Core Collapse and Then?
The Route to Massive Star Explosions

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Abstract. The rapidly growing base of observational data for supernova explosions of massive stars demands theoretical explanations. Central of these is a self-consistent model for the physical mechanism that provides the energy to start and drive the disruption of the star. We give arguments why the delayed neutrino-heating mechanism should still be regarded as the standard paradigm to explain most explosions of massive stars and show how large-scale and even global asymmetries can result as a natural consequence of convective overturn in the neutrino-heating region behind the supernova shock. Since the explosion is a threshold phenomenon and depends sensitively on the efficiency of the energy transfer by neutrinos, even relatively minor differences in numerical simulations can matter on the secular timescale of the delayed mechanism. To enhance this point, we present some results of recent one- and two-dimensional computations, which we have performed with a Boltzmann solver for the neutrino transport and a state-of-the-art description of neutrino-matter interactions. Although our most complete models fail to explode, the simulations demonstrate that one is encouragingly close to the critical threshold because a modest variation of the neutrino transport in combination with postshock convection leads to a weak neutrino-driven explosion with properties that fulfill important requirements from observations.

1 Introduction

The primary energy source for powering supernovae of massive stars is the gravitational binding energy of the newly formed proto-neutron star or proto-black hole (energy from nuclear reactions contributes at a minor level). To initiate and drive the explosion, energy from some temporary storage, e.g., internal or rotational energy of the compact remnant, must be transferred to the outer stellar layers to be finally converted to kinetic energy of the ejecta. This might be achieved by hydrodynamical shocks, by neutrinos, or by magnetic fields as mediators. Accordingly, one distinguishes between

(i) the (prompt) mechanism, which works on a dynamical timescale by the hydrodynamical shock that is created at the moment of core bounce,
(ii) the delayed, neutrino-driven mechanism which starts the explosion on the secular timescale of neutrino-energy deposition behind the supernova shock,

(iii) and the magnetohydrodynamical (MHD) mechanism, which requires that initial seed magnetic fields are amplified to a dynamically relevant strength by differential rotation.

Intense radiation or relativistic outflows of charged particles might also play a role for very special conditions. They may, for example, originate from the vicinity of an accreting black hole that has formed after the collapse of a rotating stellar core. Relativistic jets as driving mechanism are currently discussed for stellar explosions that have been observed in association with gamma-ray bursts (see the contributions by S. Woosley and A. MacFadyen at this conference).

Depending on the mediator, the conditions for efficient energy transfer, the corresponding timescale, and the tapped energy reservoir are different. A lot of work has been spent in the past 40 years on the search for a viable supernova mechanism and the study of the various theoretical suggestions. A brief review of these efforts and the current status of our knowledge can be found in Ref. [25].

The relevance of the different mechanisms for stellar explosions listed above depends on the (poorly known) physical conditions in collapsed stellar cores and on the properties of the progenitor stars. Some of the involved requirements are more likely to be fulfilled than others, some combinations of necessary conditions may be more frequent and more typical, while others may be realized only in rare cases and for very special, exceptional circumstances.

The neutrino-driven mechanism [54,2] involves a minimum of controversial assumptions and uncertain degrees of freedom in the physics of collapsing stars. It relies on the importance of neutrinos and their energetic dominance in the supernova core. After the detection of neutrinos in connection with Supernova 1987A and the overall confirmation of theoretical expectations for the neutrino emission, this can no longer be considered as a speculative assumption but is an established fact. Of course, this does not mean that such a minimal input is sufficient to understand the cause of supernova explosions and to explain all observable properties of supernovae. But at least it can be taken as a good reason to investigate how far one can advance with a minimum of imponderabilities.

2 Observational Facts

Progress in our understanding of the processes that lead to the explosion of massive stars is mainly based on elaborate numerical modeling, supplemented by theoretical analysis and constrained by a growing data base of observed properties of supernovae. The latter may carry imprints from the physical conditions very close to the center of the explosion. Observable features at very large radii, however, can be linked to the actual energy source of the explosion only indirectly through a variety of intermediate steps and processes. Any interpretation with respect to the mechansim that initiates the explosion therefore requires caution.

A viable model for the explosion mechanism of massive stars should ultimately be able to explain the observed explosion energies, nucleosynthetic yields (in particular of radioactive isotopes like ^{56}Ni, which are created near the mass cut), and the masses of the compact remnants (neutron stars or black holes) and their connection with the progenitor mass.

Recent evaluations of photometric and spectroscopic data for samples of well-observed Type-II plateau supernovae reveal a wide continuum of kinetic energies and ejected nickel masses. Faint, low-energy cases seem to be nickel-poor whereas bright, high-energy explosions tend to be nickel-rich and associated with more massive progenitors [14]. This direct correlation between stellar and explosion properties, however, is not apparent in an independent analysis by Nadyozhin [39] who speculates that more than one stellar parameter (rotation or magnetic fields besides the progenitor and core mass) might determine the explosion mechanism. A large range of nickel masses and explosion energies was also found for Type Ib/c supernovae [14]. Interpreting results obtained by the fitting of optical lightcurves and spectra, Nomoto et al. [41] came up with the proposal that explosions of stars with main sequence masses above 20–25 $M_\odot$ split up to a branch of extraordinarily bright and energetic events ("hypernovae") at the one extreme and a branch of faint, low-energy or even "failed" supernovae at the other. Stars with such large masses might collapse to black holes rather than neutron stars. The power of the explosion could depend on the amount of angular momentum in the collapsing core, which in turn can be sensitive to a number of effects such as stellar winds and mass loss, metallicity, magnetic fields, binarity or spiraling-in of a companion star in a binary system.

