Neutrino Effects on the r-Process in Black-Hole Forming Supernovae

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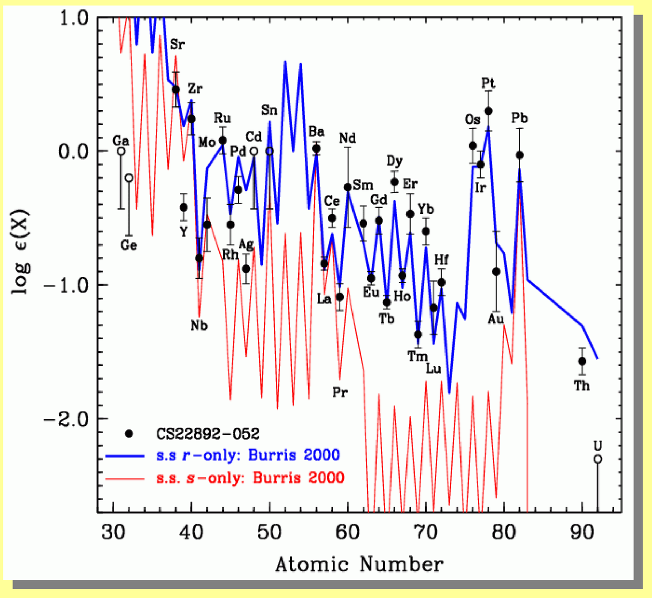
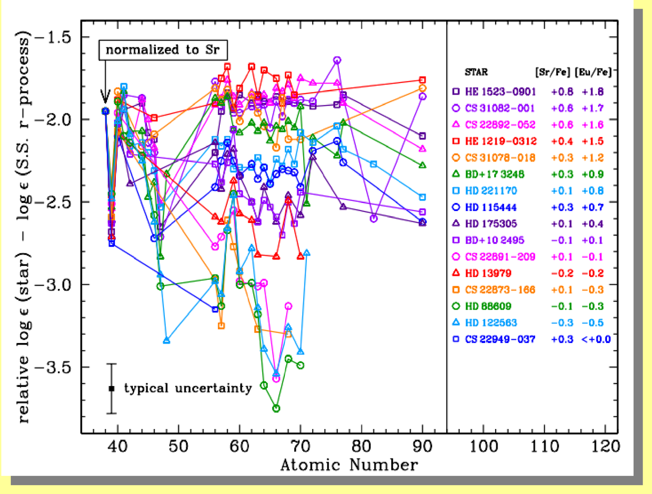
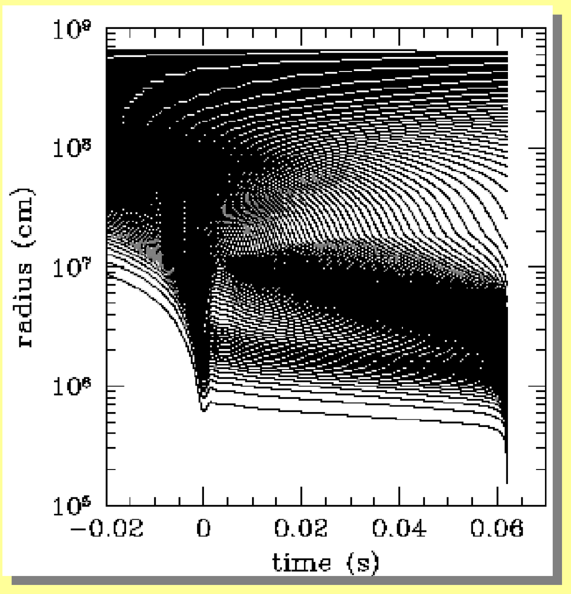
I. Introduction

The production of the heavier r-process nuclides in many metal poor stars appears to be very uniform, and it also produces relative abundances that are essentially the same as those found in more modern stars. However, some metal poor stars exhibit some of the features of r-process nucleosynthesis, but their abundances represent a surprisingly poor match with the ``standard" abundance template,[1,2,3] perhaps most frequently identified as that observed in CS-22892-052 (right, top).[4] A recent paper[3] has summarized the situation that exists for metal-poor stars. The data in that paper seem to suggest that a distribution of r-process abundances exists in metal poor stars, with some resembling the standard abundance set, but with a significant fraction of stars having abundances that do not match the standard template (right, bottom). These latter stars appear to favor the lighter r-process nuclides at varying levels, and many seem to have abundance patterns that terminate around Dy, that is, around mass 160.



