Core-collapse supernova simulations: Variations of the input physics

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Abstract

Spherically symmetric simulations of stellar core collapse and post-bounce evolution are used to test the sensitivity of the supernova dynamics to different variations of the input physics. We consider a state-of-the-art description of the neutrino-nucleon interactions, possible lepton-number changing neutrino reactions in the neutron star, and the potential impact of hydrodynamic mixing behind the supernova shock.

Improvements of the neutrino-nucleon interaction rates

Recently, spherically symmetric Newtonian [1, 2], and general relativistic [3] hydrodynamical simulations of stellar core-collapse and the post-bounce evolution including a Boltzmann solver for the neutrino transport have become possible. No supernova explosions were obtained.

Having reached a new level of accuracy of the numerical treatment, it is a natural next step to reconsider the input physics that enters the models, remove imponderabilities of their description and also test possible alternatives. Within the set of so-called "standard" neutrino opacities [4] which have been widely used in supernova models so far, for example, the rates of charged-current interactions of electron neutrinos and antineutrinos with free nucleons as well as neutral-current scatterings of neutrinos off free nucleons were calculated with the assumption that the nucleons can be considered as isolated, infinitely massive particles at rest. It is, however, well known that these interaction rates are significantly changed when energy transfer between the nucleons and leptons ("recoil"), nucleon-nucleon correlations due to Fermi statistics and nuclear forces, and other so far disregarded effects like weak magnetism corrections, are adequately taken into account (see Ref. [5]). Effectively, at densities $\rho \gtrsim 10^{13}\,\mathrm{g/cm^3}$, the opacities become considerably smaller than in the "standard" approximation. Correspondingly, neutrino diffusion through the nascent neutron star and the emission from the neutrinosphere are enhanced and higher neutrino luminosities must be expected.

Figure 1 shows results of Newtonian simulations of iron core-collapse and the post-bounce evolution of a $15\,M_\odot$ star [6] using Boltzmann neutrino transport [7]. One model was calculated with an improved description of neutrino-nucleon interactions, which includes the detailed reaction kinematics and nucleon phase-space blocking, nucleon-nucleon correlations in the dense medium [8, 9], weak magnetism [5] and the possible quenching of the axial coupling g_A in nuclear matter [10]. For a reference calculation the conventional "standard" opacities [4] were used. In both simulations we also included nucleon-nucleon bremsstrahlung $NN \rightleftharpoons \nu\bar{\nu}\,NN$ ($N \in \{n,p\}$ denotes a free nucleon), which is the dominant production reaction of μ and τ neutrinos and antineutrinos in the denser regions of the newly formed neutron star [11, 12].

