# Modeling Core-Collapse Supernovae in 3-Dimensions

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## ABSTRACT

We present the first complete 3-dimensional simulations of the core-collapse of a massive star from the onset of collapse to the resultant supernova explosion. We compare the structure of the convective instabilities that occur in 3-dimensional models with those of past 2-dimensional simulations. Although the convective instabilities are clearly 3-dimensional in nature, we find that both the size-scale of the flows and the net enhancement to neutrino heating does not differ greatly between 2- and 3-dimensional models. The explosion energy, explosion timescale, and remnant mass does not differ by more than 10% between 2- and 3-dimensional simulations.

*Subject headings:* stars: evolution - supernova: general

## 1. Introduction

Convective instabilities have been invoked to help drive core-collapse supernova explosions since Epstein (1979) first argued that negative lepton gradients would drive Ledoux convection in the core. Epstein (1979) argued that this convection would increase the transport of energy out of the core and help facilitate a supernova explosion. Bruenn, Buchler, & Livio (1979) confirmed that this convection could indeed increase the neutrino luminosity and help drive a supernova explosion. Considerable work studying convective instabilities, including multi-dimensional models (e.g. Buchler, Livio, & Colgate 1980), followed soon after. Although entropy gradients caused by the shock were suggested during this time (see Bruenn, Buchler, & Livio 1979), Burrows (1987) first suggested that this entropy-driven convection could also boost the neutrino luminosity and help drive a supernova explosion.

The work of the past two decades has led to two separate convective regions: one within the extremely dense proto-neutron star core (see Keil, Janka, & Müller 1996 for a review) and the other in the region between the proto-neutron star and the accretion shock where the bounce stalled. In this latter region, neutrino heating powers an unstable entropy gradient that drives convection (see Bethe 1990 for a review). In the dense proto-neutron star, convection driven by lepton gradients (Epstein 1979, Keil et al. 1996), entropy gradients (Burrows 1987, Burrows & Lattimer 1988), and doubly diffusive ("salt-finger") instabilities (Mayle & Wilson 1988) have all been invoked to increase the neutrino luminosity and hence, the neutrino heating. In the neutrino heating region, entropy-driven convection helps to convert thermal energy gained from neutrino heating into kinetic energy, improving the over-all efficiency at which neutrinos from the core deposit energy into the outer layers of the star. This latter convection has been studied in a number of 2-dimensional simulations over the last decade (Miller, Wilson, & Mayle 1993; Herant et al. 1994; Burrows & Hayes 1995; Janka & Müller 1996; Mezzacappa et al. 1998).

This entropy driven convection occurs shortly after the collapse of the massive star. When this core reaches nuclear densities and nuclear forces rapidly raise the pressure, its collapse halts, sending a bounce shock through the star. This bounce shock stalls and leaves behind an unstable entropy profile that seeds convection in the region between the proto-neutron star and the edge of the stalled supernova shock. Neutrinos leak out from the proto-neutron star and heat this region, continuing to drive this entropy-driven convection. It is

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this convection that many groups now agree helps drive the supernova explosion (Herant et al. 1994; Burrows & Hayes 1995; Janka & Müller 1996).

However, due to limitations in computer hardware and simulation software, all of the past work was limited to 2-dimensional simulations, leaving behind a number of unanswered questions. Whether or not this increased efficiency is sufficient to drive a supernova explosion with the current supernova mechanisms is still a matter of debate: compare the explosions of Herant et al. (1994) and Burrows & Hayes (1995) to the fizzles of Mezzacappa et al. (1998). A key uncertainty in all of these simulations lies in the fact that the 2-dimensional simulations are being used to study an inherently 3-dimensional event in nature. Some scientists have argued that nature will produce convective instabilities that are much different than what we see in the current 2-dimensional simulations. In other convective problems (e.g. novae) it has been found that 2-dimensional models of these inherently 3-dimensional processes can lead to vastly incorrect answers (compare the differences between the 2- and 3-dimensional work of Kercek, Hillebrandt, & Truran 1998, 1999).