Anisotropic processes and large-scale mixing between the deep interior and the hydrogen layer had to be invoked in case of Supernova 1987A to explain the shape of the lightcurve, the unexpectedly early appearance of X-ray and γ-ray emission, and Doppler features of spectral lines (for a review, see [40]). More than ten years after the explosion, the expanding debris exhibits an axially symmetric deformation [50]. Supernova 1987A therefore seems to possess an intrinsic, global asymmetry. The same conclusion was drawn for other core-collapse supernovae (Type-II as well as Ib/c) based on the fact that their light is linearly polarized at a level around 1% with a tendency to increase at later phases when greater depths are observed [49,28]. This has been interpreted as evidence that the inner portions of the explosion, and hence the mechanism itself, are strongly non-spherical [20,53], possibly associated with a "jet-induced" explosion [50,26]. This is a very interesting and potentially relevant conjecture. It does, however, not necessarily constrain the nature of the physical process that mediates the energy transfer from the collapsed core of the star to the ejecta and thereby creates the asphericity.

Rotation plus magnetic fields were proposed as the "most obvious" way to break the spherical symmetry and to explain the global asphericity of core-collapse supernovae [52,1,51]. It was argued that current numerical calculations may be missing a major ingredient necessary to yield explosions. A proper treatment of rotation *and* magnetic fields may be necessary to fully understand when and how collapse leads to explosions. Of course, this might be true. But a confirmation or rejection will require computer models with ultimately the full physics.

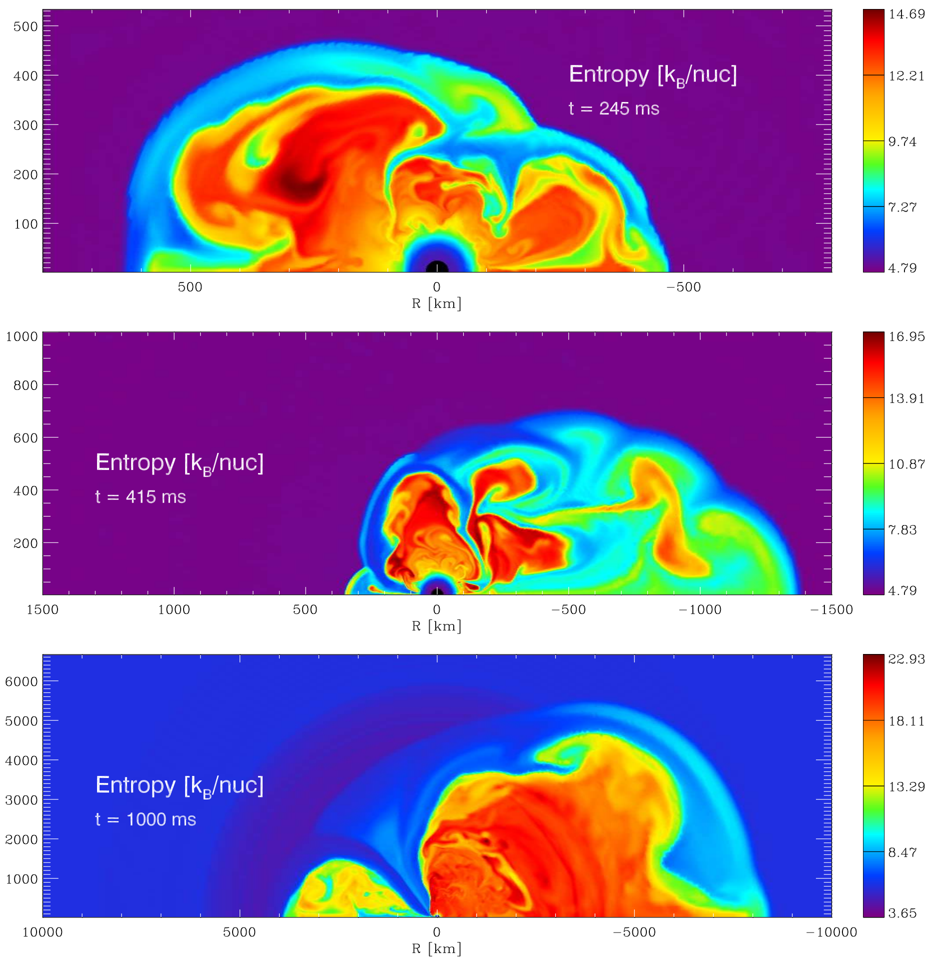

Fig. 1. Explosion that is driven by neutrino-energy deposition in combination with convective overturn in the region behind the supernova shock. The anisotropy of the neutrino- and shock-heated ejecta is growing in time and becomes very large due to an increasing contribution of the $m = 0$, $l = 1$ mode in the convective pattern. The snapshots (from top to bottom) show the entropy distribution (values between about 4 and 23 k_{B} per nucleon) at post-bounce times $t_{\mathrm{pb}} = 245\,\mathrm{ms}$, $415\,\mathrm{ms}$, and $1000\,\mathrm{ms}$. Note that the radial scales of the figures differ. The neutron star is at the origin of the axially symmetric (2D) grid and plays the role of an isotropic neutrino "light bulb" [42].

