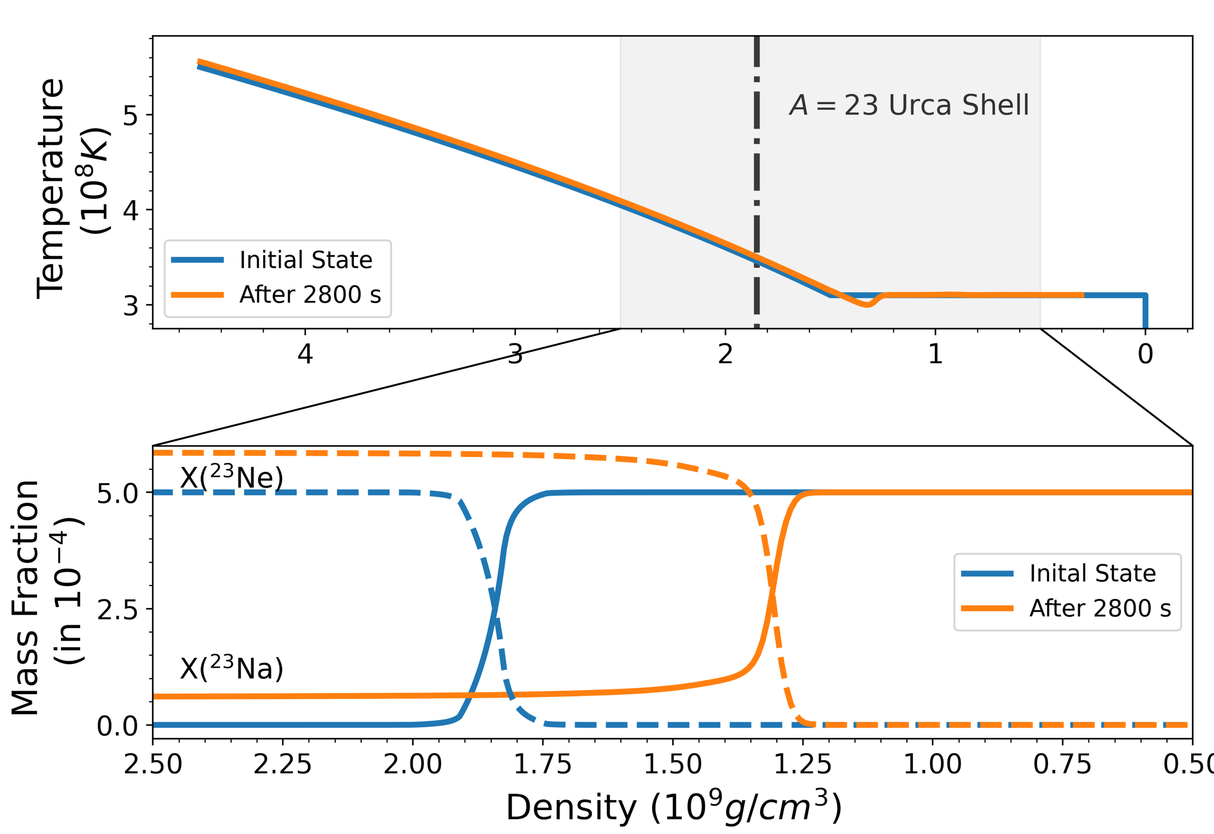

Figure 1. Temperature-density profile for initial state and after 2800s of simulation time. Additionally a blow out of the distribution of Urca pair at the same two times.

Results: Convective Velocity

The characteristic velocity of the core convection is about 15 km/s with a convective turnover timescale is about 150-200 s. We find the large scale structure is that of a dipole (see Fig. 2). The convection zone was initialized to extend past the Urca shell and it has since grown further away indicating the initial conditions were underplayed the extent of convection (see Fig. 1a and 3).

