Full 3D Fluid Simulations of the Convective Urca Process in a Simmering White Dwarf Star

Brendan Boyd [1,2] Alan Calder [1,2] Dean Townsley [3] Michael Zingale [1]

[1]Department of Physics and Astronomy, Stony Brook University [2]Institute for Advanced Computational Science, Stony Brook University [3]Department of Physics and Astronomy, University of Alabama

Stony Brook University

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.

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 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). The full source code for MAESTROeX can be found at **github.com/AMReX-Astro/MAESTROeX**, all contributions are welcome.

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:

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

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, only 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 Y_e), and a potential impact on convection itself [2, 4].

Initial Model

We set the initial state to represent a 40% - 60% Carbon-Oxygen WD with trace amount of Urca nuclei, $X(^{23}\mathrm{Na}) + X(^{23}\mathrm{Ne}) = 5 \times 10^{-4}$. We start in hydrostatic equilibrium with an isentropic core and isothermal envelope (see Fig. 1). The Urca pair are initialized in local equilibrium around the Urca Shell (see dashed lines in Fig. 4). This setup was motivated by 1D stellar evolution models [3] and was developed by Don Wilcox for his dissertation [5].

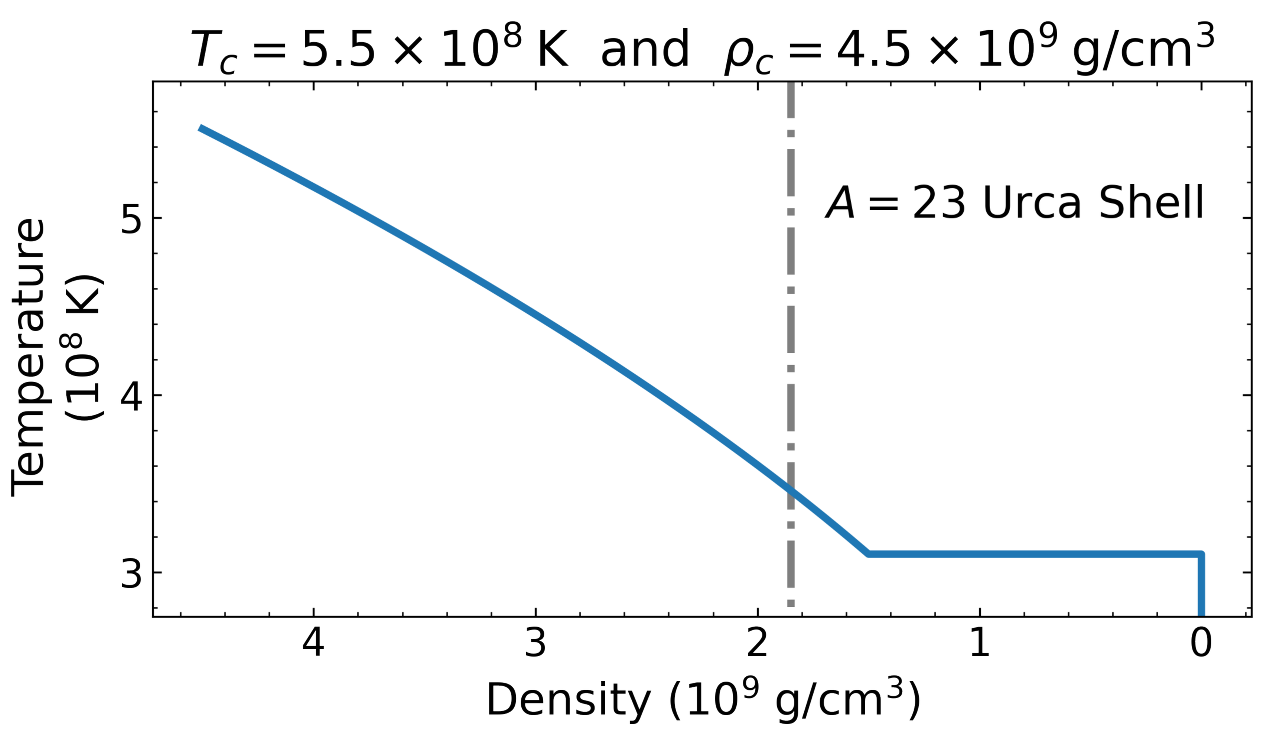

Figure 1. Temperature-density profile of the initial WD model. The A=23 Urca shell is marked by the vertical black line.

