Core-Collapse Supernovae at the Threshold

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Summary. Recent progress in modeling core-collapse supernovae is summarized and set in perspective. Two-dimensional simulations with state-of-the-art treatment of neutrino transport still fail to produce powerful explosions, but evidence is presented that they are very close to a success.

1 Aiming high

Despite of still bothering uncertainties and ongoing controversy, the convectively supported neutrino-heating mechanism (1) must be considered as a promising way to explain supernova explosions of massive stars. Neutrinos drive the evolution of the collapsing stellar core and of the forming neutron star and dominate the event energetically by carrying away about 99% of the gravitational binding energy of the compact remnant. A detailed description of their processes in models which couple (relativistic) hydrodynamics and accurate neutrino transport is therefore indispensable for making progress towards an understanding of the remnant-progenitor connection, supernova energetics, explosion asymmetries, pulsar kicks, nucleosynthesis, and observable neutrino and gravitational-wave signals. It is a necessary ingredient in any calculation which claims a higher degree of realism.

2 Stepping forward

Successful simulations of neutrino-driven supernova explosions have so far either employed special, usually controversial, assumptions about the physics at neutron star conditions or have made use of crude approximations in the neutrino transport. They are contrasted by simulations with widely accepted microphysics and an increasing sophistication of the transport treatment, which have not been able to produce explosions.

It must be stressed, however, that these simulations do not conflict with each other. They were performed with largely different numerical descriptions and the discrepant results simply demonstrate the sensitivity of the delayed explosion mechanism to variations at the level of the different approaches.

2.1 Successful explosions on the one hand...

Wilson and collaborators (2) found explosions in one-dimensional simulations by assuming that neutron finger convection below the neutrinosphere boosts the neutrino emission from the nascent neutron star and thus increases the neutrino heating behind the stalled supernova shock. Neutron finger convection, however, requires a faster exchange of energy than lepton number between fluid elements, an assumption that could not be confirmed by detailed analysis of the multi-flavor neutrino transport (3). Another ingredient to the energetic explosions of Wilson's group is a nuclear equation of state (EoS) which yields high neutron star temperatures and ν_e luminosities because of the formation of a pion condensate at rather low densities (4). The adopted dispersion relation of the pions in dense matter, however, is not supported by accepted nuclear physics.

In the early 1990's it was recognized that violent convective overturn between the neutrinosphere and the supernova shock is helpful for the neutrino-heating mechanism and a possible origin of the anisotropies and large-scale mixing observed in SN 1987A (1). Two-dimensional hydrodynamic models (5) and, more recently, 3D simulations (6) that take this effect into account produced explosions, but used grey (i.e., spectrally averaged), flux-limited diffusion for decribing the neutrino transport, an approximation which fell much behind the elaborate multi-group diffusion that had been applied by Bruenn in spherical symmetry (7).

2.2 ...and failures on the other

Bruenn, using standard microphysics and a sophisticated multi-group flux-limited diffusion treatment of neutrino transport, could never confirm explosions in one-dimensional simulations (8). But there was hope that an even better description of the transport might bring success.

A new level of accuracy has indeed been reached with the use of solvers for the Boltzmann transport equation. Employing different numerical techniques, they were only recently applied in time-dependent hydrodynamic simulations of spherical stellar core collapse with Newtonian gravity (9), approximate treatment of relativistic effects (10), and general relativity (11). These simulations, all performed with the EoS of Lattimer & Swesty (12), agree that neither prompt explosions by the hydrodynamic bounce-shock mechanism, nor delayed, neutrino-driven explosions could be obtained without the help of convection, not even with the best available treatment of the neutrino physics and general relativity.

Mezzacappa et al. (13) also expressed concerns that the success of multi-dimensional calculations (5; 6) might disappear once the neutrino transport is improved to the sophistication reached in 1D models. They demonstrated this by mapping transport results from 1D supernova models to 2D hydrodynamics. The lacking self-consistency of this approach, however, was an obvious weakness of the argument.