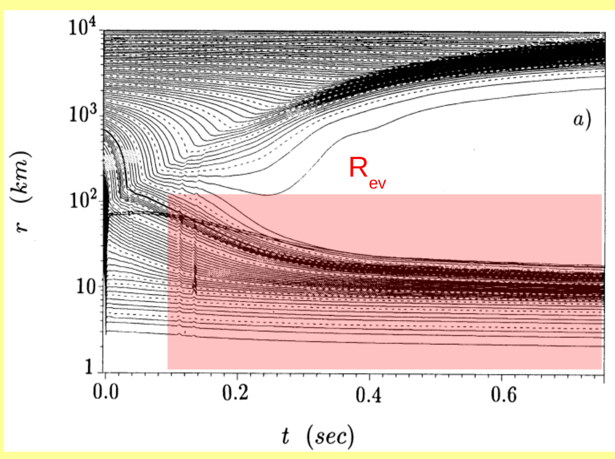


II. Simple First Model



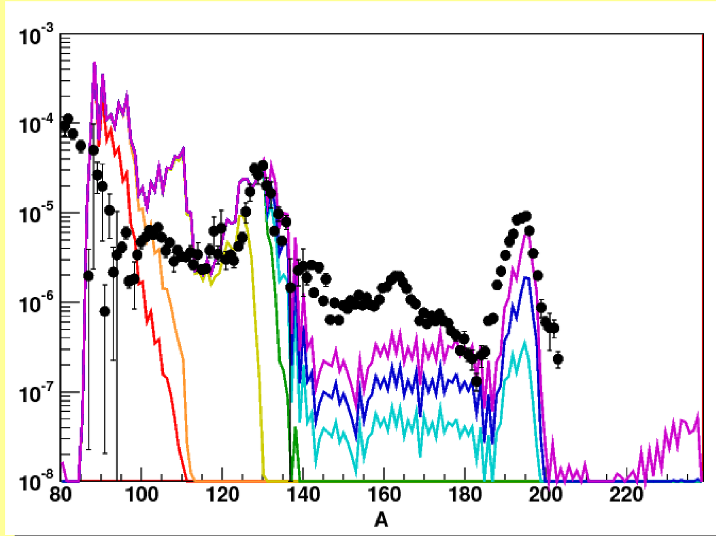
We start with a simple model based on the spherical collapse of a massive progenitor with the formation of a black hole from fallback as in the example figure shown (left).[5]

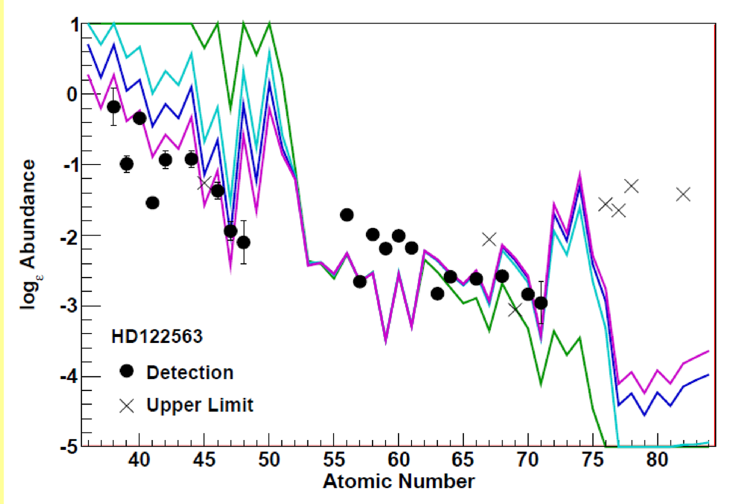
To study the truncated r-process in the neutrino-driven wind, we applied the basic idea behind the study of Woosley et al.,[6] which assumed that the r-process occurred in the neutrino wind from a core collapse supernova. In that study, a succession of 40 ``trajectories" (that is, thin shell wind elements), all assumed to have originated deep within the (assumed spherically symmetric) star, but having initially different conditions of density, temperature, entropy, fraction, and electron fraction, were emitted into the interstellar medium, thus contributing to the total r-process nucleosynthesis. The bubble was evolving in time, so that the conditions under which the individual trajectories were processed changed with the identity of the trajectory. We assumed that the different trajectories were emitted from the star successively, but ceased to be emitted when the collapse to the black hole occurred. Trajectories falling inside the collapse do not escape (left, bottom).