It must be stressed, however, that current observations do not necessitate such conclusions and hydrodynamical simulations suggest other possible explanations. Strong convection in the neutrino-heating region behind the supernova shock can account for huge anisotopies of the inner supernova ejecta, even without invoking rotation. If the explosion occurs quickly, much power remains on smaller scales until the expansion sets in and the convective pattern gets frozen in. If, in contrast, the shock radius grows only very slowly and the explosion is delayed for several 100 ms after bounce, the convective flow can merge to increasingly larger structures. In two-dimensional (2D) hydrodynamic calculations including cooling and heating by neutrinos between the neutron star and the shock (with parameter choices for a central, *isotropic* neutrino "light bulb" which enabled explosions), Plewa et al. [42] found situations where the convective pattern revealed a contribution of the $l = 1$, $m = 0$ mode that was growing with time and was even dominant at about one second after bounce (Fig. 1). Herant [17] already speculated about such a possibility. Certainly three-dimensional (3D) calculations of the full sphere (and without the coordinate singularity on the axis of the spherical grid) are indispensable to convincingly demonstrate the existence of this phenomenon[1].

3 Do Neutrino-Driven Explosions Work?

Spherically symmetric simulations with the current input physics (neutrino interactions and the equation of state of dense matter) do not yield explosions by the neutrino-heating mechanism. There is no controversy about that. All computations are in agreement, independent of Newtonian or relativistic gravity and independent of the neutrino transport being treated in an approximate way by flux-limited diffusion methods (e.g., [38,37,5,6]) or very accurately by solving the frequency- and angle-dependent Boltzmann transport equation [43,35,31,30].

Whether neutrinos succeed in reviving the stalled shock depends on the efficiency of the energy transfer to the postshock layer, which in turn increases with the neutrino luminosity and the hardness of the neutrino spectrum. Wilson and collaborators [55,56,32,48] have obtained explosions in one-dimensional (1D) simulations for more than ten years now. In these models it is, however, *assumed* that neutron-finger convection in the hot neutron star boosts the neutrino luminosities. Moreover, Mayle et al. [32] used a special equation of state with a high abundance of pions in the nuclear matter, which again leads to higher neutrino fluxes from the neutron star and thus to enhanced energy-deposition behind the shock. Both assumptions are not generally accepted.

Two-dimensional [18,19,46,10,23,36,47] and 3D simulations [45,13] have shown that the neutrino-heating layer is unstable to convective overturn. The associated effects have a very helpful influence and can lead to explosions even in cases where spherical models fail. In the multi-dimensional situation downflows of cooler, low-entropy matter that has fallen through the shock, coexist with rising bubbles of high-entropy, neutrino-heated gas. On the one hand, the downflows take cool material close to the gain radius where it absorbs energy readily from the intense neutrino fluxes. On the other hand, the rising bubbles allow

[1] Another interesting possibility was pointed out by A. Mezzacappa at this conference. He showed results of 2D and 3D calculations performed in collaboration with J.M. Blondin [3], which revealed hydrodynamical instabilities growing to large-scale modes in the flow behind the accretion shock even in the absence of neutrino heating.

heated matter to expand and cool quickly, thus reducing the energy loss by the reemission of neutrinos. They also increase the postshock pressure and hence push the shock farther out. This in turn enlarges the gain layer and thus the gas mass which can accumulate in the neutrino-heating region. It also means that the gas stays longer in the gain layer, in contrast to one-dimensional models where the matter behind the accretion shock has negative velocity and is quickly advected down to the cooling layer. When the gas arrives there, neutrino emission sets in and extracts again the energy which had been absorbed from neutrino heating shortly before. Due to the combination of all these effects postshock convection enhances the efficieny of the neutrino-heating mechanism. Therefore the multi-dimensional situation is *generically different* from the spherically symmetric case.

Nevertheless, the existence of convective overturn in the neutrino-heating layer does not guarantee explosions [23,36]. For insufficient neutrino heating the threshold to an explosion will not be overcome. Since neutrinos play a crucial role, an accurate description of the neutrino physics — transport and neutrino-matter interactions — is indispensable to obtain conclusive results about the viability of the neutrino-driven mechanism. All published multi-dimensional explosion models, however, have employed crude approximations or simplifications in the treatment of neutrinos.

