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Nucleosynthesis Calculations from Core-Collapse Supernovae

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We review some of the uncertainties in calculating nucleosynthetic yields, focusing on the explosion mechanism. Current yield calculations tend to either use a piston, energy injection, or enhancement of neutrino opacities to drive an explosion. We show that the energy injection, or more accurately, an entropy injection mechanism is best-suited to mimic our current understanding of the convection-enhanced supernova engine. The enhanced neutrino-opacity technique is in qualitative disagreement with simulations of core-collapse supernovae and will likely produce errors in the yields. But piston-driven explosions are the most discrepant. Piston-driven explosion severely underestimate the amount of fallback, leading to order-of-magnitude errors in the yields of heavy elements. To obtain yields accurate to the factor of a few level, we must use entropy or energy injection and this has become the NuGrid collaboration approach.

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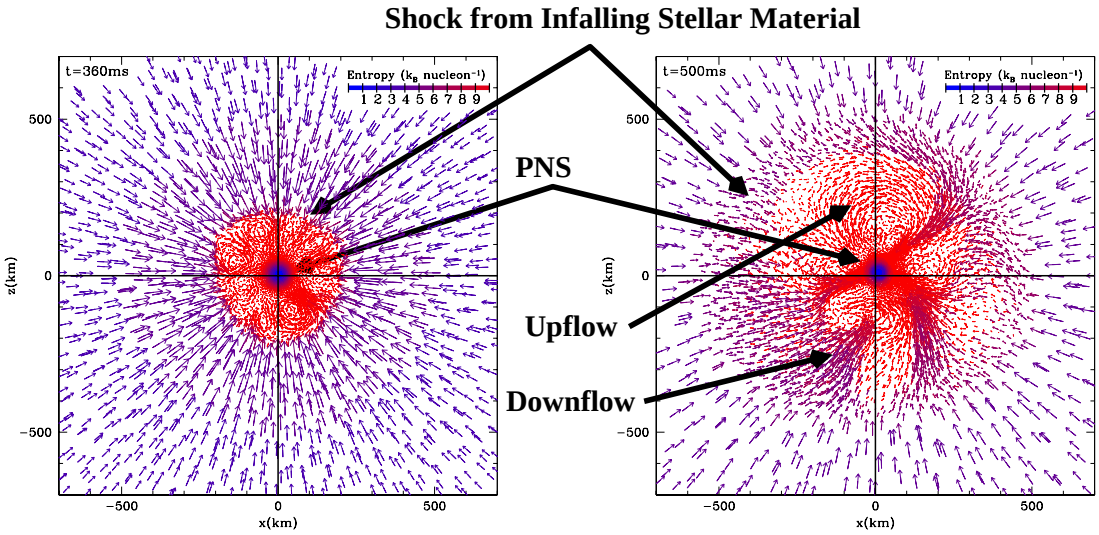

Figure 1: A slice of the x-y plane of a 3-dimensional supernova explosion calculation modeling the collapse of a $23\,M_\odot$ star [6]. The proto-neutron star (PNS) and outer edge of the convective region defined at the position where the infalling stellar material shocks against the convection are labeled. Note that this outer edge moves outward with time. Energy is injected into this convective region rather uniformly, striving to produce a constant entropy profile as the region expands.

1. Nucleosynthesis and Understanding Supernova Explosions

The first step in producing a yield for core-collapse supernovae is to introduce a realistic explosion. Although scientists are still working hard to determine the exact physics behind core-collapse supernova explosions, there is growing support for the convection-driven mechanism [1, 2, 3, 4]. Even so, a lot of work remains (both in the progenitor evolution and the explosion mechanism itself) if we want to accurately predict the explosion energy for a given stellar mass. For the foreseeable future, we will have to artificially induce explosions and explore a range of explosion energies (producing error bars) for nuclear yields. However, a qualitative understanding of the explosion mechanism can help us better induce these explosions so that our range of answers will actually bracket the true answer. As we shall see, some mechanisms used to induce explosions will not produce results consistent with the convection-enhanced neutrino driven mechanism.

