Explosion Mechanism of Core-Collapse Supernovae — a View Ten Years after SN 1987A

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Abstract. The observation of neutrinos from Supernova 1987A has confirmed the theoretical conjecture that these particles play a crucial role during the collapse of the core of a massive star. Only one per cent of the energy they carry away from the newly formed neutron star may account for all the kinetic and electromagnetic energy responsible for the spectacular display of the supernova explosion. However, the neutrinos emitted from the collapsed stellar core at the center of the explosion couple so weakly to the surrounding matter that convective processes behind the supernova shock and/or inside the nascent neutron star might be required to increase the efficiency of the energy transfer to the stellar mantle and envelope. The conditions for a successful explosion by the neutrino-heating mechanism and the possible importance of convection in and around the neutron star are shortly reviewed.

1. Introduction

Even after ten exciting years SN 1987A keeps rapidly evolving and develops new, unexpected sides like an aging character. In the first few months the historical detection of 24 neutrinos in the underground facilities of the Kamiokande, IMB, and Baksan laboratories caused hectic activity among scientists from very different fields. In the subsequent years the scene was dominated by the rise and slow decay of light emission in all wavelengths which followed the outbreak of the supernova shock and contained a flood of data about the structure of the progenitor star and the dynamics of the explosion. Now that the direct emission has settled down to a rather low level, the supernova light which is reflected from circumstellar structures provides insight into the progenitor's evolution. Even more information about the latter can be expected when the supernova shock hits the inner ring in a few years.

The neutrino detections in connection with SN 1987A were the final proof that neutrinos take up the bulk of the energy during stellar core collapse and neutron star formation. Lightcurve and spectra of SN 1987A bear clear evidence of large-scale mixing in the stellar mantle and envelope and of fast moving Ni clumps (see, e.g., J. Spyromilio, D. Wooden, K. Nomoto, this volume). Both might indicate that macroscopic anisotropies and inhomogeneities were already present near the formation region of Fe group elements during the very early stages of the explosion. Spherically symmetric models had been suggesting for some time already that regions inside the newly formed neutron star and in the

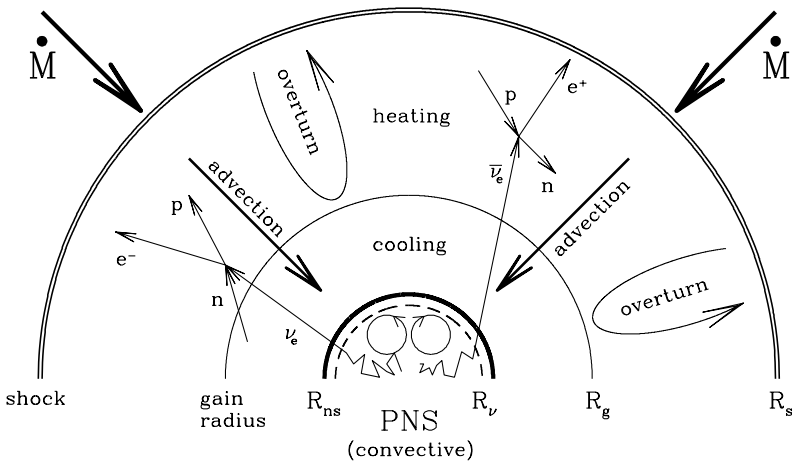

Figure 1. Sketch of the post-collapse stellar core during the neutrino heating and shock revival phase.

neutrino-heated layer around it might be convectively unstable. These theoretical results and the observational findings in SN 1987A were motivation to study stellar core collapse and supernova explosions with multi-dimensional simulations.

In this article convective overturn in the neutrino-heated region around the collapsed stellar core is discussed concerning its effects on the neutrino energy deposition and its potential importance for the supernova explosion. Convective activity inside the proto-neutron star is suggested as a possibly crucial boost of the neutrino luminosities on a timescale of a few hundred milliseconds after core bounce. The first two-dimensional simulations that follow the evolution of the nascent neutron star for more than one second are shortly described.