3 Pushing the limits

In this situation the core-collapse group at Garching has advanced to the next level of improvements in supernova modeling. To this end we have generalized our 1D neutrino-hydrodynamics code (VERTEX; (10)) for performing multi-dimensional supernova simulations with a state-of-the-art treatment of neutrino transport and neutrino-matter interactions, calling the extended code version MuDBaTH (14).

3.1 A new tool...

The hydrodynamics part of the program is based on the PROMETHEUS code, which is an Eulerian finite-volume method for second-order, time-explicit integration of the hydrodynamics equations. It employs a Riemann solver for high-resolution shock capturing, a consistent multi-fluid advection scheme, and general relativistic corrections to the gravitational potential. "Odd-even decoupling" at strong shocks is avoided by an HLLE solver. More details about technical aspects and corresponding references can be found in Refs. (10; 14).

The hydro routine is linked to a code which solves the multi-frequency transport problem for neutrinos and antineutrinos of all flavors by closing the set of moment equations for particle number, energy and momentum with a variable Eddington factor that is computed from a model Boltzmann equation. The transport is done in a time-implicit way and takes into account moving medium effects and general relativistic redshift and time dilation. Transport and hydro components are joined by operator-splitting. The multi-dimensional version of the code assumes that the neutrino flux is radial and the neutrino pressure tensor can be taken as diagonal, thus ignoring effects due to neutrino viscosity. While the variable Eddington factor is determined as an average value at all radii by solving the transport equations on an angularly averaged stellar background, the multi-dimensionality of the problem is retained on the level of the moment equations, which are radially integrated within every angular zone of the spherical coordinate grid. In addition, lateral gradients that correspond to neutrino pressure and advection of neutrinos with the moving stellar fluid are included in the moment equations ("ray-by-ray plus"). Note that neutrino pressure cannot be ignored in the protoneutron star interior and advective transport of neutrinos is faster than diffusion below the neutrinosphere.

Electron neutrinos and antineutrinos are produced by e^- captures on nuclei and protons and e^+ captures on neutrons, respectively. Nucleon-nucleon bremsstrahlung and e^+e^- annihilation are considered for the creation of $\nu\bar{\nu}$ pairs of all flavors. Muon and tau neutrino-antineutrino pairs are also made by $\nu_e\bar{\nu}_e$ annihilation. Neutrino scattering off n, p, $e^{\pm}$, and nuclei is included, for muon and tau neutrinos also off ν_e and $\bar{\nu}_e$. The charged-current reactions of neutrinos with nucleons take into account nucleon thermal motions, recoil and phase-space blocking, weak magnetism corrections, the reduction of the effective nucleon mass and the quenching of the axial-vector coupling in nuclear matter, and nucleon correlations at high densities.

Recently, the treatment of electron captures on heavy nuclei has been improved in collaboration with K. Langanke and coworkers (15). Details were reported at this

