Electron Capture and Shock Formation in Core-Collapse Supernovae

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New supernova progenitor models incorporating modern electron capture and beta decay rates have recently become available. One of the more notable differences in these new models is an increase in the electron fraction throughout the iron core when compared to earlier models. We describe fully self-consistent radiation hydrodynamic simulations of core collapse and shock formation using both sets of models, including both a standard set of electron capture rates for supernova simulations and a parameterized scheme meant to approximate the modern updates.

1. Introduction

Heger et al.[1](HLMPW01) have repeated the evolution calculations of Woosley & Weaver[2](WW95) for initial progenitor masses of $15\,M_\odot$, $25\,M_\odot$, and $40 M_\odot$, replacing the weak interaction rates for electron and positron captures and β^- and β^+ decays. The WW95 models used the electron capture rates of Fuller, Fowler, & Newman[3](FFN) and older sets of beta decay rates [4][5]. HLMPW01 have updated both with a new set of shell model weak interaction rates for electron capture, positron capture, and β^- and β^+ decays [6][7]. The most noticeable effect of these changes is a marked increase in the electron fraction (Y_e) throughout the iron core before collapse. Because the final size of the homologous core, and therefore the shock formation radius, is proportional to the square of the trapped lepton fraction (Y_l^2) at core bounce [8], the persistence of these initial differences in Y_e throughout collapse might have a discernible effect on the shock energetics.

2. Collapse Simulations

In an initial attempt to determine the influence of these improved rates on iron core collapse, we have performed full radiation hydrodynamic collapse simulations using the neutrino radiation hydrodynamics code AGILE-BOLTZTRAN [9][10][11][12].

We observe no difference in initial shock formation position between the two sets of progenitor models when our set of standard physics is used [13]. In these cases, capture rates on nuclei are quickly shut off when $A > 65$, and the capture rate on free nucleons

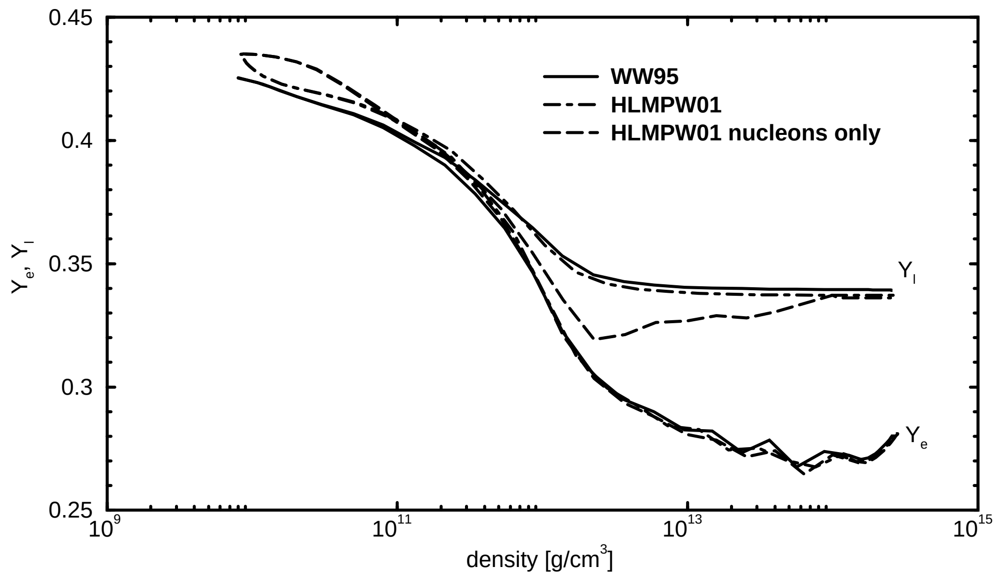

Figure 1. The total lepton fraction and electron fraction as a function of density for a mass element at $0.05 M_\odot$ in the $15\,M_\odot$ models is shown. A trajectory from a simulation with no captures on nuclei included is also shown.