2. Neutrino-driven explosions and Convective overturn

Convective instabilities in the layers adjacent to the nascent neutron star are a natural consequence of the negative entropy gradient built up by neutrino heating (Bethe 1990) and are seen in recent two- and three-dimensional simulations (Burrows et al. 1995; Herant et al. 1992, 1994; Janka & Müller 1995, 1996; Mezzacappa et al. 1997; Miller et al. 1993; Shimizu et al. 1994). Although there is general agreement about the existence of this unstable region between the radius of maximum neutrino heating (which is very close outside the "gain radius" $R_{\rm g}$, i.e. the radius where neutrino cooling switches into net heating) and the shock position $R_{\rm s}$, the strength of the convective overturn and its importance for the success of the neutrino-heating mechanism in driving the explosion of the star is still a matter of vivid debate.

The effect of convective overturn in the neutrino-heated region on the shock is two-fold. On the one hand, heated matter from the region close to the gain radius rises outward and at the same time is replaced by cool gas flowing down from the postshock region. Since the production reactions of neutrinos ($e^{\pm}$

capture on nucleons and thermal processes) are very temperature sensitive, the expansion and cooling of rising plasma reduces the energy loss by reemission of neutrinos. Moreover, the net energy deposition by neutrinos is enhanced as more cool material is exposed to the large neutrino fluxes just outside the gain radius where the neutrino heating rate peaks (the radial dilution of the fluxes roughly goes as $1/r^2$). On the other hand, hot matter floats into the postshock region and increases the pressure there. Thus the shock is pushed further out which leads to a growth of the gain region and therefore also of the net energy transfer from neutrinos to the stellar gas.

Figure 1 displays a sketch of the neutrino cooling and heating regions outside the proto-neutron star at the center. The main processes of neutrino energy deposition are the charged-current reactions $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$. The heating rate per nucleon (N) is approximately

$$Q_\nu^+ \approx 110 \cdot \frac{L_{\nu,52}\langle\epsilon^2_{\nu,15}\rangle}{r_7^2\, f} \cdot \left\{ \begin{array}{c} Y_n \\ Y_p \end{array} \right\} \quad \left[\frac{\mathrm{MeV}}{\mathrm{s}\cdot N}\right] , \tag{1}$$

where Y_n and Y_p are the number fractions of free neutrons and protons, respectively, $L_{\nu,52}$ denotes the luminosity of ν_e or $\bar{\nu}_e$ in 10^{52} erg/s, r_7 the radial position in 10^7 cm, and $\langle\epsilon^2_{\nu,15}\rangle$ the average of the squared neutrino energy measured in units of 15 MeV. f is the angular dilution factor of the neutrino radiation field (the "flux factor", which is equal to the mean value of the cosine of the angle of neutrino propagation relative to the radial direction) which varies between about 0.25 at the neutrinosphere and 1 for radially streaming neutrinos far out. Using this energy deposition rate, neglecting loss due to re-emission of neutrinos, and assuming that the gravitational binding energy of a nucleon in the neutron star potential is (roughly) balanced by the sum of internal and nuclear recombination energies after accretion of the infalling matter through the shock, one can estimate the explosion energy to be of the order

$$E_{\mathrm{exp}} \approx 2.2 \cdot 10^{51} \cdot \frac{L_{\nu,52}\langle\epsilon^2_{\nu,15}\rangle}{r_7^2\, f} \left(\frac{\Delta M}{0.1\, M_\odot}\right) \left(\frac{\Delta t}{0.1\,\mathrm{s}}\right) - E_{\mathrm{gb}} + E_{\mathrm{nuc}} \quad [\mathrm{erg}] . \tag{2}$$

ΔM is the heated mass, Δt the typical heating timescale, E_{gb} the (net) total gravitational binding energy of the overlying, outward accelerated stellar layers, and E_{nuc} the additional energy from explosive nucleosynthesis which is typically a few 10^{50} erg and roughly compensates E_{gb} for progenitors with main sequence masses of less than about $20\, M_\odot$ (see also Burrows, this volume). Since the gain radius, shock radius, and Δt and thus also ΔM depend on $L_\nu\langle\epsilon^2_\nu\rangle$, the sensitivity of E_{exp} to the neutrino emission parameters is even stronger than suggested by Eq. (2).