Convective Velocity

Our initial state set the isentropic zone to be at a radius of 465 km, however the convection zone has grown to around 500 km radially. The characteristic velocity is roughly 15 km/s with a convective turnover timescale of 50-100 s. The large scale structure is dipolar (see Fig. 2). The convective zone mixes material across the Urca shell as can be seen below and in (Fig. 3).

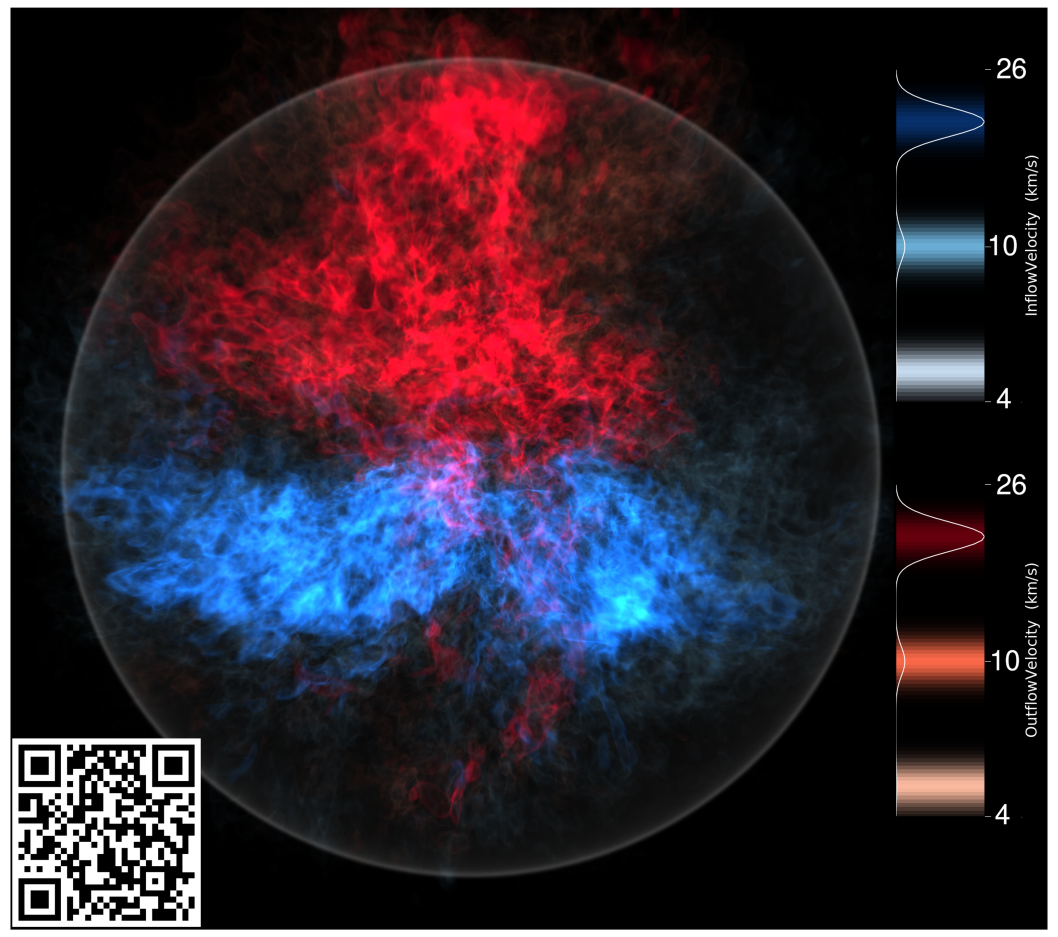

Figure 2. A volume render of the core convection. The red regions represent fluid flowing away from the center. The blue regions represent fluid flowing toward the center. The white ring marks the Urca shell. The plot is oriented so the primary flow is upward. See the QR code for a video of the volume rotating.

Urca Pair Mixing

A key aspect of the Convective Urca process is the mixing of material across the Urca shell. This leads to a dynamic equilibrium based on both the reaction timescales and the mixing timescale (this differs from the static equilibrium see Fig. 4). Due to the directional dependence of the convective flow, the Urca pair are not distributed evenly.

Interior to the Urca shell, the ratio of $^{23}\mathrm{Ne}$ to $^{23}\mathrm{Na}$ approaches 12.6. In comparison, by integrating the reaction rates over the convection zone, we naively estimate a ratio of 12.0. This indicates the physics of mixing plays a role in finding the equilibrium Urca distribution.