In this letter, we present the first complete 3-dimensional simulations of the evolution of a massive star from collapse to explosion, with particular emphasis on the differences between 2 and 3-dimensional models of the entropy-driven convection. We follow these simulations until a strong supernova shock has been launched, and can hence see how these differences affect the final explosion energy, remnant mass, and nucleosynthetic yield of these supernovae.

## 2. 3-Dimensional Simulations

Our collapse simulations use the smooth particle hydrodynamics (SPH) technique with the parallel tree algorithm developed by Warren & Salmon (1993, 1995). To this parallel code, we have added the equation of state and neutrino physics from the supernova code developed by Herant et al. (1994). The equation of state uses the nuclear equation of state by Lattimer & Swesty (1991) at high densities and the Blinnikov, Dunina-Barkovskay, & Nadyozhin (1996) equation of state at low densities. Nuclear burning is approximated by a nuclear statistical equilibrium scheme (Hix & Thielemann 1996). The neutrino transport is mediated by the single energy flux-limiter developed by Herant et al. (1994) with appropriate geometrical factors for 3-dimensional models. Details and tests of this code are described in Warren, Gentle, & Fryer (2002). To facilitate comparison with past 2-dimensional simulations (Fryer 1999), the gravity is calculated assuming a spherically symmetric potential.

Our progenitor is the standard $15\,M_\odot$ star (s15s7b2) produced by Woosley & Weaver (1995). By using the same equation of state for low densities used by Woosley & Weaver (1995), we can seamlessly map these 1-dimensional progenitors into our 3-dimensional collapse code. To study the convection in detail, we have run 3 core-collapse simulations this progenitor with a range of resolutions from 300,000 to 3 million particles (see Table 1). We compare these simulations to past 2-dimensional simulations which have the same physics implementations (Fryer 1999) to determine the differences between 2-dimensional and 3-dimensional models of convection and more fully understand the role convection plays in the supernova mechanism.

Figure 1 shows the results of models A, B, and C 75 ms after bounce. The isosurface shows material with radial velocities of $1000\,\mathrm{km\,s^{-1}}$ and outlines the outward moving convective bubbles. Between this surface lies the convective downflows. Note that even in the high resolution runs, the total number of bubbles is low, roughly consistent with the number of modes one might expect from the 2-dimensional simulations. A 2-dimensional slice of model B (Fig. 2) reveals convective overturns which are very similar to the 2-dimensional simulations (see Fryer 1999).

The 3-dimensional simulations produce nearly the same neutrino fluxes and energies that were found in the 2-dimensional simulations (Fig. 3). Although this is not surprising because the transport methods were identical (except for geometrical factors), it does show that the small differences in the convective motions do not seem to dramatically affect the neutrino emission.

Given that the 3-dimensional simulations appear similar to the 2-dimensional simulations, it is not surprising that most of the quantitative results between these simulations are the same. The ultimate explosion energy, explosion times, and remnant masses are all within 10% of each other. Although on the surface, the amount of neutron rich ejecta is similar, the 3-dimensional simulations produce more extremely low ($Y_e < 0.45$) ejecta than the 2-dimensional models, and 3-dimensional models, if anything, exacerbate the problem of ejecting too much neutron rich material.

## 3. Implications

Although the structure of the entropy-driven convection in core-collapse supernova is definitely 3-dimensional, there is close resemblance between our 3-dimensional simulations and past 2-dimensional simulations. This suggests that, for the accuracy currently needed in supernova simulations, 2-dimensional models may be sufficient to determine the convective enhancement to the neutrino-driven supernova mechanism. Certainly, the uncertainties in the nuclear equation of state and in the neutrino cross-sections and transport are much larger than the uncertainties caused by assuming 2-dimensional convection. The fact that the 3-dimensional models continue to produce too much neutron rich ejecta implies that there still persists missing pieces to the supernova puzzle (probably the neutrino transport, neutrino cross-sections, and equation of state are all culprits).