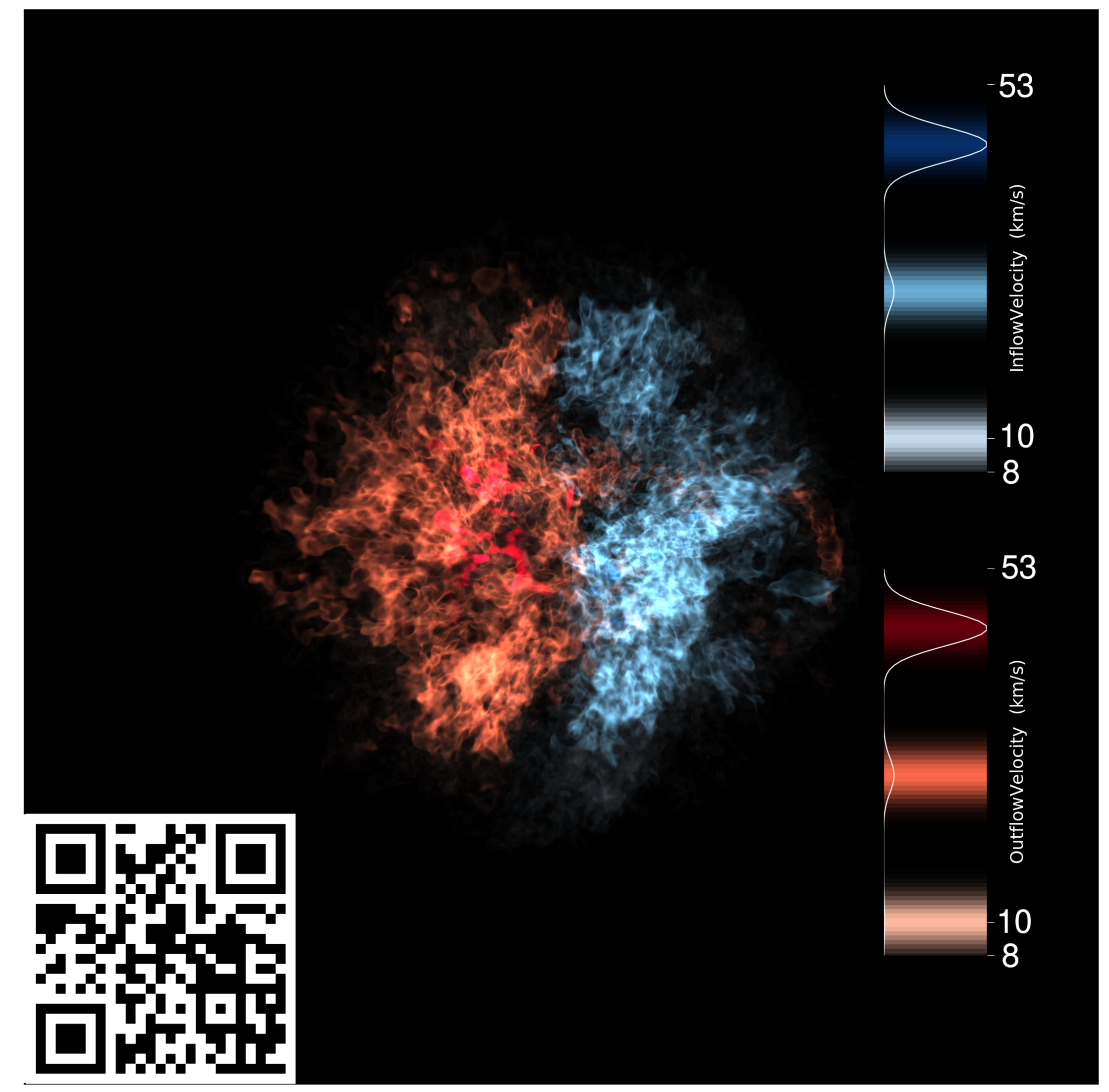

Figure 2. A volume render of the core convection. The blue regions represent fluid flowing toward the center. The red regions represent fluid flowing away from the center. See the QR code for a video of the volume rotating.

Results: Composition

The electron fraction, $\mathrm{Y_e} = \sum_i \frac{Z_i}{A_i}$, is an important quantity that alters the nucleosynthesis of a SN Ia. Both carbon burning and the Urca reactions alter $\mathrm{Y_e}$, lowering the value in the core region. The light blue regions represent areas where substantial amounts of ${}^{23}\mathrm{Ne}$ and ${}^{23}\mathrm{Na}$ are present, note that this only occurs near the edge of the convection zone and not the Urca shell (also see orange lines in Fig. 1b).