Our current understanding of the explosion mechanism behind core-collapse supernovae involves a series of phases (for a review, see [5]). When the mass of a core becomes so large that electron capture and iron dissociation can occur, the core collapses. The core collapses to nuclear densities and bounces, sending a shock through the star. Most of the energy in the shock is thermal and, when neutrinos can escape the shock, they sap the bounce shock's energy and itself. After the bounce shock stalls, the region between the edge of the proto-neutron star and the shock front of the infalling material is unstable to a number of convective instabilities. It is in this convective region that neutrino energy leaking out of the core is converted into kinetic energy that eventually pushes out the infalling star and drives an explosion. Figure 1 shows annotated plots of a convection-driven explosion at 2 different times. As the energy in the convective region grows (and the infall rate decreases), the outer edge of the convective region moves out. Ultimately, the convective region has

enough energy to drive an explosion (although in this case, the explosion is so weak that most of the star will fall back onto the proto-neutron star, forming a black hole).

What can we learn from simulations of this convection-enhanced explosion mechanism? First, energy is deposited in a region covering a few tenths of a solar mass. Convection strives to flatten the entropy gradient, so energy is deposited fairly uniformly across the convective region. As long as the shock (outer edge of the convective region) is moving out slowly (slow enough that convection can redistribute the energy), energy is deposited throughout the convective region. In mass coordinates, the region does not change dramatically with time. Finally, no energy is deposited beyond the convective region.

With this understanding, let's compare the different mechanisms currently used to drive explosions for nucleosynthesis: piston-driven explosions, energy-driven explosions, and enhanced neutrino-opacity driven explosions. Piston-driven explosions have been used extensively in the past and much of the comprehensive yields in the literature are based on these explosions. Piston-driven explosions work by placing a hard surface at the inner boundary (generally assumed to be at the edge of the iron core, but it would be more realistic to use the outer edge of the convective region). This hard surface is then pushed outward, accelerating the star and driving an explosion. Such an approximation keeps accelerating the inner material in the ejecta, not allowing it to slow down and ultimately fall back on the star, severely underestimating the fallback and overestimating the amount of heavy elements (such as ^{56}Ni) for a given explosion energy. This has been discussed at some detail [7] and it is now generally accepted in the explosion community that piston-driven yields are not accurate.

Two alternate options are being used in the literature. A straight energy deposition in the inner few tenths of a solar mass. This method is designed to incorporate the energy increase in the convective region. The energy is limited to a few tenths of a solar mass (the rough mass size of the convective region throughout most calculations). And the energy is injected uniformly (in specific internal energy) across this region (as we would expect from convection). More realistic might be to uniformly increase the entropy throughout this region.

The second method is to artificially increase the neutrino opacity in this region. The argument for this method is that it includes neutrino changes to the electron fraction (albeit at an exaggerated level). The disadvantages are many. First, it injects energy even beyond the convective region. Although it is true that neutrinos in a realistic engine will do this, the opacity is lower, so we are over-estimating this energy injection. Second, the energy deposition is highly peaked toward the dense material and not distributed across the convective engine as we would expect in a real convection-enhanced supernova. Although these artifacts are probably small when compared to the piston/energy deposition differences, they all point a direction opposite from what we would expect from the convection mechanism. This method will be less like the convective engine than a simple direct energy deposition.

2. Comparing Nuclear Yields

We have now discussed in detail the differences between the methods used to simulate a explosions for supernova nucleosynthesis. Table 1 shows the yields for models in the 20-25 $M_\odot$ range by 3 different groups [6, 8, 9]. The stars are all evolved with an initial metallicity at solar, but pre-