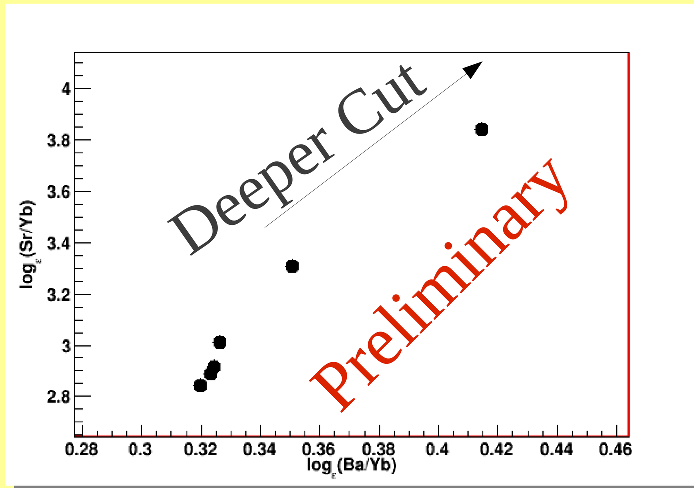


III. Nuclear Reaction Network Coupling

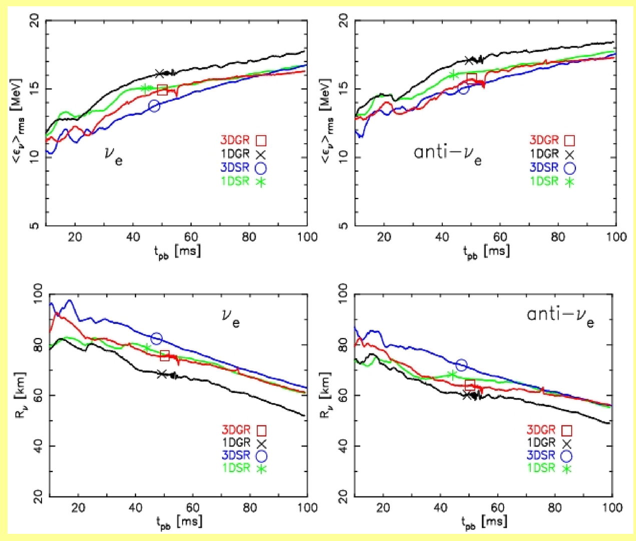
Truncating the r-process at higher trajectories has the effect of terminating the r-process as expected (right). Comparison to the low-metallicity star HD122563 (below) indicates that a physical truncation of the r-process below the mass cut of an accretion-induced black hole may produce a light-element enriched r-process. The [Sr/Ba] observable is shown (below, right) as a function of the mass cut in this model, indicating a large variation of the possible observed value.