In order to get explosions by the delayed neutrino-heating mechanism, certain conditions need to be fulfilled. Expansion of the postshock region requires sufficiently large pressure gradients near the radius R_{cut} of the developing mass cut. If one neglects self-gravity of the gas in this region and assumes the density profile to be a power law, $\rho(r) \propto r^{-n}$ (which is well justified according to numerical simulations which yield a power law index of $n \approx 3$; see also Bethe 1993), one gets $P(r) \propto r^{-n-1}$ for the pressure, and outward acceleration is maintained

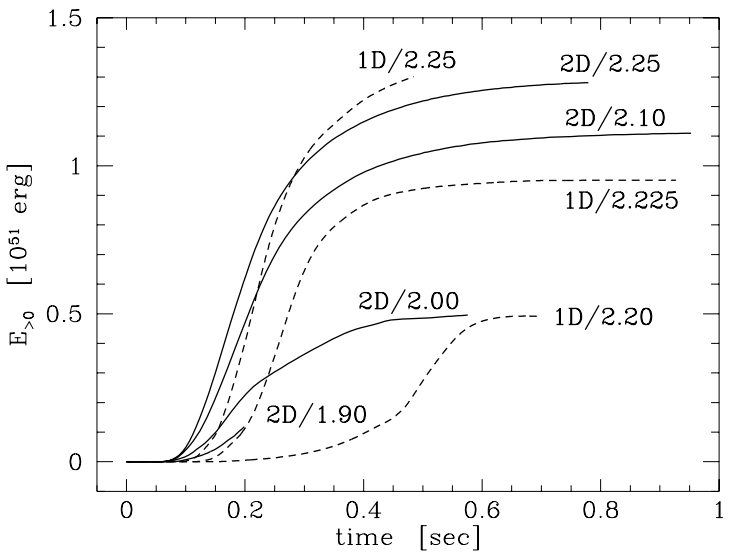

Figure 2. Explosion energies $E_{>0}(t)$ for 1D (dashed) and 2D (solid) simulations with different assumed ν_e and $\bar{\nu}_e$ luminosities (labels give values in 10^{52} erg/s) from the proto-neutron star. Below the smallest given luminosities the considered $15\,M_\odot$ star does not explode in 1D and acquires too low an expansion energy in 2D to unbind the stellar mantle and envelope.

as long as the following condition for the "critical" internal energy density ε holds:

$$\left.\frac{\varepsilon_{\rm c}}{GM\rho/r}\right|_{R_{\rm cut}} > \frac{1}{(n+1)(\gamma-1)} \cong \frac{3}{4}\,, \tag{3}$$

where use was made of the relation $P = (\gamma-1)\varepsilon$. The numerical value was obtained for $\gamma = 4/3$ and $n = 3$. This condition can be converted into a criterion for the entropy per baryon, s. Using the thermodynamical relation for the entropy density normalized to the baryon density n_b, $s = (\varepsilon+P)/(n_bT) - \sum_i \eta_i Y_i$ where η_i ($i = n$, p, e^-, e^+) are the particle chemical potentials divided by the temperature, and assuming completely disintegrated nuclei behind the shock so that the number fractions of free protons and neutrons are $Y_p = Y_e$ and $Y_n = 1 - Y_e$, respectively, one gets

$$s_{\rm c}(R_{\rm cut}) \gtrsim 15\,\left.\frac{M_{1.1}}{r_7\,T}\right|_{R_{\rm cut}} - \left.\ln\left(1.27\cdot 10^{-3}\,\frac{\rho_9\,Y_n}{T^{3/2}}\right)\right|_{R_{\rm cut}} \quad [k_{\rm B}/N]\ . \tag{4}$$

In this approximate expression a term with a factor Y_e was dropped (its absolute value being usually less than 0.5 in the considered region), nucleons are assumed to obey Boltzmann statistics, and, normalized to representative values, $M_{1.1}$ is measured in units of $1.1\,M_\odot$, ρ_9 in 10^9 g/cm^3, and r_7 in 10^7 cm. Inserting typical numbers ($T \approx 1.5$ MeV, $Y_n \approx 0.3$, $R_{\rm cut} \approx 1.5\cdot 10^7$ cm), one obtains $s > 15\,k_{\rm B}/N$, which gives an estimate of the entropy in the heating region when the star is going to explode.