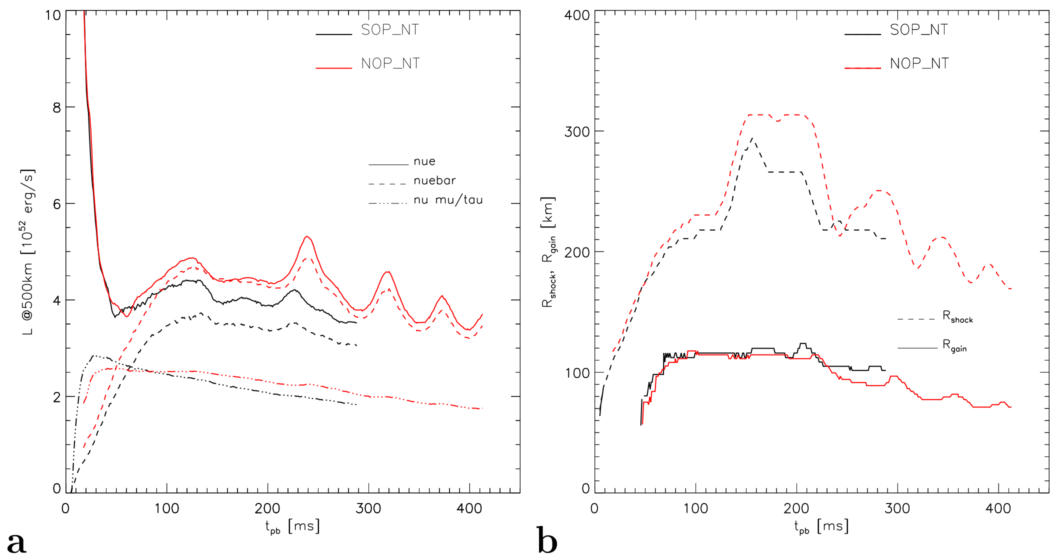

Figure 1: Comparison of the post-bounce evolution of a model computed with "standard" neutrino opacities (black lines) and a model which employs the improved description of neutrino-nucleon interactions (red lines). Panel **a** shows the luminosities of ν_e (solid lines), $\bar{\nu}_e$ (dashed lines), and ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$ (individually; dash-dotted lines) as functions of time. In Panel **b** the radial positions of the shock (dashed lines) and the gain radius (solid lines) of the two models are compared.

As expected from the arguments above, the model calculated with the new implementation of the opacities shows enhanced luminosities for ν_e and, even more pronounced, for $\bar{\nu}_e$. This is caused by the fact that for ν_e and $\bar{\nu}_e$ recoil and nucleon correlations have the strongest effect at high densities, while for $\bar{\nu}_e$ the weak magnetism reduces the opacities also at moderate densities $\rho \lesssim 10^{13}\,\mathrm{g/cm^3}$ [5], where most of the neutrino emission is produced during the time of consideration. In contrast, for ν_e both "corrections" counteract and almost cancel each other [5]. The higher luminosities (see Fig. 1a) and somewhat larger mean energies of ν_e and $\bar{\nu}_e$ increase the neutrino heating in the gain region below the hydrodynamic shock. Consequently, the shock propagates to larger radii when compared with the reference model (see Fig. 1b).

In view of the appreciable differences between both models we consider the inclusion of a state-of-the-art description of neutrino-nucleon interactions as a mandatory step towards more realistic supernova simulations, although the improved opacities *alone* do not lead to a successful supernova explosion in spherical symmetry.

Lepton-number changing neutrino reactions

Lepton-number changing interactions are expected in various extensions of the particle-physics standard model, notably in R-parity violating models of supersymmetry; see Ref. [13] for an overview and current experimental limits. Such processes might significantly affect the supernova dynamics [14]. As a proxy for this class of interactions we implemented the reaction $\nu_e + N \rightleftharpoons \bar{\nu}_e + N$ which opens a channel for "internal deleptonization", i.e. quickly running down electron lepton number without diffusion to the stellar surface. This effect leads to a

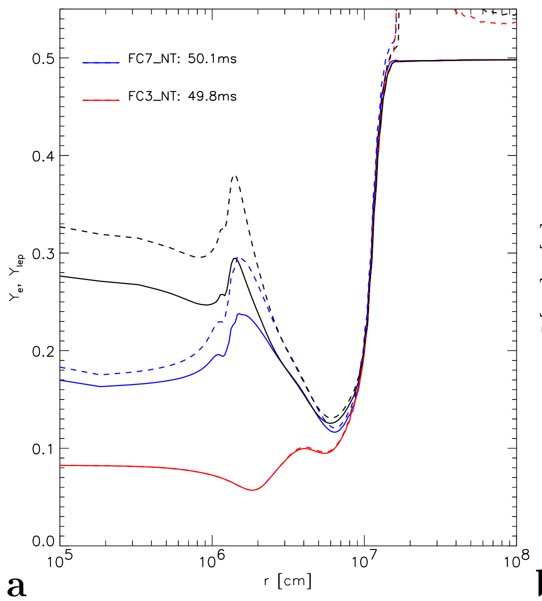

Figure 2: Radial profiles of the electron fraction (Panel **a**, solid lines), total lepton fraction (Panel **a**, dashed lines), temperature (Panel **b**, dashed lines) and specific entropy (Panel **b**, solid lines) 50 ms after core bounce. Results of the models with lepton-number changing reactions are plotted as red ($\sigma/\sigma_{\rm SM} = 10^{-3}$) and blue lines ($\sigma/\sigma_{\rm SM} = 10^{-7}$). For comparison quantities of the reference model ($\sigma/\sigma_{\rm SM} = 0$) are shown as black lines.

