

An Investigation of Neutrino-Driven Convection and the Core Collapse Supernova Mechanism Using Multigroup Neutrino Transport

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Abstract

We investigate neutrino-driven convection in core collapse supernovae and its ramifications for the explosion mechanism. We begin with an “optimistic” $15 M_{\odot}$ precollapse model, which is representative of the class of stars with compact iron cores. This model is evolved through core collapse and bounce in one dimension using multigroup (neutrino-energy-dependent) flux-limited diffusion (MGFLD) neutrino transport and Lagrangian hydrodynamics, providing realistic initial conditions for the postbounce convection and evolution. Our two-dimensional simulation begins at 106 ms after bounce at a time when there is a well-developed gain region, and proceeds for 400 ms. We couple two-dimensional (PPM) hydrodynamics to one-dimensional MGFLD neutrino transport.

At 225 ms after bounce we see large-scale convection behind the shock, characterized by high-entropy, mushroom-like, expanding upflows and dense, low-entropy, finger-like downflows. The upflows reach the shock and distort it from sphericity. The radial convection velocities become supersonic just below the shock, reaching magnitudes in excess of 10^9 cm/sec. Eventually, however, the shock recedes to smaller radii, and at ~ 500 ms after bounce there is no evidence in our simulation of an explosion or of a developing explosion.

Failure in our “optimistic” $15 M_{\odot}$ Newtonian model leads us to conclude that it is unlikely, at least in our approximation, that neutrino-driven convection will lead to explosions for more massive stars with fatter iron cores or in cases in which general relativity is included.

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1. Introduction

Despite the best efforts of theorists over three decades, the core collapse supernova mechanism, at least in detail, remains elusive. Current supernova modeling is centered around the idea that the supernova shock wave, which stalls in the stellar core because of dissociation and neutrino losses, is reenergized by electron neutrino and antineutrino absorption on nucleons behind it (Bethe & Wilson 1985; Wilson 1985), although no recent numerical simulations produce explosions unless the neutrino luminosities or the energy deposition efficiencies are boosted by convection (Wilson & Mayle 1993, Herant et al. 1994, Burrows et al. 1995, Janka & Müller 1996). One potentially important mode is neutrino-driven convection below the shock (Herant et al. 1992), which is the subject of this Letter. It is driven by a negative entropy gradient established by neutrino heating (primarily absorption) as the shocked matter infalls.

Two-dimensional simulations of neutrino-driven convection and core collapse supernovae have produced mixed results. Herant et al. (1992, 1994) find that neutrino-driven convection consistently yields robust explosions, whereas Miller et al. (1993), Burrows et al. (1995), and Janka and Müller (1996) do not. Burrows et al. (1995) point out that success or failure in their algorithm depends sensitively on the choice of neutrino–matter coupling above the neutrinospheres; Janka and Müller have shown systematically that neutrino-driven convection only aids in generating explosions for a narrow range of neutrino luminosities; Miller et al. (1993) find that neutrino-driven convection develops too slowly to be relevant for the postbounce supernova evolution.

These disparate outcomes most likely result from differences in the numerical hydrodynamics methods and neutrino transport approximations used by each group, although differences in equations of state, neutrino opacities, etc. probably contribute, too. Most important, no group has yet implemented neutrino transport that simultaneously (a) is multidimensional, (b) is multigroup (neutrino-energy-dependent), and (c) simulates with sufficient realism the transport of neutrinos in all three important regions: opaque, semitransparent, and transparent. It has been shown that the initial conditions for convection and the postbounce supernova evolution are sensitive to the sophistication of neutrino transport during core collapse and bounce, with greater sophistication leading to weaker shocks and the establishment of smaller initial entropy gradients to drive convection [e.g., see Bruenn & Mezzacappa (1994)]. Moreover, it is well established that the neutrino shock-reheating mechanism is extremely sensitive to the luminosities, spectra, and flux factors of the electron neutrinos and antineutrinos that emerge from the neutrinospheres [e.g., see Burrows et al. (1995) and Janka & Müller (1996)].

Our goal in this Letter is to fulfill criteria (b) and (c) in the context of multidimensional supernova modeling: We couple one-dimensional multigroup flux-limited diffusion neutrino transport to two-dimensional hydrodynamics. This satisfies (b) and (c), and is the first implementation of multigroup transport in this context.