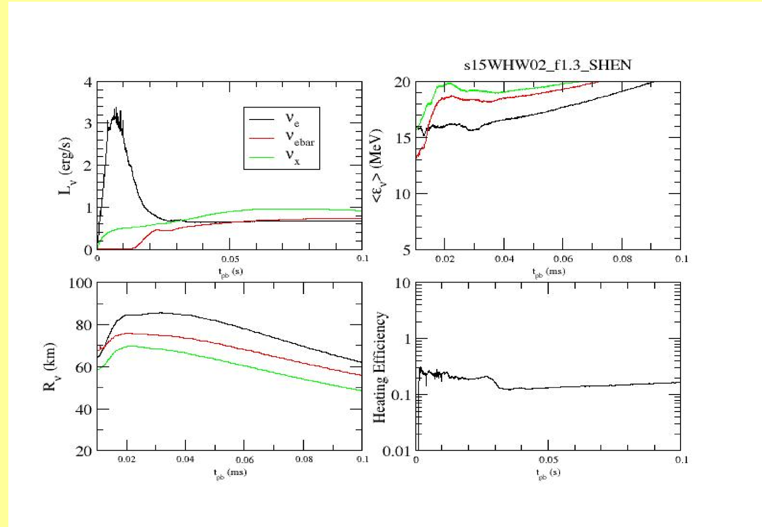




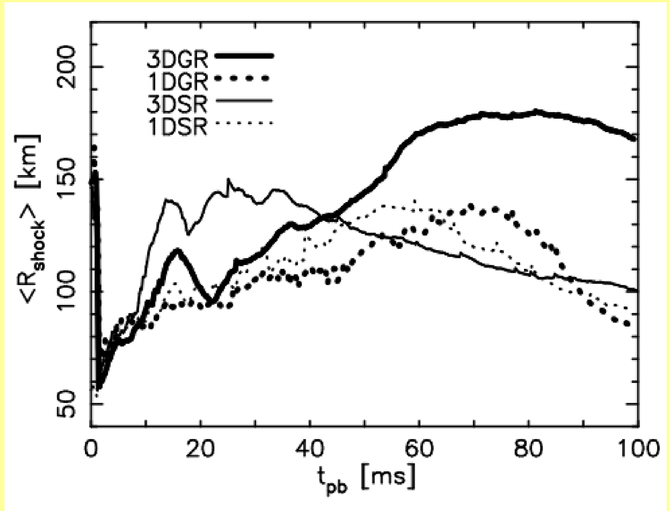


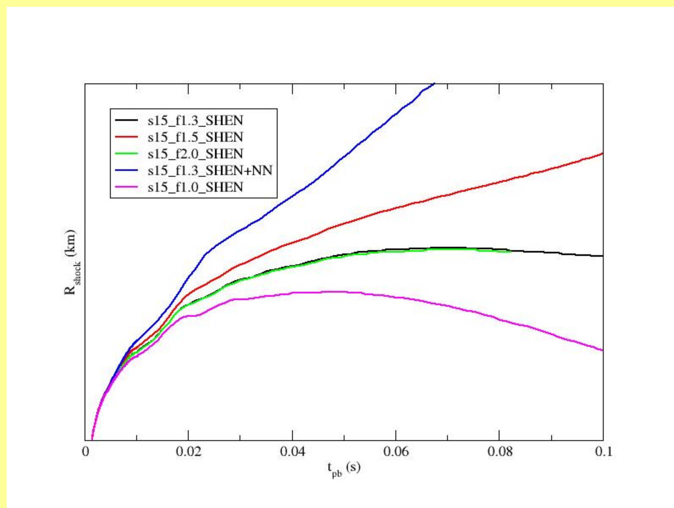
IV. Spherical Collapse Model





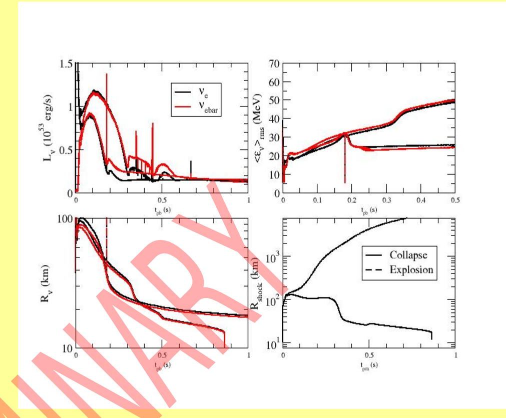
We then proceed to a more formal treatment of the r-process in core collapse supernovae and subsequent black hole formation. In this case, the neutrino heating may be a significant factor. As it is desired to perform hydrodynamics calculations beyond several seconds for several models, a simpler 1D general relativistic code is chosen with an adjustable heating parameter.[7] The neutrino luminosity, RMS energies and neutrinospheres in the spherical code (right) are compared to a 3D GR code (left).[8] The shock radii are compared in this 15 solar mass model utilizing the Shenn EOS (below) ans a solar metallicity profile.[9]