corresponding increase of the temperature of the stellar plasma by conversion of degeneracy energy to thermal energy (Fig. 2). The relevant time scale is fixed by the effective strength of the lepton-number changing reaction. We parametrize it by $\sigma/\sigma_{\rm SM}$, which is the lepton-number changing cross section normalized to the standard-model one for $\nu_e + N \rightleftharpoons \nu_e + N$. We have calculated one model with $\sigma/\sigma_{\rm SM} = 10^{-7}$ where the deleptonization time scale is too slow to be effective during infall, and an extreme case where $\sigma/\sigma_{\rm SM} = 10^{-3}$ and where coherent enhancement by the scattering off heavy nuclei is allowed, $\nu_e + A \rightleftharpoons \bar{\nu}_e + A$. Despite of sizeable differences in the physical conditions in the core of the nascent neutron star (Fig. 2) we find a remarkable insensitivity of the overall dynamical evolution of the models to the dramatic modifications of the microphysics. In both models the hydrodynamic shock reaches a maximum radius of about 300 km at $\approx$ 200 ms after bounce. These values are very close to the reference calculation with $\sigma/\sigma_{\rm SM} = 0$. This finding is probably explained by the accelerated deleptonization and heating being confined to the innermost $\approx$ 20 km of the neutron star (Fig. 2), because only there the lepton-number changing reactions are fast enough and the optical depth for these processes is larger than unity. During the first few hundred milliseconds after bounce most of the neutrino luminosity, on the other hand, originates from regions beween 50 km and 100 km where the temperature is essentially the same in all models (Fig. 2b). Continuing the simulations over a period of nearly one second, we find slightly enhanced neutrino luminosities and mean energies and thus heating in the gain region at later times after bounce, but not to a degree that the conditions for explosions [15] would become more favourable.

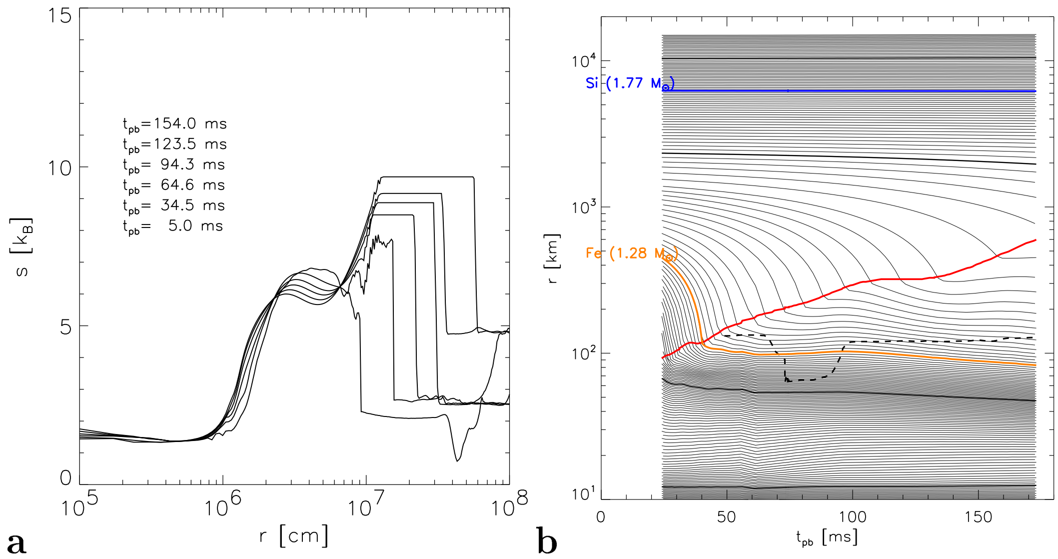

Figure 3: Panel **a** shows the effect of our "mixing" algorithm on the temporal evolution of the radial profile of the specific entropy. From bottom to top the times correspond to profiles with increasing values of the postshock entropy. For the same model the trajectories of different mass shells (with a spacing of 0.02 $M_\odot$) are plotted as black lines in Panel **b**. The red line traces the radial position of the supernova shock. Note that the model includes only ν_e and $\bar{\nu}_e$, and can be directly compared with the simulation published in Ref. [1].