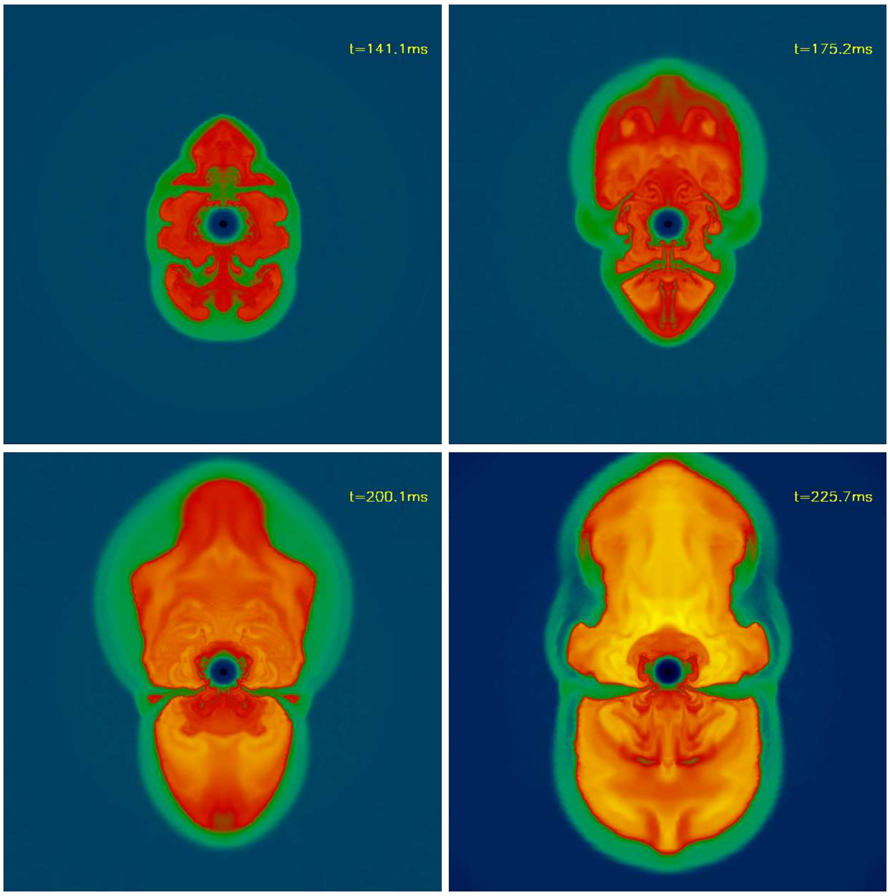

Fig. 1. Sequence of snapshots showing the large-scale convective overturn in the neutrino-heated postshock layer at four post-bounce times ($t_{\rm pb} = 141.1$ ms, 175.2 ms, 200.1 ms, and 225.7 ms, from top left to bottom right) during the evolution of a (non-rotating) $11.2\,\mathrm{M}_\odot$ progenitor model from Woosley et al. (17). The entropy is color coded with highest values being represented by red and yellow, lowest values by blue and black. The dense neutron star is visible as low-entropy circle at the center. The convective layer interior of the neutrinosphere cannot be visualized with the employed color scale because the entropy contrast there is small. Convection in this region is driven by a negative gradient of the lepton number. The computation was performed with spherical coordinates, assuming axial symmetry, and employing the "ray-by-ray plus" variable Eddington factor technique developed by Rampp & Janka (10) and Buras et al. (18) for treating neutrino transport in multi-dimensional supernova simulations. Equatorial symmetry is broken on large scales soon after bounce, and low-mode convection begins to dominate the flow between the neutron star and the strongly deformed supernova shock. The "face" on the top right does not need to look so sad, because the model continues to develop a weak explosion. The scale of the plots is 1200 km in both directions.

meeting by G. Martínez-Pinedo. Previously these reactions were described rather schematically (7) and were switched off above a few $10^{10}\,\mathrm{g\,cm^{-3}}$. Therefore e^- captures on p determined the subsequent evolution. In the new models, in contrast, nuclei dominate the ν_e production by far. This leads to a significant shrinking of the homologously collapsing inner core and shock formation at a smaller mass coordinate (15). Despite of this conceptually and quantitatively important change the subsequent shock propagation and expansion remains astonishingly similar because of differential changes of the core structure and cancellations of effects (16).

3.2 ...for a new generation of multi-dimensional models...

Running simulations for progenitors with different main sequence masses (Woosley et al.'s 11.2, 15, and 20 $\mathrm{M}_\odot$ models (17)) in 1D and 2D, we could confirm the finding of previous multi-dimensional models with simpler neutrino transport, namely that two spatially separated regions exist in the supernova core where convection sets in on a timescale of some ten milliseconds after bounce (18).