4 A New Generation of 2D Supernova Simulations

In order to take a next step of improvement in supernova modelling, we have coupled a new Boltzmann code for the neutrino transport to the PROMETHEUS hydrodynamics program, which allows for spherically symmetric as well as multi-dimensional simulations [44]. Below we present some results of our first 2D supernova simulations with this new code, which we named MuDBaTH (**Mu**lti-**D**imensional **B**oltzm**a**nn **T**ransport and **H**ydrodynamics).

4.1 Technical Aspects and Input Physics

The Boltzmann solver scheme is described in much detail in Ref. [44]. The integro-differential character of the Boltzmann equation is tamed by applying a variable Eddington factor closure to the neutrino energy and momentum equations (and the simultaneously integrated first and second order moment equations for neutrino number). For this purpose the variable Eddington factor is determined from the solution of the Boltzmann equation, and the system of Boltzmann equation and its moment equations is iterated until convergence is achieved. Employing this scheme in multi-dimensional simulations in spherical coordinates, we solve the (one-dimensional) moment equations on the different angular bins of the numerical grid but calculate the variable Eddington factor only once on an angularly averaged stellar background. We point out here that it turned out to be necessary to go an important step beyond this simple "ray-by-ray" approach. Physical constraints, namely the conservation of lepton

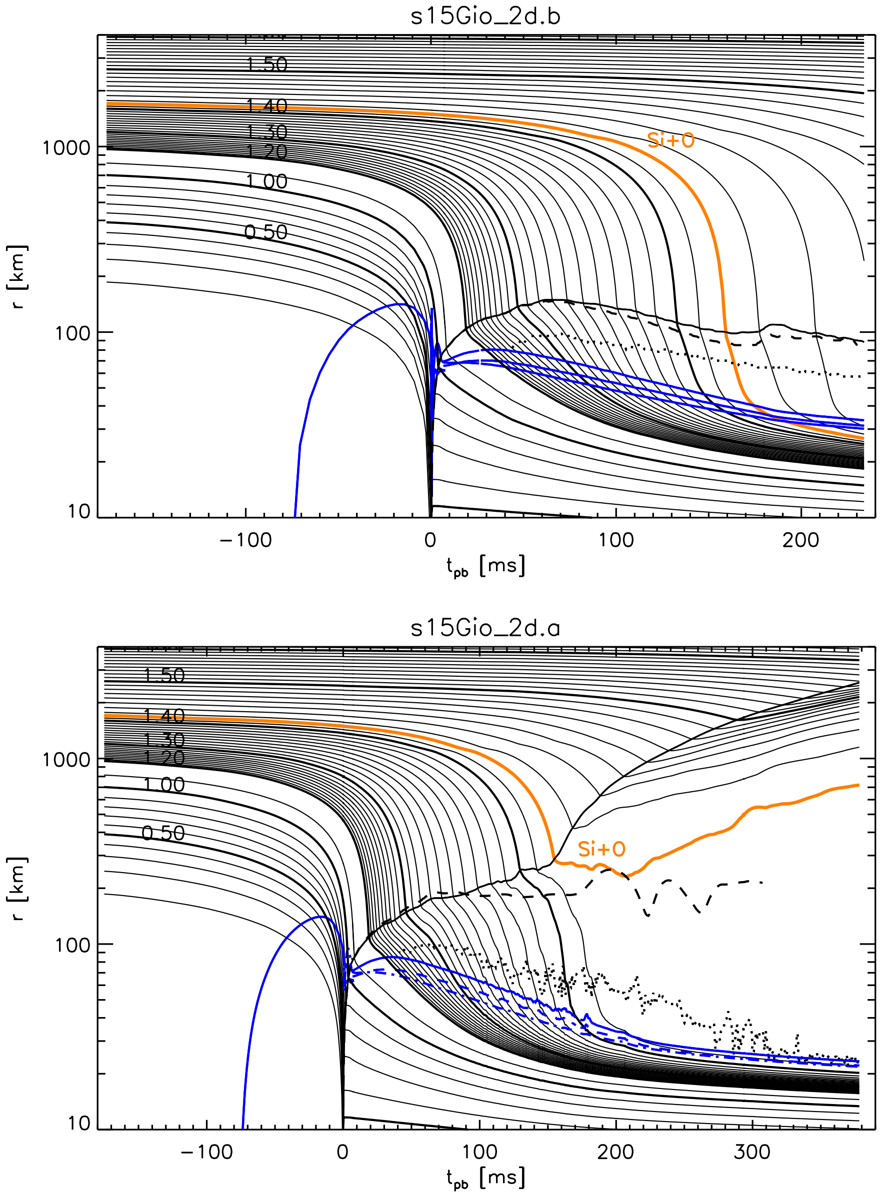

Fig. 2. Trajectories of mass shells (time being normalized to bounce) for the non-exploding (top) and the exploding 2D model. In the latter case one can see the shock starting a rapid expansion at about 150 ms after bounce. The dashed lines indicate the shock positions in the corresponding 1D simulations, where no explosions were obtained. The angle-averaged gain radius is given by the dotted line, and the neutrinospheres of ν_e, $\bar{\nu}_e$ and the heavy-lepton neutrinos are also marked.

number and entropy within adiabatically moving fluid elements, and numerical requirements, i.e., the stability of regions which should not develop convection according to a mechanical stability analysis, make it necessary to take into account the coupling of neighbouring rays at least by lateral advection terms and neutrino pressure gradients [7].