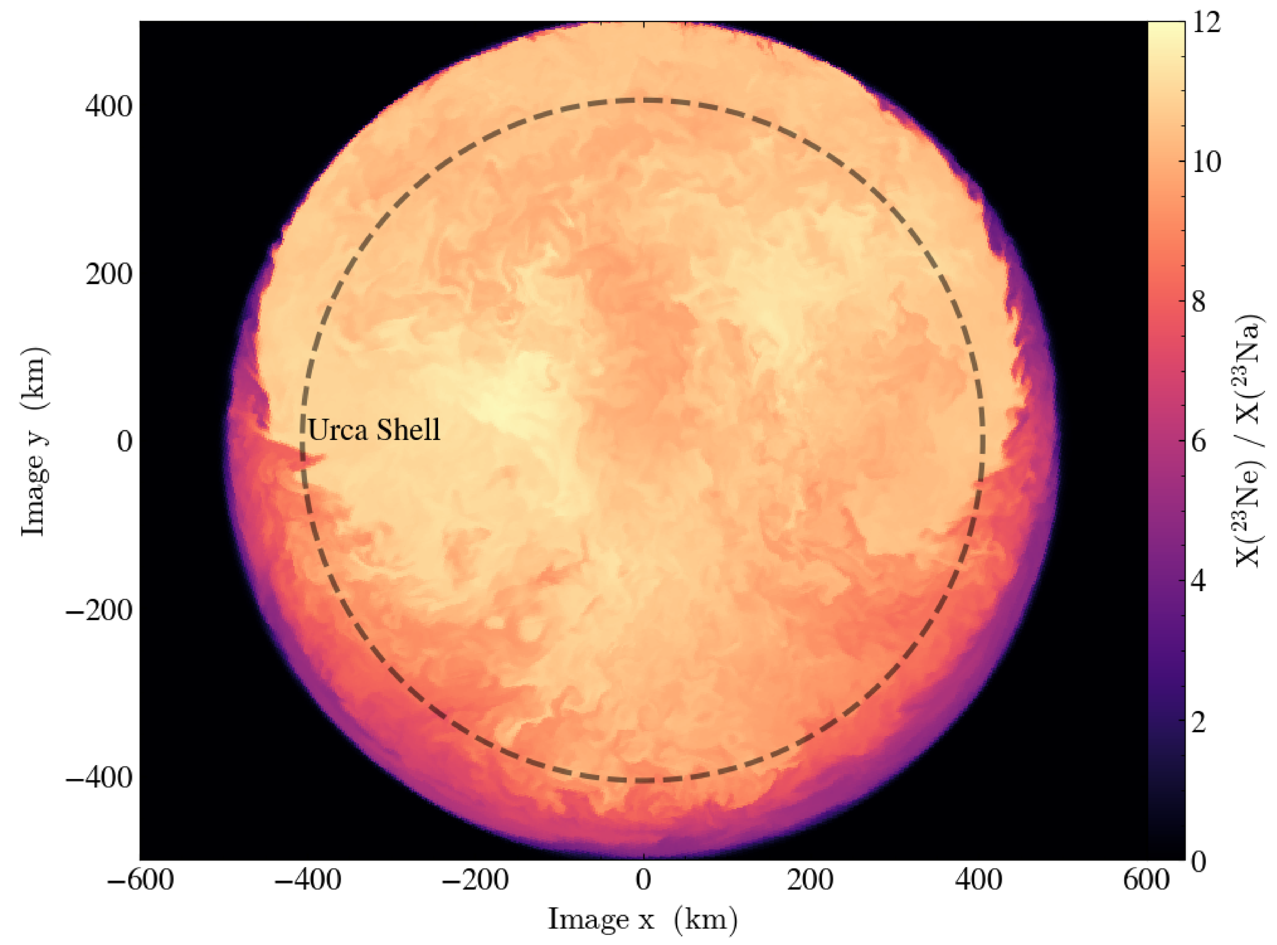

Figure 3. Slice through the center of the WD displaying the core region. The color bar represents the ratio of $^{23}\mathrm{Ne}$ to $^{23}\mathrm{Na}$. Black dotted circle marks the location of the A=23 Urca shell. The orientation is the same as Fig. 2.

Dynamic Equilibrium vs Local Equilibrium

The average distribution of the Urca isotopes has relaxed from our initial conditions to a dynamic equilibrium. This equilibrium balances the contribution of $^{12}\mathrm{C}$ burning (i.e. $^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$), the Urca reactions, and the mixing across the Urca shell.