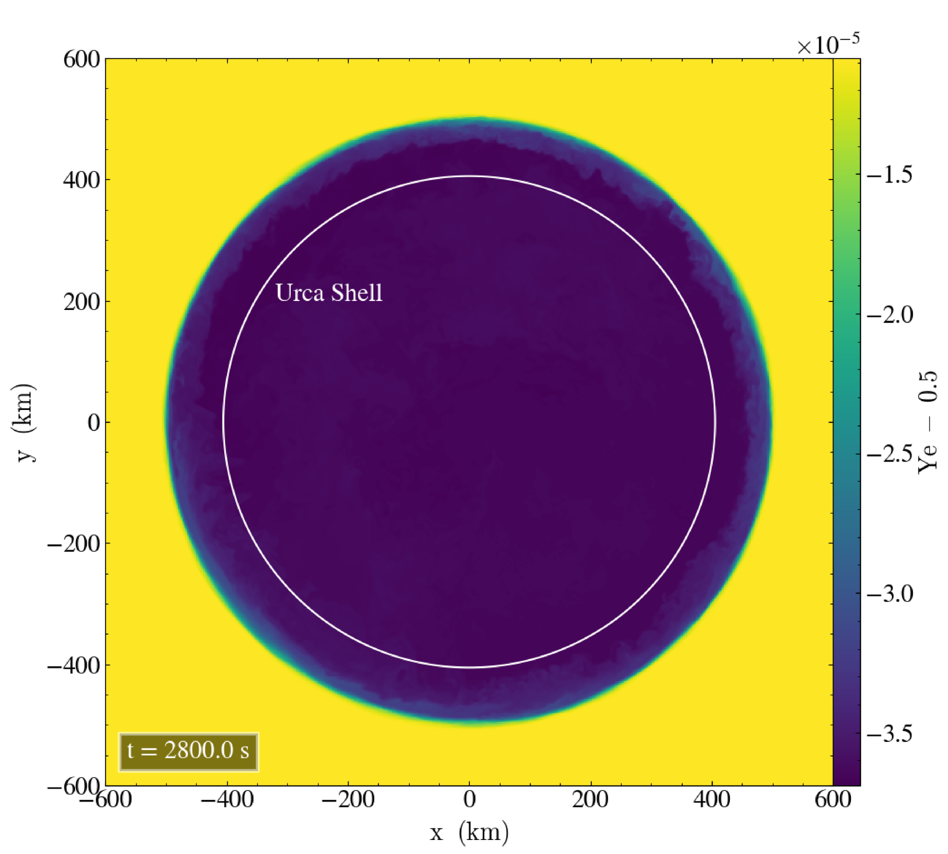

Figure 3. Slice through the center of the WD displaying the core region. Purple represents the electron poor interior while yellow exterior is electron rich in comparison. The white circle reprents the location of the A=23 Urca shell.

Results: Nuclear Energy Generation

The nuclear energy is generated primarily by the carbon burning in the core of the WD with a total ouput of $2.59 \times 10^{43}\ erg/s$. However, just outside the core there is a high number of electron captures of ${}^{23}\mathrm{Na}$ produced by carbon burning and mixed from above the Urca shell. The Urca shell is clearly seen as the $\dot{e}_{nuc} = 0$ contour at roughly 400 km. Outside the Urca shell there is a region where ${}^{23}\mathrm{Ne}$ beta-decays as it is being mixed from the interior across the Urca shell.