Our simulations are designed to study the nature of the convection above the proto-neutron star in core-collapse supernovae. The convection arising in our 3-dimensional simulations shows a remarkable resemblance to 2-dimensional core-collapse simulations. Unlike the nova simulations of Kercek, Hillebrandt, & Truran (1998, 1999), the structure, extent and energetics of the convection in core-collapse simulations are the same in 2 and 3-dimensions.

We cannot stress enough the fact that the numbers provided in this paper are not final answers to the collapse of a $15\,M_\odot$ star. With better neutrino transport techniques, neutrino cross-sections and equations of state, these values will change. However, changes in the neutrino physics and equation of state are unlikely to change the nature of the convection above the proto-neutron star. Unless the nature of the convection changes dramatically with these improvements, our 3-dimensional models show that the convection above the proto-neutron star in core-collapse supernovae is modeled accurately in 2-dimensions. Indeed, for the level of convection arising from our simulations of the core-collapse of a $15\,M_\odot$ star, we find that 2-dimensional models are sufficiently accurate to model the supernova mechanism. Of course, 3-dimensional models will still be essential for studies of inherently 3-dimensional aspects of core-collapse (neutron star kicks, gravitational wave emission, etc.).

Note also, that for these simulations (where the gravity is set to be spherically symmetric), there are no large asymmetries in the explosion. Because there are so many convective modes, it is unlikely that any large asymmetry will develop without some large-scale force driving that asymmetry (e.g. asymmetries in the neutrino emission or initial collapse conditions). It is possible that the convection will reduce to fewer modes for those explosions with long delays (Janka - pvt. communication). If so, it may be possible to produce the observed neutron star kicks. But with the current models, convection alone can not explain the large neutron star kicks. In future work, we will address these asymmetry issues by modeling with full gravity and considering changes to the initial conditions from rotation to initial asymmetries.

We are grateful to H.-T. Janka, A. Hungerford, A. Burrows, S. Woosley, and W. Miller for useful discussions and support. This work was funded by a Feynman Fellowship at LANL, DOE SciDAC grant number DE-FC02-01ER41176 , and LANL-based ASCI grant.

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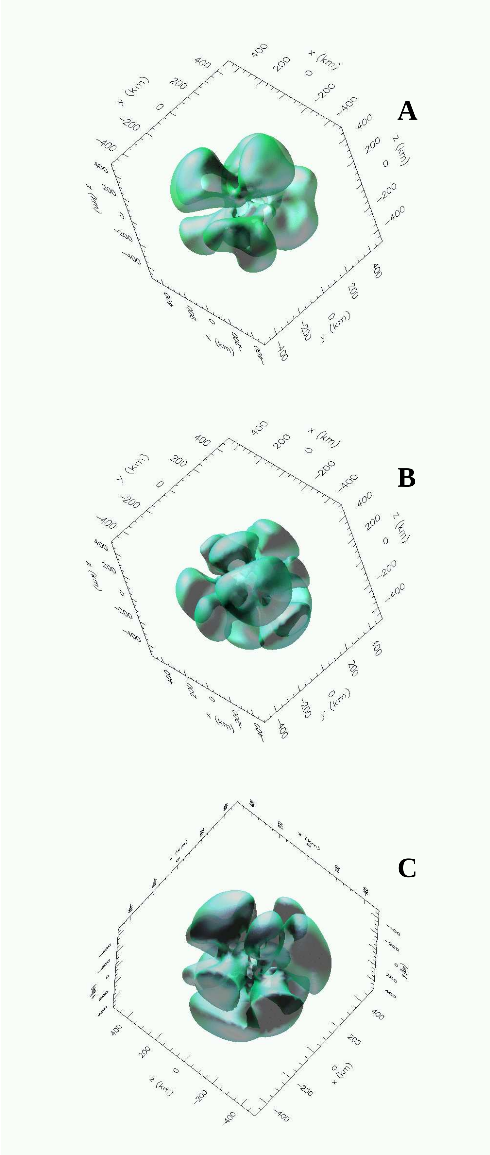


Fig. 1.— The isosurface of material with radial velocities of $1000\,\mathrm{km\,s^{-1}}$ for models A, B and C. The isosurface outlines the outward moving convective bubbles. The open spaces mark the downflows. Note that the upwelling bubbles are large and have very similar size-scales to the 2-dimensional simulations.