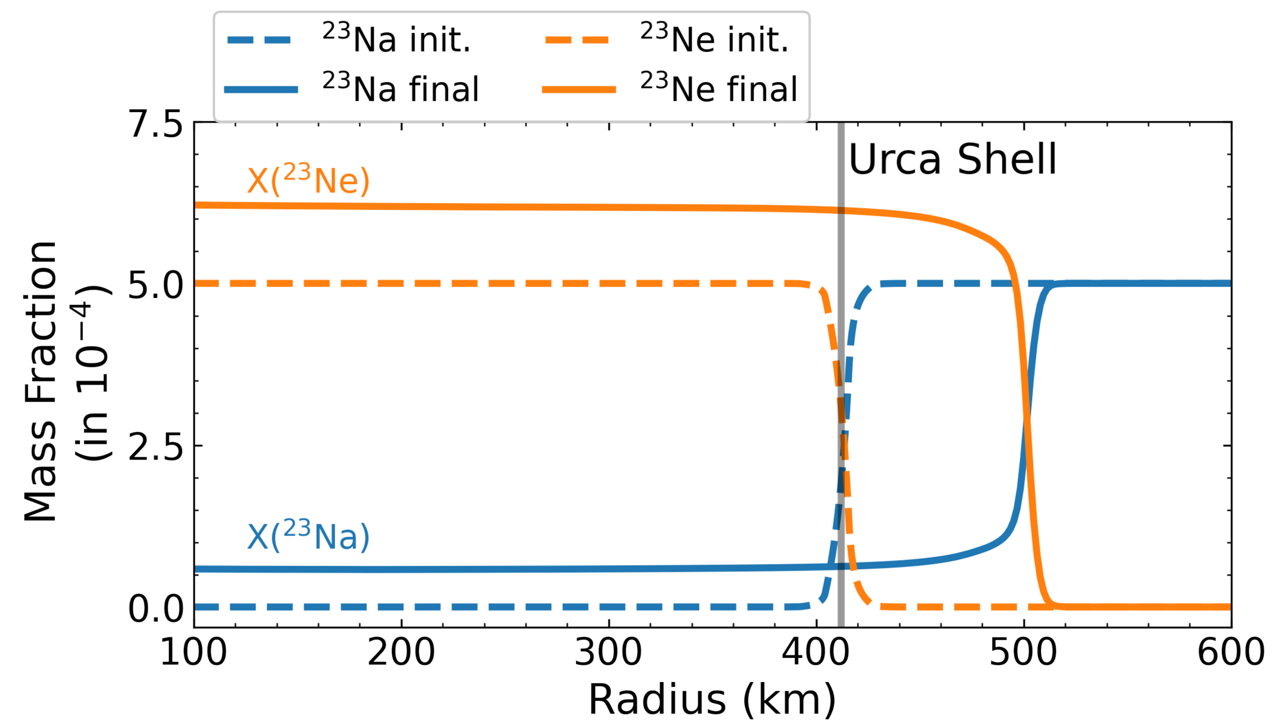

Figure 4. Average mass fraction for each Urca isotope. The dashed lines denote our initial model (a local, static equilibrium). The solid lines are the distribution after 3360 s. The grey vertical line marks the Urca shell.

Energy Generation Rate

The nuclear energy is generated primarily by the $^{12}\mathrm{C}$ burning in the core of the WD with a total output of 2.85×10^{43} erg/s. Further from the center, electron captures of $^{23}\mathrm{Na}$ become more important until the Urca shell ($\sim$400 km), where beta decays of $^{23}\mathrm{Ne}$ produce additional energy. For every Urca reaction, a small amount of energy is lost to neutrinos free-streaming from the star. The total neutrino loss rate for the WD is 3.62×10^{42} erg/s.