Model Name and citation	Model Charact. E_{exp} 10^{51} erg	M_{rem} $M_\odot$	Yields ^{28}Si $M_\odot$	^{45}Sc $10^{-5}\,M_\odot$	^{44}Ti $10^{-5}\,M_\odot$	^{60}Co $10^{-5}\,M_\odot$	^{56}Ni $M_\odot$
WW-S22A[8]	1.47	2.02	0.356	1.20	6.15	2.43	0.205
WW-S25A[8]	1.18	2.07	0.315	0.228	3.04	5.36	0.129
23e-1.5[7]	3.2	1.5	0.303	0.082	0.513	1.03	0.0013
23e-2.0[7]	2.6	2.0	0.461	0.080	6.95	1.04	0.283
d0.2-1.5[7]	2.6	1.5	0.463	0.081	2.62	0.99	0.240
d0.7-1.5[7]	2.3	1.5	0.482	0.091	10.0	1.01	0.216
23p-1.2[7]	3.2	1.2	0.362	0.080	0.655	0.992	0.0066
23p-1.6[7]	2.4	1.6	0.439	0.079	23.5	0.996	0.613
CL-20[9]	1.6	-	0.156	0.542	4.03	1.13	0.10
CL-25[9]	1.8	-	0.245	1.26	2.19	2.44	0.10

Table 1: Yields for a range of models of a roughly 20-25 $M_\odot$ star by different groups. Where given in the literature, we include remnant mass and explosion energy. Except for models 23e-series[7], the models all use piston explosions. This is is evident from the small remnant masses for a given explosion (this can not be reproduced in a real explosion calculation). Note that for a given explosion energy and remnant mass, we get considerable scatter in the yield (more than an order of magnitude). Most of the difference is caused by those results using piston explosions and those using the more realistic models (which include fallback).

scriptions for winds vary somewhat and each group uses its own method to drive explosions. The first difference between the models can be seen in the remnant masses. Note that the WW models both predict remnant masses below $1.5\,M_\odot$ for explosion energies of roughly 2×10^{51} erg. The CL remnants are also small. But at the same energy, the 23e-series produces a $2.6M_\odot$ remnant.

The difference between these remnant masses is entirely an artifact of our method of artificially induced explosions. Different methods produce very different amounts of fallback. To better understand the fallback, let's briefly review its history. The idea of fallback was first brought up by Colgate [10] to overcome nucleosynthesis issues arising from the supernova ejection of neutron rich material produced in stellar cores [11, 12]. Colgate argued that the inner layers of the ejected material would deposit its energy to the stellar material above it, ultimately reducing its energy below that needed to escape the neutron star, and it would fall back onto the neutron star. In such a scenario, one would expect the inner material to fall back quickly (within the first few to ten seconds). It was argued that this material (the neutron rich material from the initial explosion) would accrete onto the neutron star, alleviating any nucleosynthesis issues.

Piston models for explosions misled many scientists on the issue of fallback and the supernova field in general. By artificially preventing fallback, piston modelers became concerned with the ejecta of neutron rich material (recall, this is why Colgate first thought about fallback in the first place). Supernova modelers have worked extensively to try to reset the electron fraction and nucleosynthesis modelers put in knobs to reset the electron fraction and move out the mass cut. The Colgate idea of fallback was all but forgotten. With more modern, energy-injected explosion models, fallback occurs (renewing Colgate's original idea) and removes issues with neutron rich ejecta. This makes it easier for explosion models to match compact remnant mass measurements [14] and

may even explain the r-process [15].

Table 1 also shows the yields for some key elements from these models. There is a lot of scatter in these models, so it is difficult to pick out any specific trend, but note that some elements (e.g. ^{45}Sc) are overproduced by piston models by more than a factor of 10. Also, the ratio of ^{44}Ti to ^{56}Ni can be an order of magnitude higher in some energy-driven explosions (making it easier to explain the supernova that produced Cassiopeia A). Not until we model a full suite of models will we truly understand the extent of the errors introduced by piston-driven models.

For our in-progress NuGrid calculations, we use a constant entropy injection process. This is the closest match to the convection-enhanced explosion mechanism. When the shock moves beyond 1000 km, we stop the energy injection (which due to the entropy increase process starts to decrease as the density lowers anyway). This still leaves 2 parameters: total energy injection and rate at which the energy is injected. The rate has been studied at some level [7] and it can lead to order of magnitude differences in the yield. Fortunately, for a given explosion energy, we can constrain the delay time [13], so we believe we can fix this parameter somewhat, limiting its errors.

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