The one region is characterized by a negative entropy gradient which is left behind by the weakening shock and enhanced by the onset of neutrino heating between gain radius and shock. Despite of a positive gradient of the electron fraction, this region is Ledoux unstable and Rayleigh-Taylor mushrooms start to grow between 40 ms and 80 ms post bounce (slower for higher-mass progenitors). The violent convective overturn that develops in this region supports the shock expansion and allows for larger shock radii. Two effects seem to be mainly responsible for this helpful influence on the neutrino-heating mechanism. On the one hand bubbles of neutrino-heated matter can rise, which pushes the shock farther out and reduces the energy loss by the reemission of neutrinos. On the other hand, cold, lower-entropy matter is carried by narrow downflows from the shock to near the gain radius, where it is heated by neutrinos at very high rates. This enhances the efficiency of neutrino energy transfer. Fully developed, the convective overturn can become so violent that downflows penetrate with supersonic velocities through the electron neutrinosphere, thereby increasing the luminosity of ν_e and $\bar{\nu}_e$.

The second region of convective activity lies beneath the neutrinosphere. Convection there is driven by a negative lepton gradient and sets in between about 20 ms post bounce and about 60 ms post bounce (again later for the more massive progenitors). Despite of the transport of energy and lepton number and the corresponding change of the outer layers of the protoneutron star, the effect on the luminosities of ν_e and $\bar{\nu}_e$ is rather small. The neutrinosphere of heavy-lepton neutrinos, however, is located within the convective layer and an enhancement of muon- and tauneutrino luminosities (10–20%) is visible at times somewhat later than 100 ms. The influence on the shock propagation and the explosion mechanism is marginal and mostly indirect by modifying the neutron star structure and ν_μ and ν_τ emission.

Although convective overturn behind the shock strongly affects the post-bounce evolution, we were disappointed by not obtaining explosions in a recently published first set of simulations (18). These results seem to confirm the suspicion (13) that a more accurate treatment of neutrino transport might not allow one to reproduce the convectively supported neutrino-driven explosions seen previously.

3.3 ...with ultimate success?

But there is light at the end of the long tunnel and the situation is more favorable than it looks at first glance. There are reasons to believe that our models are very close to explosions, in fact graze the threshold of conditions which are required to drive mass ejection by the outward acceleration of the supernova shock.

One of our models (a $15\,M_\odot$ star) included rotation at a rate that is consistent with pre-collapse core rotation of magnetized stars (19). The assumed initial angular velocity was chosen to be slightly faster ($\Omega = 0.5$ rad s^{-1}) than predicted by Heger et al. (19). It would lead to a neutron star spinning with a period of 1–2 ms if the angular momentum in the protoneutron star is conserved after the end of our simulations. We intentionally did not consider more extreme rotation rates which are expected for collapsars and needed for gamma-ray burst models, but which are probably not generic for supernovae.

Rotation makes a big difference! Centrifugal forces reduce the infall velocity near the equatorial plane and help to support the shock at a larger radius. Enhanced by rotationally induced vortex motion extremely violent convective overturn develops behind the shock. Powerful non-radial oscillations are initiated and drive the shock temporarily to distances near 300 km along the rotation axis where the more rapidly decreasing density favors strong shock expansion.

Huge global deformation was also observed in case of the (non-rotating) $11.2\,M_\odot$ star when we increased the angular grid from a $\sim$90° wedge ($\pm 46.8^\circ$ around the equatorial plane of the coordinate grid with periodic boundary conditions) to full 180°. The $11.2\,M_\odot$ model is characterized by a small iron core ($\sim 1.25\,M_\odot$) and an abrupt entropy jump at the edge of the Si shell (at $\sim 1.3\,M_\odot$). A strong dipolar expansion occurs and the shock is slowly pushed outward by the pulsational expansion of two huge bubbles which are alternately fed by neutrino heated matter that comes from a single (due to the assumed symmetry, toroidal), waving downflow near the equatorial plane of the coordinate grid (Fig. 1). The shock has reached a maximum radius of more than 600 km with no sign of return until we had to stop the simulation 226 ms after bounce.