2. Initial Models, Codes, and Methodology

We begin with the $15 M_{\odot}$ precollapse model S15s7b provided by Woosley (1995). The initial model was evolved through core collapse and bounce using MGFLD neutrino transport and Lagrangian hydrodynamics, providing realistic initial conditions for the postbounce convection and evolution. The one-dimensional data at 106 ms after bounce (305 ms after the initiation of core collapse) were mapped onto our two-dimensional Eulerian grid. We selected an initial postbounce slice that had a well-developed gain region. The inner and outer boundaries of our grid were chosen to be at radii of 20 km and 1000 km, respectively. 128 nonuniform radial spatial zones were used, and 128 uniform angular zones spanning a range of 180 degrees were used for θ (together with reflecting boundary conditions). [For more detail, see Mezzacappa et al. (1996a) and Calder et al. (1996ab).]

The initial Ledoux (entropy and electron fraction) unstable region below the shock at the onset of our simulation extended from a radius of 99 km to a radius of 170 km. At the base of the unstable region, the electron fraction, Y_e , is equal to 0.2375; at the top, $Y_e = 0.4956$. The maximum entropy per baryon (in units of Boltzmann’s constant) is 10.66, and drops to 8.574 at the top of the region.

When the matter in our simulations is in nuclear statistical equilibrium (NSE), we describe its thermodynamic state using the Lattimer–Swesty equation of state (Lattimer & Swesty 1991). At late times in our outermost zones, the densities and/or temperatures become low enough that the infalling matter is no longer in NSE. In this instance, i.e., when our deflashing threshold ($\rho < 1.674 \times 10^7 \text{ g/cm}^3$ and/or $T < 0.3447 \text{ MeV}$) is crossed in any given zone, the zone is deflashed to silicon in an energy conserving way. An ideal gas equation of state is then used to describe the silicon in its subsequent evolution, which includes internal degrees of freedom to mimic the Lattimer-Swesty equation of state to provide a seamless thermodynamic transition between NSE and non-NSE.

In our two-dimensional simulations, the Newtonian gravity was assumed to be spherically symmetric. The gravitational field in the convectively unstable region was dominated by the enclosed mass at the region’s base, which at the start of our simulations was $1.33 M_{\odot}$; at this time, the enclosed mass at the top of the region was $1.36 M_{\odot}$.

Details of our codes and more detail on our methodology can be found in Mezzacappa et al. (1996a) and Calder et al. (1996ab).

3. Results

Figure 1 illustrates the evolution of entropy and neutrino-driven convection during the course of our two-dimensional $15 M_{\odot}$ simulation. At $t = 424 \text{ ms}$ (i.e., 119 ms from the start of our simulation and 225 ms after bounce), $R_{\text{shock}} \approx 205 \text{ km}$, and neutrino-driven convection is fully

developed. Semiturbulent, large-scale, convective flows below the shock are evident, qualitatively similar to the convection seen by Burrows et al. (1995) and Janka and Müller (1996) using the same numerical hydrodynamics method (PPM), but more turbulent than the convective flows seen by Herant et al (1994) using smooth particle hydrodynamics. High-entropy, mushroom-like, rising plumes reach the shock and distort it from sphericity, while material behind the shock infalls in dense, low-entropy, fingers.

At $t = 424$ ms, the angle-averaged entropy defined by $\langle s \rangle(r) = \sum_{\theta} s(r, \theta)A(r, \theta)/A$, where $A = 4\pi r^2$ and $A(r, \theta) = 2\pi r^2 \sin \theta \Delta \theta$, has a maximum $s_{\max} = 13.5$. The convection is subsonic over most of the convecting region but becomes supersonic just below the shock. The average radial convection velocities, defined by $\langle v_r^C \rangle(r) = \sum_{\theta} [|v_r(r, \theta)| - \langle v_r \rangle(r)]A(r, \theta)/A$, where $\langle v_r \rangle(r) = \sum_{\theta} |v_r(r, \theta)|A(r, \theta)/A$, reach magnitudes in excess of 10^9 cm/sec [for details, see Calder et al. (1996b)].

