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Elucidating the Convective Urca Process in Pre-Supernova White Dwarfs Using Three-Dimensional Simulations

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It has long been understood that pre-supernova white dwarf (WD) stars can possess sufficiently high densities that Na-23 synthesized via C-fusion undergoes electron capture to Ne-23. These Ne-23 nuclei may be carried by convection to regions of lower density where they revert via beta decay to Na-23. Cyclic reactions of this sort constitute the Urca process in WDs, which is theorized to significantly influence stellar structure by opposing convective buoyancy, transporting energy, and effecting energy loss via neutrinos. However, the details of these influences have remained elusive systematics in studies of Type Ia supernovae progenitors, as they require WD simulations which accurately capture both weak reaction rates and three-dimensional turbulence. These constitute a computationally challenging problem for compressible hydrodynamics methods due to the timestep constraints imposed by the very small convective velocities during the pre-supernova simmering phase of WDs. We present new three-dimensional simulations of the Urca process in WDs using the low-Mach hydrodynamics code MAESTRO together with recent fine tabulations of the weak reaction rates driving the A=23 Urca process. Our simulations are inspired by recent stellar evolution models of simmering WDs at the time core-driven convection reaches the A=23 Urca shell, and we characterize the location, extent, and energetics of the Urca shell as well as the surrounding flow field. We compare our simulations with previous studies of the convective Urca process in one and two dimensions and discuss the ramifications of our chosen weak reaction rates, low-Mach method, and three dimensional treatment of turbulence. Finally, we discuss the implications of our results for one-dimensional stellar evolution calculations and nucleosynthesis in Type Ia supernovae.

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