dominates. The steep dependence of the free proton fraction on changes in the electron fraction assures convergence to the same Y_e profile inside the homologous core. The evolution of Y_e and Y_l for the mass parcel at $0.05\,M_\odot$ is shown in Figure 1. This trajectory is representative of the whole of the homologous core. We have also performed simulations in which the electron capture rate on nuclei was turned off as well as simulations in which the capture rate on free nucleons was increased by a factor of 10. Neither parameterization had any discernible effect on the shock formation radius. In an attempt to investigate the impact of including the updated electron capture rates during core collapse we have also performed collapse simulations with the HLMPW01 $15\,M_\odot$ core with a parameterized form of our usual electron capture rates. We write the neutrino emissivity from nuclei as [14][15]:

$$j_{nuclear} \;=\; \frac{2}{7}\frac{(2\pi)^4 G_F^2}{\pi h^4 c^4}\, g_A^2\, \frac{\rho X_H}{m_B A}\, N_p(Z) N_h(N)(E+Q')^2 \,[1-(\frac{M_e}{E+Q'})^2]^{1/2}\, F_e(E+Q'), \quad (1)$$

where

$$N_p(Z) = \begin{cases} 0 & Z < 20 \\ Z-20 & 20 < Z < 28 \\ 8 & Z > 28 \end{cases} \quad \text{and} \quad N_h(N) = \begin{cases} 6 & N < 34 \\ 40-N & 34 < N < 40 \\ 0 & N > 40\;. \end{cases} \quad (2)$$

To parameterize this rate we replace the product $N_p(Z)N_h(N)$ with a constant (0.1, 1, 10, or 100). This parameterization has a significant effect on the formation of the bounce shock. Setting the capture parameter equal to 10 moves the shock formation point inward more than $0.1\,M_\odot$ ($0.64\,M_\odot$ versus $0.52\,M_\odot$). The most important feature of the parameterization is the persistence of captures on nuclei throughout collapse. The

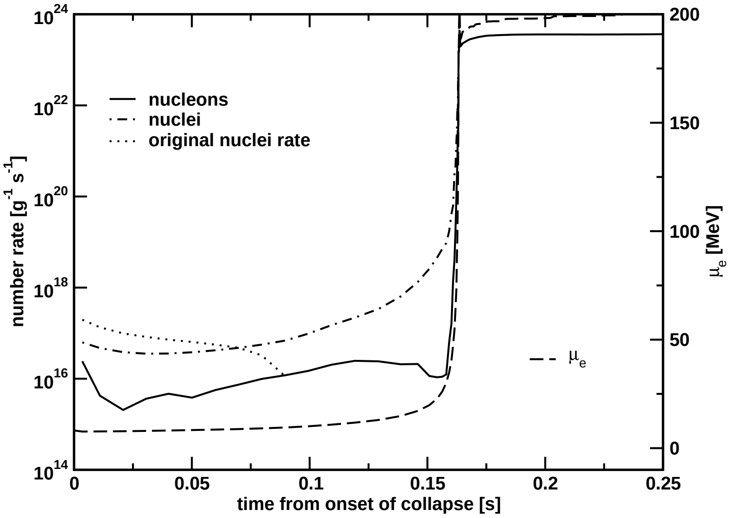

Figure 2. The number rate of electron captures on nuclei and nucleons during core collapse as a function of time is plotted. The parametrized rate with $N_p(Z)N_h(N) = 10$ is shown, along with the capture rate on nucleons and the expected standard rate on nuclei. The electron chemical potential is also shown.

precise value of the parameter is of secondary importance. The fundamentally different behavior of the parametrized rate as compared to the standard rate is shown in Figure 2. Work remains to be done to fully incorporate the new electron capture rates into collapse simulations.

3. Acknowledgements

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