General relativistic effects are treated only approximately in our code [44]. The current version contains a modification of the gravitational potential by including correction terms due to pressure and energy of the stellar medium and neutrinos, which are deduced from a comparison of the Newtonian and relativistic equations of motion. The neutrino transport contains gravitational redshift and time dilation, but ignores the distinction between coordinate radius and proper radius. This simplification is necessary for coupling the transport code to our basically Newtonian hydrodynamics.

As for the neutrino-matter interactions, we discriminate between two different sets of input physics. On the one hand we have calculated models with conventional ("standard") neutrino opacities, i.e., a description of the neutrino interactions which follows closely the one used by Bruenn and Mezzacappa and collaborators [4,33,34]. It assumes nucleons to be uncorrelated, infinitely massive scattering targets for neutrinos. In these reference runs we have usually also added neutrino pair creation and annihilation by nucleon-nucleon bremsstrahlung [15]. Details of our implementation of these neutrino processes can be found in [44].

A second set of models was computed with an improved description of neutrino-matter interactions. Besides including nucleon thermal motions and recoil, which means a detailed treatment of the reaction kinematics and allows for an accurate evaluation of nucleon phase-space blocking effects, we take into account nucleon-nucleon correlations (following Refs. [8,9]), the reduction of the nucleon effective mass, and the possible quenching of the axial-vector coupling in nuclear matter [11]. In addition, we have implemented weak-magnetism corrections as described in Ref. [22]. The sample of neutrino processes was enlarged by also including scatterings of muon and tau neutrinos and antineutrinos off electron neutrinos and antineutrinos and pair annihilation reactions between neutrinos of different flavors (i.e., $\nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \longleftrightarrow \nu_e + \bar{\nu}_e$; [16]).

Our current supernova models are calculated with the nuclear equation of state of Lattimer and Swesty [27], which we suitably extended to lower densities [44].

4.2 Models and Results

None of our spherically symmetric simulations, neither with the standard nor with the improved description of neutrino opacities, has produced an explosion. A compilation of a subset of our calculations which we did for a $15\,\mathrm{M}_\odot$ progenitor star, Model s15s7b2, provided to us by S. Woosley, can be found in Refs. [24,7]. Here we discuss only two 2D runs (Models s15Gio_2d.a and s15Gio_2d.b), which both were performed with our approximation of relativistic effects and the state-of-the-art improvement of neutrino-matter interactions (cf. Sect. 4.1). We used a spherical coordinate grid with 32 equidistant zones within an angular wedge from

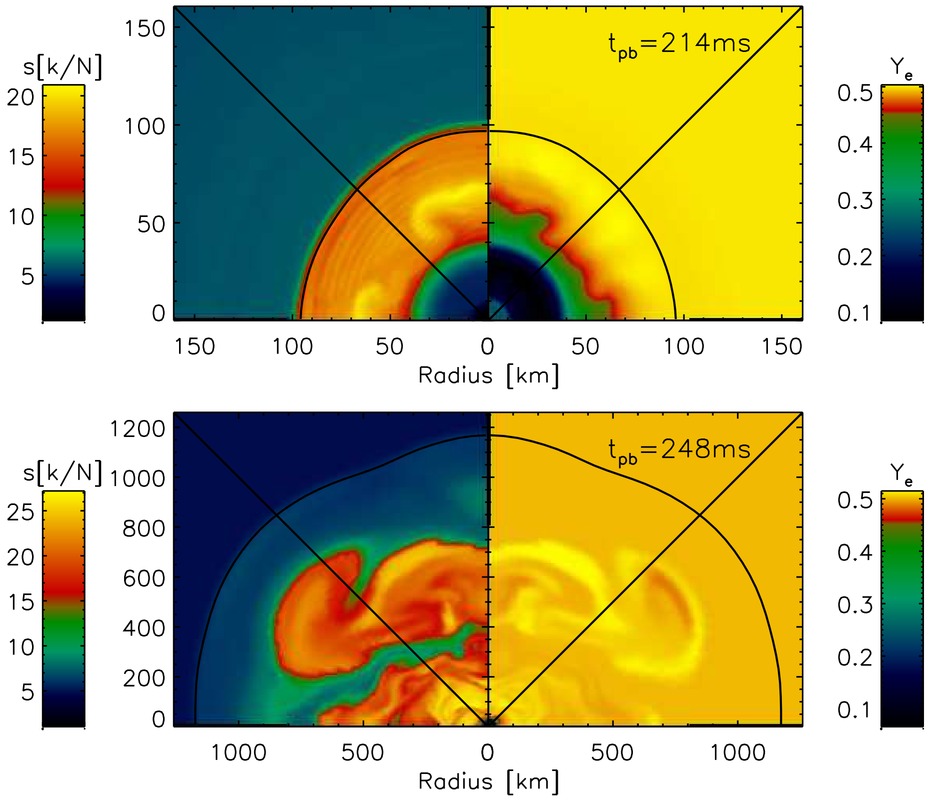

Fig. 3. Convection in the neutrino-heating region for the non-exploding 2D model (Model s15Gio_2d.b, top) and the exploding one (Model s15Gio_2d.a) at the post-bounce times indicated in the plots. The figures show the entropy distribution (left) and the electron fraction (proton-to-baryon ratio). A wedge of $\pm 43.2^{\mathrm{o}}$ around the equatorial plane (marked by the diagonal solid lines) of the spherical coordinate grid was used for the computations.