Specific Nuclear Energy Generation Rate

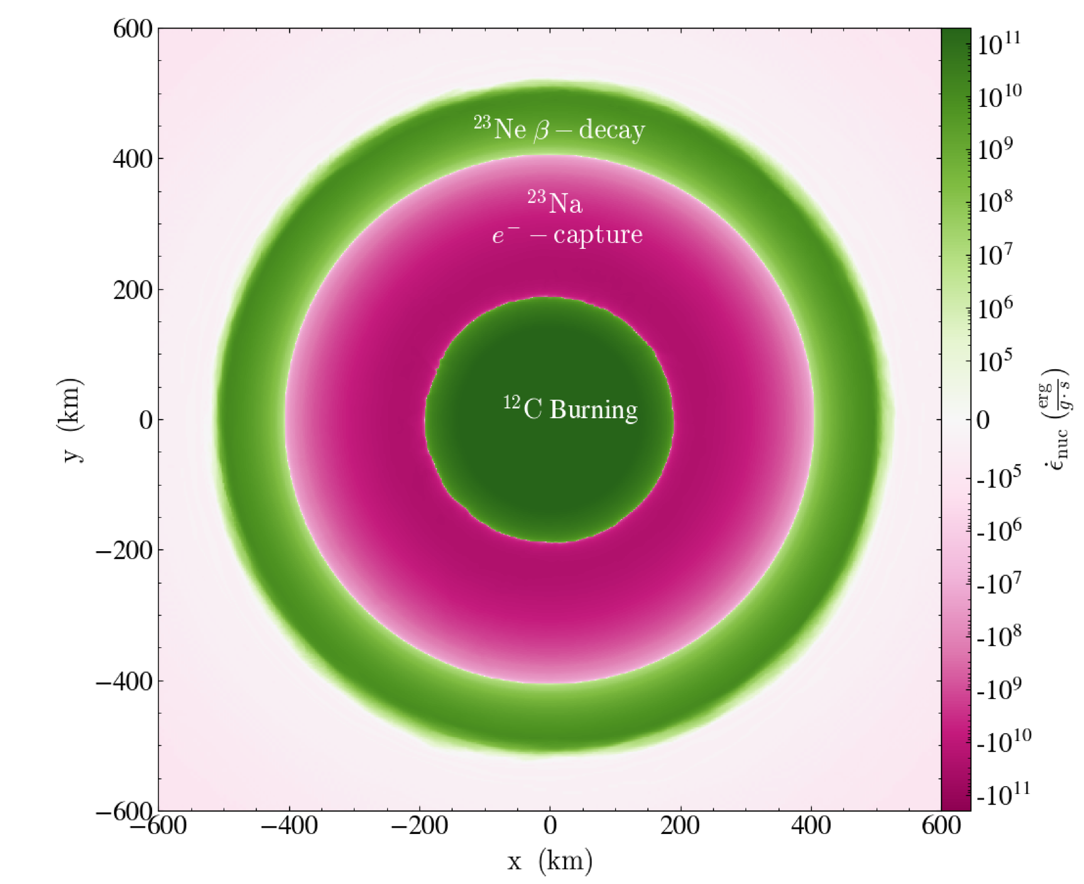

Figure 4. Slice through center of WD showing core region. Green denotes positive specific energy generation rate in erg/g/s. The purple denotes energy lost, primarily due to endothermic electron-captures. The main reaction is annotated in the three regions.

Neutrino Loss Rate

During one cycle of the convective Urca process, two neutrinos will be emitted and freely stream away from the star, providing local cooling. The total neutrino loss rate for the WD is $3.62 \times 10^{42}\ erg/s$ or in terms of a neutrino luminosity, $\mathrm{Log(L_\nu/L_\odot)} = 8.98$

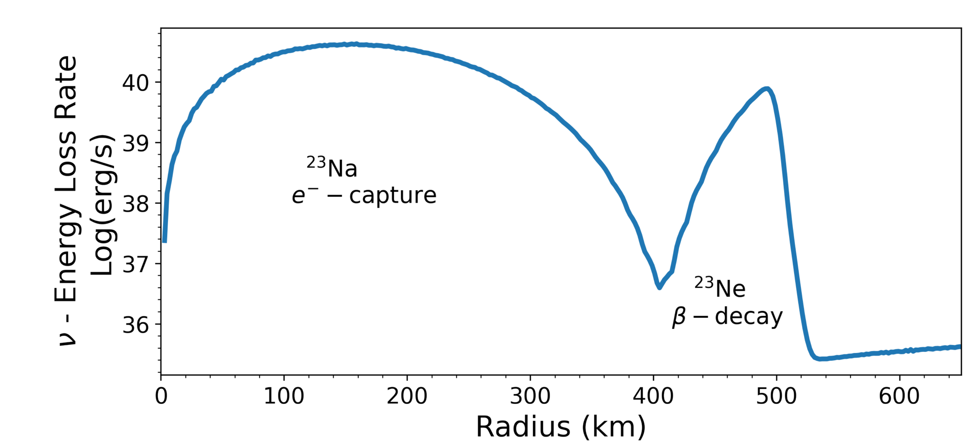

Figure 5. Energy loss due to neutrino emission. Includes both thermal neutrino emission and emission from Urca reactions. The dominant reaction in each region is annotated. Outside 500 km, the loss rate is dominated by thermal emission.

References

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