AN INVESTIGATION OF NEUTRINO-DRIVEN CONVECTION AND THE CORE-COLLAPSE SUPERNOVA MECHANISM USING MULTIGROUP NEUTRINO TRANSPORT[1]

A. Mezzacappa, A. C. Calder[2], S. W. Bruenn[3], J. M. Blondin[4], M. W. Guidry[5], M. R. Strayer, A. S. Umar[6]

We investigate neutrino-driven convection in core collapse supernovae and its ramifications for the explosion mechanism. We begin with a postbounce model that is optimistic in two important respects: (1) we begin with a 15 $M_\odot$ precollapse model, which is representative of the class of stars with compact iron cores; (2) we implement Newtonian gravity. Our precollapse model is evolved through core collapse and bounce in one dimension using multigroup (neutrino energy-dependent) flux-limited diffusion (MGFLD) neutrino transport and Newtonian Lagrangian hydrodynamics, providing realistic initial conditions for the postbounce convection and evolution.

Our two-dimensional simulation begins at 12 ms after bounce and proceeds for 500 ms. We couple two-dimensional piecewise parabolic method (PPM) hydrodynamics to precalculated one-dimensional MGFLD neutrino transport. (The neutrino distributions used for matter heating and deleptonization in our two-dimensional run are obtained from an accompanying one-dimensional simulation. The accuracy of this approximation is assessed.) For the moment, we sacrifice dimensionality for realism in other aspects of our neutrino transport. MGFLD is an implementation of neutrino transport that simultaneously (1) is multigroup and (2) simulates with sufficient realism the transport of neutrinos in opaque, semitransparent, and transparent regions. Both are cruicial to the accurate determination of postshock neutrino heating, which sensitively depends on the luminosities, spectra, and flux factors of the electron neutrinos and antineutrinos emerging from their respective neutrinospheres.

By 137 ms after bounce, we see neutrino-driven convection rapidly developing beneath the shock. By 212 ms after bounce, this convection becomes large scale, characterized by higher-entropy, expanding upflows and lower-entropy, denser, finger-like downflows. The upflows reach the shock and distort it from sphericity. The radial convection velocities at this time become supersonic just below the shock, reaching magnitudes in excess of 10^9 cm s^{-1}. Eventually, however, the shock recedes to smaller radii, and at $\sim$500 ms after bounce there is no evidence in our simulation of an explosion or of a developing explosion.

Our angle-averaged density, entropy, electron fraction, and radial velocity profiles in our two-dimensional model agree well with their counterparts in our accompanying one-dimensional MGFLD run above and below the neutrino-driven convection region. In the convection region, the one-dimensional and angle-averaged profiles differ somewhat because (1) convection tends to flatten the density, entropy, and electron fraction profiles, and (2) the shock radius is boosted somewhat by convection. However, the differences are not significant, indicating that, while vigorous, neutrino-driven convection in our model does not have a significant impact on the overall shock dynamics.

The differences between our results and those of other groups are considered. These most likely result from differences in (1) numerical hydrodynamics methods, (2) initial

postbounce models, and, most important, (3) neutrino transport approximations. We have compared our neutrino luminosities, rms energies, and inverse flux factors with those from the exploding models of other groups. Above all, we find that the neutrino rms energies computed by our multigroup (MGFLD) transport are significantly lower than the values obtained by Burrows and coworkers, who specified their neutrino spectra by tying the neutrino temperature to the matter temperature at the neutrinosphere and by choosing the neutrino degeneracy parameter arbitrarily, and by Herant and coworkers in their transport scheme, which (1) is gray and (2) patches together optically thick and thin regions. The most dramatic difference between our results and those of Janka and Müller is exhibited by the difference in the net cooling rate below the gain radii: Our rate is 2–3 times greater during the critical 50–100 ms after bounce.

We have computed the mass and internal energy in the gain region as a function of time. Up to $\sim$150 ms after bounce, we find that both increase as a result of the increasing gain region volume, as the gain and shock radii diverge. However, at all subsequent times, we find that the mass and internal energy in the gain region decrease with time in accordance with the density falloff in the preshock region and with the flow of matter into the gain region at the shock and out of the gain region at the gain radius. Therefore, we see no evidence in the simulations presented here that neutrino-driven convection leads to mass and energy accumulation in the gain region.

We have compared our one- and two-dimensional densities, temperatures, and electron fractions in the region below the electron neutrino and antineutrino gain radii, above which the neutrino luminosities are essentially constant (i.e., the neutrino sources are entirely enclosed), in an effort to assess how spherically symmetric our neutrino sources remain during our two-dimensional evolution, and therefore, in an effort to assess our use of precalculated one-dimensional MGFLD neutrino distributions in calculating the matter heating and deleptonization. We find no difference below the neutrinosphere radii. Between the neutrinosphere and gain radii we find no differences with obvious ramifications for the supernova outcome. We note that the interplay between neutrino transport and convection below the neutrinospheres is a delicate matter and is discussed at greater length in another paper (Mezzacappa and coworkers). However, the results presented therein do support our use of precalculated one-dimensional MGFLD in the present context.

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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[2]National Center for Supercomputing Applications, University of Illinois, Urbana.
[3]Florida Atlantic University, Boca Raton, FL.
[4]North Carolina State University, Raleigh.
[5]Adjunct staff member from University of Tennessee, Knoxville.
[6]Vanderbilt University, Nashville, TN.