-43.2^{o} to $+43.2^{\mathrm{o}}$ around the equatorial plane and assumed periodic conditions at the boundaries.

Both 2D simulations differ only in one important aspect: In Model s15Gio_2d.a the velocity dependent (Doppler shift and aberration) terms in the neutrino momentum equation (and the corresponding terms in the Boltzmann equation for the antisymmetric average of the specific intensity; see Ref. [44]) were omitted. These terms are formally of order v/c and are small for low velocities.

This simplification of the neutrino transport, however, has a remarkable consequence: The model with the most complete implementation of the transport equations, Model s15Gio_2d.b, fails to explode. In case of Model s15Gio_2d.a, however, the stalled shock is successfully revived by neutrino heating because very strong convection can develop in the gain region[2]. The time evolution of both models is displayed by the trajectories of mass shells in Fig. 2.

The reason for this dramatic difference is the following. Some of the velocity dependent terms (those in which derivatives with respect to the neutrino energy do not show up) in the neutrino momentum equation have a simple formal interpretation: In regions with mass infall (negative velocity) they effectively act like a reduction of the neutrino-medium interaction on the right hand side of this equation. The changes can be 10% or more for neutrino energies in the peak of the spectrum, depending also on time, radius, and the size of the postshock velocities. As a consequence, the neutrino flux streams more readily and the comoving-frame neutrino (energy) density is decreased. This is associated with somewhat larger neutrino losses in the cooling layer around the neutrinosphere and a significantly reduced neutrino heating between gain radius and shock.

Although the differences are moderate (10–30%, depending on the quantity) the accumulating effects during the first 80 ms after bounce clearly damp the shock expansion and finally lead to a dramatic shock recession after the initial phase of expansion. Before this happens postshock convection has not become strong enough to change the evolution. With the onset of contraction, the postshock velocities decrease (become more negative) quickly, neutrino-heated matter is rapidly advected inward below the gain radius and loses its energy by reemission of neutrinos. The gain region shrinks to a very narrow layer, a fact which suppresses the convective activity lateron. This is demonstrated by Fig. 3 where convection is weak in Model s15Gio_2d.b but very strong in Model s15Gio_2d.a.

Due to a combination of unfavorable effects and a continuously amplifying negative trend, Model s15Gio_2d.b remains below the explosion threshold while Model s15Gio_2d.a is just above that critical limit. In the vicinity of the threshold the long-time evolution of the collapsing stellar core depends very sensitively on "smaller details" of the neutrino transport.

5 Conclusions and Outlook

Our 2D models with a Boltzmann solver for the neutrino transport have considerably reduced the uncertainties associated with the treatment of the neutrino physics in previous multi-dimensional simulations. With the most complete implementation of the transport physics we could not obtain explosions. This result suggests that the neutrino-driven mechanism fails with the employed input physics, at least in case of the considered $15\,\mathrm{M}_\odot$ star. We do not think that the remaining uncertainties in our simulations (mainly the approximate treatment of general relativistic effects) are likely to jeopardize this conclusion. A comparison with fully relativistic one-dimensional calculations (Liebendörfer, personal communication [29]) is very encouraging. Because of the remarkable similarity

[2] At the time of the conference, we had just this exploding 2D run and made a preliminary announcement of the success of this model. A later 2D computation with the full neutrino moment equations (Model s15Gio_2d.b) then turned out to produce a dud.

of the shock trajectories of different progenitors in spherical symmetry [30], it is likely that our negative conclusion is also valid for other pre-collapse configurations with a similar structure. Significant star-to-star variations of the progenitor properties with a non-monotonic dependence on the stellar mass [57], however, suggest that multi-dimensional core-collapse simulations of a larger sample of progenitors are needed before one can make final, more generally valid statements. The supernova problem is highly nonlinear and surprises may lurk behind every corner.

It would therefore be premature to conclude that the neutrino-driven mechanism fails and that not even postshock convection can alter this unquestioned outcome of all current spherical models. Besides studying other progenitors with multi-dimensional simulations, one should also investigate the effects of rotation and the influence of different high-density equations of state on the long-time post-bounce evolution and the neutrino-heating phase in a supernova. There is considerable uncertainty associated with the poorly known physics in the nuclear and supranuclear medium.