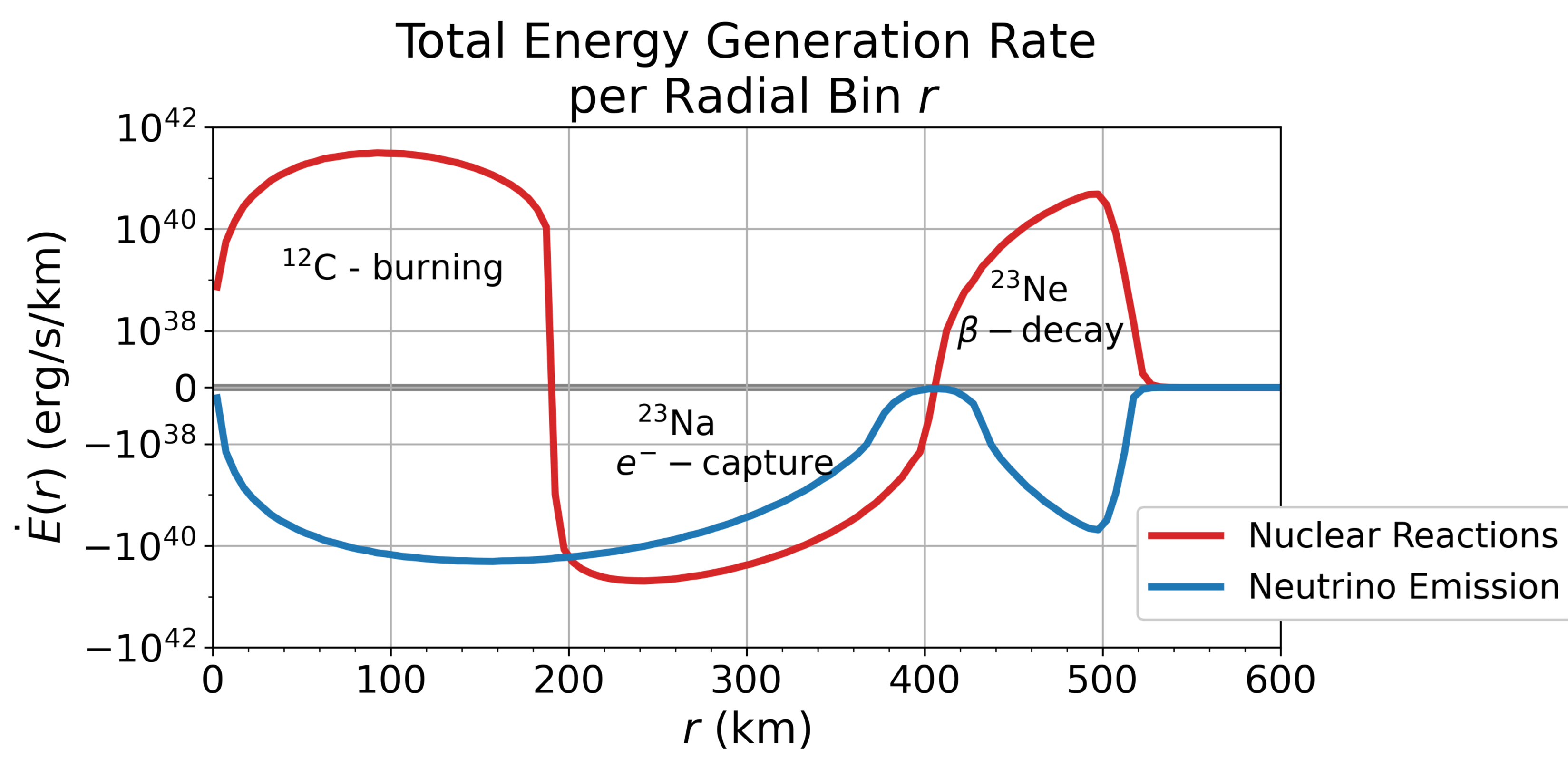

Figure 5. The total energy generation rate at a given radius on a symlog plot, the region between -1e38 and 1e38 is linear. The red line is the total energy generation rate by nuclear reactions. The blue line is the rate of energy lost to neutrino emission. The dominant reaction for each region is annotated.

References

[1] D. Fan, A. Nonaka, A. S. Almgren, A. Harpole, and M. Zingale. *ApJ*, 887(2):212, Dec. 2019.

[2] P. Lesaffre, P. Podsiadlowski, and C. A. Tout. *MNRAS*, 356(1):131–144, Jan. 2005.

[3] H. Martínez-Rodríguez, A. L. Piro, J. Schwab, and C. Badenes. *ApJ*, 825(1):57, July 2016.

[4] J. Stein and J. C. Wheeler. *ApJ*, 643(2):1190–1197, June 2006.

[5] D. E. Willcox. PhD thesis, SUNY Stony Brook, 2018.

boyd.brendan@stonybrook.edu

This research was supported in part by the US Department of Energy (DOE) under grant DE-FG02-87ER40317