Despite the development of significant neutrino-driven convection below the shock, the shock eventually recedes to smaller radii from ~ 200 km at $t = 204$ ms after bounce to ~ 100 km at $t = 506$ ms after bounce, and the convection becomes more turbulent. Our simulation ends at $t = 705$ ms (506 ms after bounce), with no evidence of an explosion or of a developing explosion. Other groups obtain explosions within the first 50–100 ms after bounce (Herant et al. 1994; Burrows et al. 1995; Janka & Müller 1996).

The neutrino heating rate (in MeV/nucleon) in the region between the neutrinospheres and the shock can be written as

$$\dot{\epsilon} = \frac{X_n}{\lambda_0^a} \frac{L_{\nu_e}}{4\pi r^2} \langle \epsilon_{\nu_e}^2 \rangle \langle \frac{1}{f} \rangle + \frac{X_p}{\bar{\lambda}_0^a} \frac{L_{\bar{\nu}_e}}{4\pi r^2} \langle \epsilon_{\bar{\nu}_e}^2 \rangle \langle \frac{1}{\bar{f}} \rangle \quad (1)$$

where $X_{n,p}$ are the neutron and proton fractions; $\lambda_0^a, \bar{\lambda}_0^a$ are the coefficients of the $\epsilon_{\nu_e, \bar{\nu}_e}^{-2}$ neutrino energy dependences in the electron neutrino and antineutrino mean free paths, respectively; $L_{\nu_e, \bar{\nu}_e}$, $\langle \epsilon_{\nu_e, \bar{\nu}_e}^2 \rangle$, and $\langle 1/f, \bar{f} \rangle$ are the electron neutrino and antineutrino luminosities, mean square energies, and mean inverse flux factors, respectively, as defined in Mezzacappa et al. (1996b). Success in generating explosions by neutrino heating must ultimately rest on these three key neutrino quantities. In Figures 2 and 3, we plot them as a function of radius for select times during our simulation. We supply this complete set of neutrino data to facilitate comparison with other groups; in the past, only partial data have been made available in the literature.

Equation (1) is appropriate for neutrino emission and absorption. In our simulation, the heating contributions from neutrino–electron scattering (NES) are negligible, amounting to 3–5% corrections for our postshock entropies ($\leq 17 - 18$). At typical postshock densities between 10^8 and 10^9 g/cm³, entropies ~ 30 (almost twice as large as our entropies) would be required before the number density of pairs would become comparable to the baryon number density, i.e., before our NES heating contributions would double.

4. Discussion

Our results depend in part on the assumption that our electron neutrino and antineutrino sources remain to a good approximation spherically symmetric during the course of our two-dimensional run. This requires that there be no significant convection in the region encompassing or below the neutrinospheres and no significant influence of neutrino-driven convection below the gain radii:

(A) *Convection Below the Neutrinospheres:* In a previous paper (Mezzacappa et al. 1996a), we demonstrated that, in the presence of neutrino transport, the convective transport of heat and leptons below the neutrinospheres by *prompt* convection is insignificant. Our numerical results were supported by timescale analyses and by a simple analytical model. These results are mentioned here in support of the conclusions reached in this Letter. In the absence of prompt convection, the imposition of a one-dimensional spherically-symmetric neutrino radiation field in the region between the neutrinospheres and the shock, which is used to compute the neutrino heating and cooling there, is a better approximation.

(B) *The Influence of Neutrino-Driven Convection Below the Gain Radii:* Because our current prescription does not implement a self-consistent two-dimensional radiation hydrodynamics solution, we cannot capture enhancements in the neutrino luminosities emanating from the neutrinosphere region that result from (1) non-spherically-symmetric accretion through the gain radius and/or (2) inwardly propagating nonlinear waves that compress and heat the neutrinosphere region in a non-spherically-symmetric way. For example, the dense, finger-like, low-entropy inflows in the neutrino-driven convection region may penetrate the gain radius and strike the protoneutron star surface (Burrows et al. 1995, Janka & Müller 1996). It has been suggested that the associated luminosity enhancements may help trigger explosions (Burrows et al. 1995), but conclusions regarding their benefit have been mixed (Janka & Müller 1996).