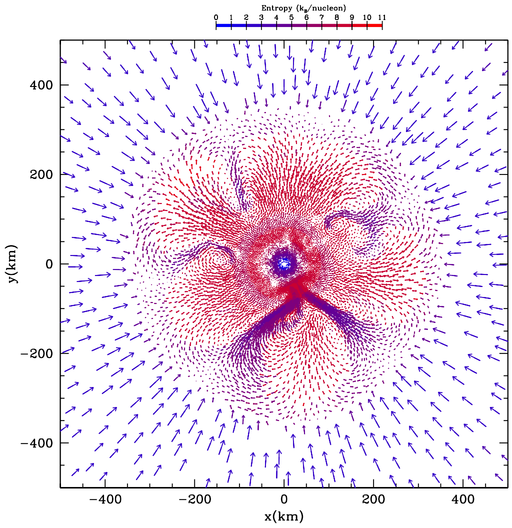


Fig. 2.— A slice of model B, colored by its entropy and showing velocity vectors. The cold, low-entropy material flows downward as the high entropy material bubbles upward. Note that the size-scale and even structure of this convection is very similar to 2-dimensional models (see Herant et al. 1994, Fryer 1999).

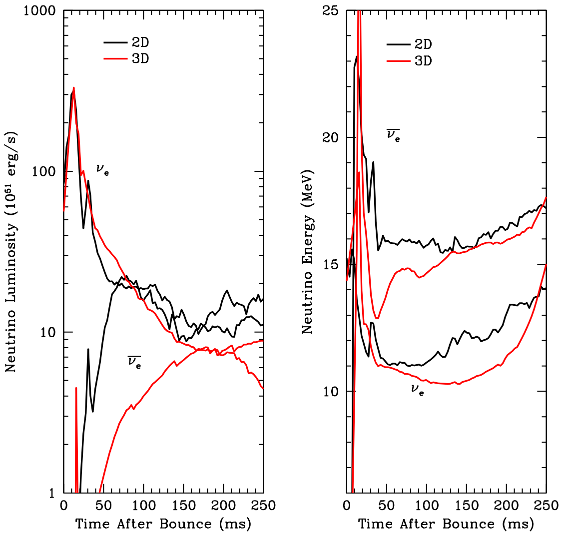


Fig. 3.— Electron and anti-electron neutrino luminosities and energies for a 2-dimensional model (Fryer 1999) and our 3-dimensional models. Note that the neutrino luminosities and energies are very similar, indicating that the differences caused by convection in 2- and 3-dimensions are not large.

Table 1

Core-Collapse Simulations

| Model | Particle Number | Explosion Energy [a] ($10^{51}$ ergs) | $\mathrm{T_{Explosion}}$ [b] s | $\mathrm{M_{core}}$ ($M_\odot$) | Low $Y_e$ Ejecta [c] ($M_\odot$) |
|---|---|---|---|---|---|
| 2D Model [d] | 15,000 | 3.0 | 0.10 | 1.1 | 0.24 |
| Model A | 300,000 | 2.9 | 0.15 | 1.15 | 0.29 |
| Model B | 1 million | 2.75 | 0.17 | 1.15 | 0.28 |
| Model C | 3 million | ~3 [e] | 0.15 | 1.15 | 0.26 |

[a] The explosion energy is as defined in Fryer (1999) and includes both internal and kinetic energy.

[b] The explosion time is determined by the duration after bounce that it takes the shock to reach 1000 km.

[c] Low $Y_e$ material refers to ejecta with electron fraction ($Y_e$) beolow 0.49.

[d] Newtonian gravity simulation from Fryer (1999).

[e] Due to the high resolution in Model C, we have not yet run the simulation out long enough to accurately determine the explosion energy.