Successful explosions by convective processes ?

Multi-dimensional hydrodynamic simulations, coupled with simplified treatments of the neutrino physics, have shown that large-scale convective overturn behind the supernova shock *can* aid the neutrino-driven mechanism and cause an explosion even if models fail in spherical symmetry (see Ref. [16] for an overview and references to original work). However, because of the uncertainties and approximations in the description of the neutrino sector, the actual role of convection in supernova models is not yet clear. Self-consistent and multi-dimensional simulations with a sufficiently accurate treatment of the neutrino transport have still to be carried out.

Convective overturn has the helpful influence of suppressing energy losses by the reemission of neutrinos, because neutrino-heated matter expands outward instead of being advected through the gain region into the cooling layer. In addition, part of the matter falling through the shock can still accrete onto the neutron star, which helps keeping up a high value of the accretion luminosity. Furthermore, the expanding, neutrino-heated matter raises the pressure immediately behind the shock and thus drives the shock farther out. We try to mimick the latter effect of a multi-dimensional fluid flow between the shock and the gain radius by artificially (and instantaneously) mixing layers of negative entropy gradient behind the shock in our spherically symmetric simulations. This leads to a flattening of the entropy profile. We achieve this behaviour by setting the entropy in such a region to a constant value $s(t,r) = s_0(t)$ (see Fig. 3a), which is calculated in each timestep from the requirement that the internal (and thus also the total) energy in the affected region is conserved. Of course, this algorithm cannot accout for all the above mentioned effects associated with multi-dimensional fluid motions, but at least one can test the sensitivity of the post-bounce supernova evolution to such a manipulation.

As a consequence of the mixing and the thus increased postshock pressure, the hydrodynamic shock — which in the absence of mixing reached a maximum radius of about 350 km before it started to recede again — is indeed pushed out to a radius beyond 600 km (Fig. 3b), presumably leading to a weak supernova explosion. We interpret this result as an interesting hint that successful neutrino-driven supernova explosions might be in reach when state-of-the-art neutrino physics and a Boltzmann treatment of the neutrino transport are eventually combined in self-consistent multi-dimensional simulations.

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References

[1] M. Rampp and H.-T. Janka, ApJ **539** (2000) L33.

[2] A. Mezzacappa, M. Liebendörfer, O. Messer, et al., Phys. Rev. Lett. **86** (2001) 1935.

[3] M. Liebendörfer, A. Mezzacappa, F. Thielemann, et al., Phys. Rev. D **63** (2001) 3004.

[4] S.W. Bruenn, ApJS **58** (1985) 771.

[5] C.J. Horowitz, Phys. Rev. D **65** (2002) 043001.

[6] S. Woosley, personal communication (1999).

[7] M. Rampp and H.-T. Janka, preprint astro-ph/0203101 (2002).

[8] S. Reddy, M. Prakash and J.M. Lattimer, Phys. Rev. D **58** (1998) 3009.

[9] A. Burrows and R.F. Sawyer, Phys. Rev. C **58** (1998) 554.

[10] G.W. Carter and M. Prakash, Physics Letters B **525** (2002) 249.

[11] S. Hannestad and G. Raffelt, ApJ **507** (1998) 339.

[12] T.A. Thompson , A. Burrows and J.E. Horvath, Phys. Rev. C **62** (2000) 035802.

[13] S. Bergmann, H.V. Klapdor-Kleingrothaus and H. Päs, Phys. Rev. D **62** (2000) 113002.

[14] G.M. Fuller, R. Mayle and J.R. Wilson, ApJ **332** (1988) 826.

[15] H.-T. Janka, A&A **368** (2001) 527.

[16] H.-T. Janka, K. Kifonidis and M. Rampp, in Proc. Workshop on Physics of Neutron Star Interiors, ed. D. Blaschke N. Glendenning and A. Sedrakian Lecture Notes in Physics **578** (Springer, 2001) 333–363; preprint astro-ph/0103015.