We consider it as very likely that a weak explosion develops in this model. It is exciting to imagine how the evolution might have proceeded with the additional help from rotation. Patience, however, is necessary when results for longer post-bounce periods or other progenitors are desired. The computations require far more than 10^{17} floating point operations and take several months on machines available to us.

We actually have hints of how an explosion can emerge in a $15\,M_\odot$ star which was computed with omitted velocity-dependent terms in the neutrino momentum equation. The resulting 20–30% change of the neutrino density between neutrinosphere and shock was sufficient to initiate an explosion, thus demonstrating that not much was missing for the convectively supported neutrino-heating mechanism to work. The explosion had an energy of about 6×10^{50} erg and left behind a neutron star

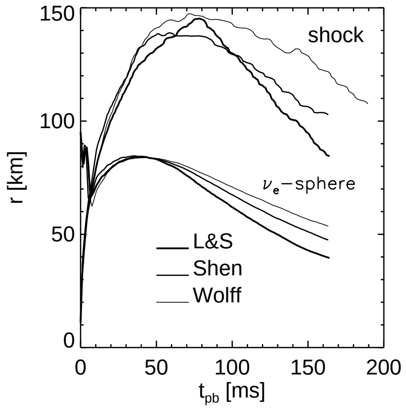

Fig. 2. Shock radii and electron neutrinospheres for simulations of a $15\,M_\odot$ star in spherical symmetry with three different nuclear EoSs (20), namely those of Lattimer & Swesty ((12); bold lines), which is the widely used standard for supernova simulations these days, Shen et al. ((21); medium), and Wolff & Hillebrandt ((22); thin). Times are synchronized at the moment of core bounce.

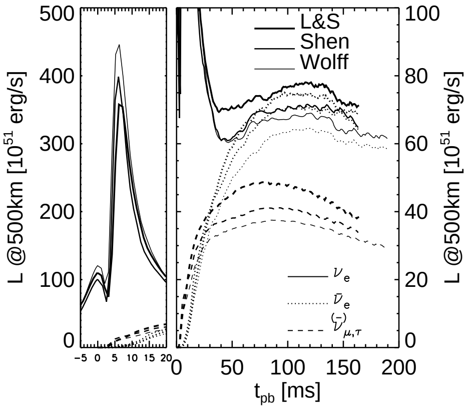

Fig. 3. Luminosities for ν_e, $\bar{\nu}_e$, and heavy-lepton neutrinos (ν_μ, ν_τ, $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ individually), measured by an observer comoving with the infalling stellar plasma at a radius of 500 km, for the three spherically symmetric simulations shown in Fig. 2 (20). The left panel displays a time interval around the prompt ν_e burst, the right panel a longer period of the post-bounce evolution. Note the different scales on the vertical axes of both frames.

with an initial baryonic mass of $\sim 1.4\,M_\odot$. The neutrino-heated ejecta did not show the dramatic overproduction of $N = 50$ closed neutron shell nuclei which signaled a problem with the neutrino transport approximations used in previous models.

These results suggest that we are on the right track. Once the critical threshold for explosions can be overcome, the subsequent evolution seems to proceed very favorably with respect to observable facts.

4 Longing for more

What can provide or support the ultimate kick beyond the explosion threshold? Is it three-dimensional effects? Very fast rotation? Truely multi-dimensional transport that accounts for lateral neutrino flow and neutrino shear? Full general relativity instead of approximations? Or yet to be improved microphysics, e.g. reactions of neutrinos with nuclei? Or the uncertain high-density equation of state which has not been extensively varied up to now but can cause sizable differences (Figs. 2,3)? Or so far ignored or unresolved modes of instability that could boost the neutrino luminosity or drive accretion shock instability? Or magnetohydrodynamic effects? Or is it the combination of all?

Much work still needs to be done for completing the supernova codes and testing these possibilities. A number of groups around the world have set out to meet this challenge!

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