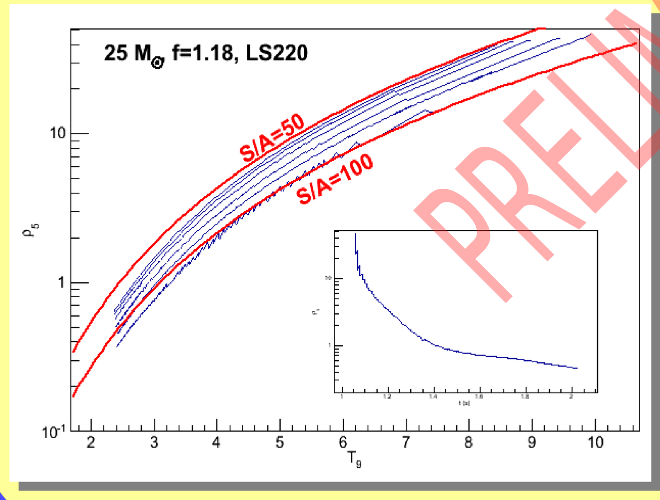


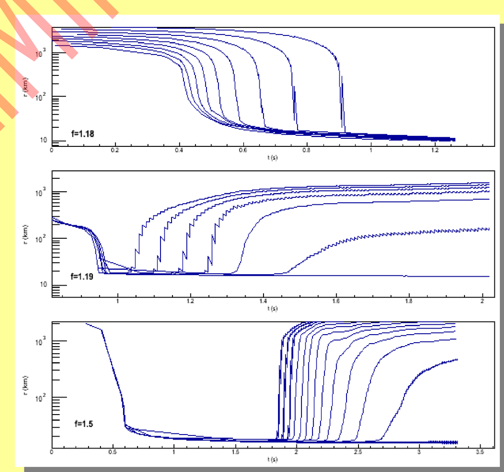


V. r-Process in the Collapse Model

Several preliminary trajectories have been calculated for various assumptions concerning the neutrino heating factor. A few examples are shown for a 25 solar mass model with a successful explosion and a collapse (right, below). The hydrodynamic trajectories for a "barely successful" explosion are shown below with entropy and the expansion timescale (inset).



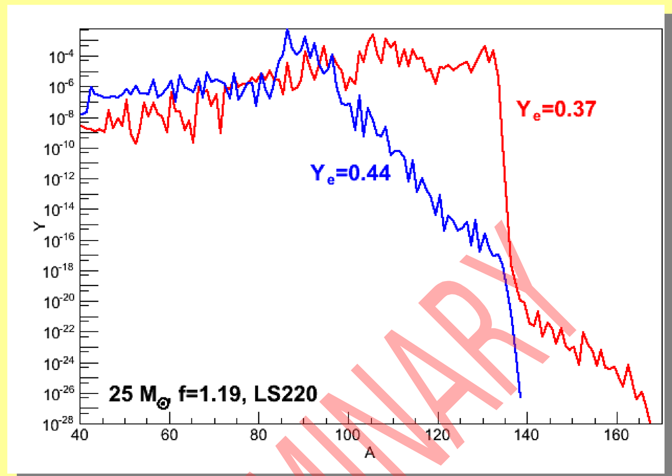


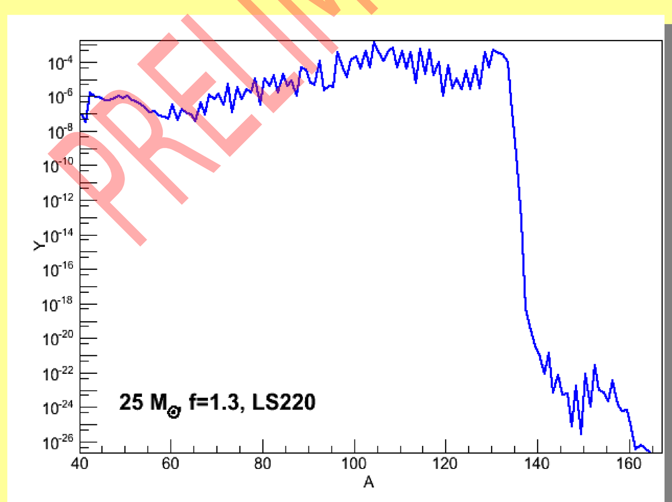


VI. Nucleosynthesis Preliminary Results

A few preliminary trajectories are shown for a 25 solar mass progenitor with zero initial metallicity. In each case, the neutrino heating factor and EOS are indicated. These trajectories are early emission mass shells, and thus similar in scope to the preliminary model used in this study. In the top case, two trajectories are shown from the same star, while in the bottom case, only one trajectory is shown. In both cases, the second r-process peak just begins to form. Future problems to be solved are:

- Studies of late-stage emission, as only early stages are shown here.
- Examination of the neutrino emission as only average neutrino spectra are used in this "grey" model.
- Neutrino cut-offs from collapse.
- Comparison to 3D hydrodynamics.





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