Our successfully exploding 2D model, Model s15Gio_2d.a, at least demonstrates that simulations which include the effects of postshock convection are rather close to an explosion. Therefore modest changes of the neutrino emission and transport seem to be already sufficient to push them beyond the critical threshold. The properties of the explosion in this case are very encouraging and may support one's belief in the basic viability of the delayed explosion mechanism. At 380 ms after bounce the shock has arrived at a radius of more than 2500 km and is expanding with about 10000 km/s. The explosion of this model does not seem to become very energetic. It is only $\sim 4 \times 10^{50}$ erg at that time, but still increasing. This may not be a serious problem if one recalls the large spread of energies of observed supernovae (Supernova 1999br, for example, is estimated to have an ejecta mass of $14\,M_\odot$ and an explosion energy of about 6×10^{50} erg [14]).

Since the explosion starts rather late (at ~ 150 ms post bounce), the proto-neutron star has accreted enough matter to have attained an initial baryonic mass of $1.4\,M_\odot$. Therefore our simulation does not exhibit the problem of previous successful multi-dimensional calculations which produced neutron stars with masses on the lower side of plausible values ($\sim 1.1\,M_\odot$). Also another problem of published explosion models (e.g., [19,10,23,12]) has disappeared: The ejecta mass with $Y_e \lesssim 0.47$ is less than $10^{-4}\,M_\odot$, thus fulfilling a constraint pointed out by Hoffman et. al. [21] for supernovae if they should not overproduce the $N = 50$ (closed neutron shell) nuclei, in particular ^{88}Sr, ^{89}Y and ^{90}Zr, relative to the Galactic abundances. Of course, final statements about explosion energy, ejecta composition, and the neutron star mass (which may grow by later fall-back, especially when the explosion energy remains low) require to follow the explosion for a longer time.

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References

1. S. Akiyama, J.C. Wheeler, D.L. Meier, I. Lichtenstadt: Astrophys. J., in press (2002) (astro-ph/0208128)
2. H.A. Bethe, J.R. Wilson: Astrophys. J. **295**, 14 (1985)
3. J.M. Blondin, A. Mezzacappa, C. DeMarino: Preprint (2002)
4. S.W. Bruenn: Astrophys. J. Suppl. **58**, 771 (1985)
5. S.W. Bruenn: 'Numerical Simulations of Core Collapse Supernovae'. In: *Nuclear Physics in the Universe*, ed. by M.W. Guidry, M.R. Strayer (IOP, Bristol 1993) pp. 31–50
6. S.W. Bruenn, K.R. De Nisco, A. Mezzacappa: Astrophys. J. **560**, 326 (2001)
7. R. Buras, M. Rampp et al.: in preparation (2002)
8. A. Burrows, R.F. Sawyer: Phys. Rev. C. **58**, 554 (1998)
9. A. Burrows, R.F. Sawyer: Phys. Rev. C. **59**, 510 (1999)
10. A. Burrows, J. Hayes, B.A. Fryxell: Astrophys. J. **450**, 830 (1995)
11. G.W. Carter, M. Prakash: Physics Letters B **525**, 249 (2002)
12. C.L. Fryer: Astrophys. J. **522**, 413 (1999)
13. C.L. Fryer, M. S. Warren: Astrophys. J. Lett. **574**, L65 (2002)
14. M. Hamuy: Astrophys. J., in press (2002) (astro-ph/0209174)
15. S. Hannestad, G. Raffelt: Astrophys. J. **507**, 339 (1998)
16. R. Buras, H.-Th. Janka, M.-Th. Keil, G. Raffelt, M. Rampp: Astrophys. J., submitted (2002) (astro-ph/0205006)
17. M. Herant: Physics Rep. **256**, 117 (1995)
18. M. Herant, W. Benz, S.A. Colgate: Astrophys. J. **395**, 642 (1992)
19. M. Herant, W. Benz, W.R. Hix, C.L. Fryer, S.A. Colgate: Astroph. J. **435**, 339 (1994)
20. P. Höflich, J.C. Wheeler, L. Wang: Astrophys. J. **521**, 179 (1999)
21. R.D. Hoffman, S.E. Woosley, G.M. Fuller, B.S. Meyer: Astrophys. J. **460**, 478 (1996)
22. C.J. Horowitz: Phys. Rev. D **65**, 043001-1 (2002)
23. H.-Th. Janka, E. Müller: Astron. Astrophys. **306**, 167 (1996)