To investigate whether these effects would have been important in our simulation, we compared our one- and two-dimensional density, temperature, and electron fraction snapshots at $t = 424$ ms, a time when neutrino-driven convection was most vigorous. Up to the neutrinosphere radii (~ 50 km), we found no differences. Between the neutrinospheres and the gain radii (~ 85 km), we found hot spots in our two-dimensional simulation where $\Delta T/T \sim 3\%$ over $\sim 1/4 - 1/3$ of the volume, and Y_e -enhanced spots where $\Delta Y_e/Y_e \sim 3 - 6\%$ over $\sim 1/5$ of the volume. Because of the T^6 dependence in the neutrino emission rates, to first order we would expect localized luminosity enhancements $\sim 18\%$. However, at $t \sim 100 - 200$ ms after bounce, $L_{\nu_e}(50 \text{ km}) \approx 2.4 \times 10^{52}$ erg/sec and $L_{\nu_e}(90 \text{ km}) \approx 3.5 \times 10^{52}$ erg/sec; therefore, only $\sim 33\%$ of the neutrino luminosities would have been affected by these temperature and electron-fraction enhancements. (The percentages for electron antineutrinos are comparable: $\sim 50\%$ at 100 ms and $\sim 33\%$ at 200 ms.)

Considering the small local enhancements in T and Y_e , the small percentage of the volume in which they occur, and the fraction of the neutrino luminosities that would be affected by them,

we do not expect these enhancements to have significant ramifications for the supernova outcome.

5. Summary and Conclusions

With two-dimensional (PPM) hydrodynamics coupled to one-dimensional multigroup flux-limited diffusion neutrino transport, we see vigorous — in some regions supersonic — neutrino-driven convection develop behind the shock, but despite this, do not obtain explosions for what should be an “optimistic” $15 M_{\odot}$ model. Beginning with realistic postbounce initial conditions, our simulation has been carried out for ~ 500 ms, a period that is long relative to the 50–100 ms explosion timescales obtained by other groups.

We have considered the non-spherically-symmetric luminosity enhancements that would occur from local temperature and electron fraction enhancements below the gain radii (which enclose the electron neutrino and antineutrino sources) that are seen in our two-dimensional run, which result either from non-spherically-symmetric accretion through the gain radius or nonlinear inwardly propagating non-spherically-symmetric waves. We see no enhancements below the neutrinosphere radii; between them and the gain radii, we see small enhancements that occur over a small fraction of the volume responsible for producing less than one third of the neutrino luminosities. From this, we conclude that the use of one-dimensional MGFLD neutrino transport in our two-dimensional simulations is a good approximation.

We do not expect to obtain explosions for more massive stars. [The results for other models will be reported in Calder et al. (1996b).] Moreover, our simulations are Newtonian; with general relativistic gravity, conditions will be even more pessimistic. The neutrino luminosities will be redshifted, the increased infall velocities and the smaller width between the gain radii and the shock will allow less time for neutrino heating to reverse infall, and everything will occur in a deeper gravitational well, making explosion more difficult.

Our results point to the need, at least in our approximation, for either improved neutrino transport (relative to MGFLD) or new physics in order to obtain consistent robust explosions. Recently, we have obtained new results from comparisons of three-flavor Boltzmann neutrino transport and three-flavor MGFLD in postbounce supernova environments (thermally frozen, hydrostatic). In particular, the Boltzmann electron neutrino and antineutrino heating rates between the neutrinospheres and the shock are larger, and the Boltzmann net heating rates in the region directly above the gain radii are significantly larger (Mezzacappa et al. 1996b). These results suggest that Boltzmann transport will yield greater neutrino heating and more vigorous neutrino-driven convection; both would increase the chances of reviving the stalled shock.

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7. References

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Fig. 1.— The two-dimensional entropy at three “early” time slices for our $15 M_{\odot}$ model. Large-scale convection with high-entropy expanding upflows and low-entropy dense downflows is evident. The upflows extend to the shock, do work, and distort it.

Fig. 2.— The electron neutrino luminosity, RMS energy, and mean inverse flux factor are plotted as a function of radius at select times during our $15 M_{\odot}$ simulation.

Fig. 3.— The electron antineutrino luminosity, RMS energy, and mean inverse flux factor are plotted as a function of radius at select times during our $15 M_{\odot}$ simulation.