24. H.-Th. Janka, R. Buras, M. Rampp: 'The Mechanism of Core-Collapse Supernovae and the Ejection of Heavy Elements'. In: *Proceedings of the 7th Int. Symposium on Nuclei in the Cosmos, Fuji-Yoshida, Yamanashi, Japan, 8–12 July, 2002*, Nuclear Physics A, in press (2002)
25. H.-Th. Janka, R. Buras, K. Kifonidis, T. Plewa, M. Rampp: 'Explosion Mechanisms of Massive Stars'. In: *Core Collapse of Massive Stars*, ed. C.L. Fryer (Kluwer, Dordrecht) in preparation
26. A.M. Khokhlov, P. Höflich, E.S. Oran, J.C. Wheeler, L. Wang, A.Yu. Chtchelkanova: Astrophys. J. Lett. **524**, L107 (1999)
27. J.M. Lattimer, F.D. Swesty: Nucl. Phys. A **535**, 331 (1991)
28. D.C. Leonhard, A.V. Filippenko, D.R. Ardila, M.S. Brotherton: Astrophys. J. **553**, 86 (2001)
29. M. Liebendörfer et al.: in preparation (2002)
30. M. Liebendörfer, O.E.B. Messer, A. Mezzacappa, W.R. Hix, F.-K. Thielemann, K. Langanke: 'The Importance of Neutrino Opacities for the Accretion in Spherically Symmetric Supernova Models'. In: *Proc. 11th Workshop on Nuclear Astrophysics, Ringberg, Feb. 11–16, 2002*, Report MPA/P13, ed. by W. Hillebrandt, E. Müller (MPI für Astrophysik, Garching 2002) pp. 126–131 (`astro-ph/0203260`)
31. M. Liebendörfer, A. Mezzacappa, F. Thielemann, O.E. Messer, W.R. Hix, S.W. Bruenn: Phys. Rev. D. **63**, 3004 (2001)
32. R.W. Mayle, M. Tavani, J.R. Wilson: Astroph. J. **418**, 398 (1993)
33. A. Mezzacappa, S.W. Bruenn: Astrophys. J. **405**, 637 (1993)
34. A. Mezzacappa, S.W. Bruenn: Astrophys. J. **410**, 740 (1993)
35. A. Mezzacappa, M. Liebendörfer, O.E.B. Messer, W.R. Hix, F.-K. Thielemann, S.W. Bruenn: Phys. Rev. Lett. **86**, 1935 (2001)
36. A. Mezzacappa, A.C. Calder, S.W. Bruenn, J.M. Blondin, M.W. Guidry, M.R. Strayer, A.S. Umar: Astroph. J. **495**, 911 (1998)
37. E.S. Myra, S.A. Bludman: Astrophys. J. **340**, 384 (1989)
38. E.S. Myra, S.A. Bludman, Y. Hoffman, I. Lichenstadt, N. Sack, K.A. van Riper: Astrophys. J. **318**, 744 (1987)
39. D.K. Nadyozhin, Astron. Astrophys., submitted (2002) (Preprint MPA 1458)
40. K. Nomoto, T. Shigeyama, S. Kumagai, H. Yamaoka, T. Suzuki: 'Supernova 1987A: From Progenitor to Remnant'. In: *Supernovae, Les Houches Session LIV, July 31–Sept. 1, 1990*, ed. S.A. Bludman, R. Mochkovitch, J. Zinn-Justin (Elsevier/North-Holland, Amsterdam 1994) pp. 489–568
41. K. Nomoto, K. Maeda, H. Umeda, T. Ohkubo, J. Deng, P. Mazzali: 'Hypernovae and their Nucleosynthesis'. In: *A Massive Star Odyssey, from Main Sequence to Supernova, Proc. IAU Symposium 212*, ed. K.A. van der Hucht, A. Herrero, C. Esteban (ASP, San Francisco) in press (`astro-ph/0209064`)
42. T. Plewa, K. Kifonidis, H.-Th. Janka: in preparation (2002)
43. M. Rampp, H.-Th. Janka: Astrophys. J. Lett. **539**, L33 (2000) B
44. M. Rampp, H.-Th. Janka: Astron. Astrophys., in press (2002) (`astro-ph/0203101`)
45. T. Shimizu, S. Yamada, K. Sato: Publ. Astron. Soc. Japan **45**, L53 (1993)
46. T. Shimizu, S. Yamada, K. Sato: Astrophys. J. Lett. **432**, L119 (1994)
47. T.M. Shimizu, T. Ebisuzaki, K. Sato, S. Yamada, Astrophys. J. **552**, 756 (2001)
48. T. Totani, K. Sato, H.E. Dalhed, J.R. Wilson: Astroph. J. **496**, 216 (1998)
49. L. Wang, D.A. Howell, P. Höflich, J.C. Wheeler: Astrophys. J. **550**, 1030 (2001)
50. L. Wang, J.C. Wheeler et al.: Astrophys. J., in press (`astro-ph/0205337`)
51. J.C. Wheeler: AAPT/AJP Resource Letter, American J. of Physics, in press (2002) (`astro-ph/0209514`)

52. J.C. Wheeler, D.L. Meier, J.R. Wilson: Astrophys. J. **568**, 807 (2002)
53. J.C. Wheeler, I. Yi, P. Höflich, L. Wang: Astrophys. J. **537**, 810 (2000)
54. J.R. Wilson: 'Supernovae and Post-Collapse Behavior'. In: *Numerical Astrophysics, Proc. Symposium in Honor of J.R. Wilson, Illinois, Oct. 1982*, ed. by J.M. Centrella, J.M. LeBlanc, R.L. Bowers, J.A. Wheeler (Jones and Bartlett, Boston 1985) pp. 422–434
55. J.R. Wilson, R. Mayle: Phys. Rep. **163**, 63 (1988)
56. J.R. Wilson, R. Mayle: Phys. Rep. **227**, 97 (1993)
57. S.E. Woosley, A. Heger, T.A. Weaver: Reviews of Modern Physics, submitted (2002)