These requirements can be coupled to the neutrino emission of the proto-neutron star by the following considerations. A stalled shock is converted into a moving one only when the neutrino heating is strong enough to increase the pressure behind the shock by a sufficient amount. Considering the Rankine-Hugoniot relations at the shock, Bruenn (1993) derived a criterion for the heating rate per unit mass, q_ν, behind the shock that guarantees a positive postshock velocity ($u_1 > 0$):

$$q_\nu \; > \; \frac{2\beta - 1}{\beta^3(\beta - 1)(\gamma - 1)} \, \frac{|u_0|^3}{\eta R_\mathrm{s}} \, . \tag{5}$$

Here β is the ratio of postshock to preshock density, $\beta = \rho_1/\rho_0$, γ the adiabatic index of the gas (assumed to be the same in front and behind the shock), and η defines the fraction of the shock radius R_s where net heating by neutrino processes occurs: $\eta = (R_\mathrm{s} - R_\mathrm{g})/R_\mathrm{s}$. u_0 is the preshock velocity, which is a fraction α (analytical and numerical calculations show that typically $\alpha \approx 1/\sqrt{2}$) of the free fall velocity, $u_0 = \alpha\sqrt{2GM/r}$. Assuming a strong shock, one has $\beta = (\gamma + 1)/(\gamma - 1)$ which becomes $\beta = 7$ for $\gamma = 4/3$. With numbers typical of the collapsed core of the $15\,M_\odot$ star considered by Janka & Müller (1996), $R_\mathrm{s} = 200\,\mathrm{km}$, $\eta \approx 0.4$, and an interior mass $M = 1.1\,M_\odot$, one finds for the threshold luminosities of ν_e and $\bar{\nu}_e$:

$$L_{\nu,52}\langle\epsilon^2_{\nu,15}\rangle \; > \; 2.0 \, \frac{M^{3/2}_{1.1}}{R^{1/2}_{\mathrm{s},200}} \, . \tag{6}$$

The existence of such a threshold luminosity of the order of $2 \cdot 10^{52}\,\mathrm{erg/s}$ is underlined by Fig. 2 where the explosion energy $E_{>0}$ as function of time is shown for numerical calculations of the same post-collapse model but with different assumed neutrino luminosities from the proto-neutron star. $E_{>0}$ is defined to include the sum of internal, kinetic, and gravitational energy for all zones where this sum is positive (the gravitational binding energies of stellar mantle and envelope and additional energy release from nuclear burning are not taken into account). For one-dimensional simulations with luminosities below $1.9 \cdot 10^{52}\,\mathrm{erg/s}$ we could not get explosions when the proto-neutron star was assumed static, and the threshold for the ν_e and $\bar{\nu}_e$ luminosities was $2.2 \cdot 10^{52}\,\mathrm{erg/s}$ when the neutron star was contracting (see Janka & Müller 1996). The supporting effects of convective overturn between the gain radius and the shock described above lead to explosions even below the threshold luminosities for the spherically symmetric case, to higher values of the explosion energy for the same neutrino luminosities, and to a faster development of the explosion. This can clearly be seen by comparing the solid (2D) and dashed (1D) lines in Fig. 2.

The results of Fig. 2 also show that the explosion energy is extremely sensitive to the neutrino luminosities and mean energies. This holds in 1D as well as in 2D. Dick McCray in his summary talk of this conference raised the question why neutrino-driven explosions should be self-regulated. Which kind of feedback should prevent the explosion from being more energetic than a few times $10^{51}\,\mathrm{erg}$? Certainly, the neutrino luminosities in current models can hardly power an explosion and therefore a way to overpower it is not easy to imagine. Nevertheless, Fig. 2 and Eq. (2) offer an answer to Dick's question: When the matter

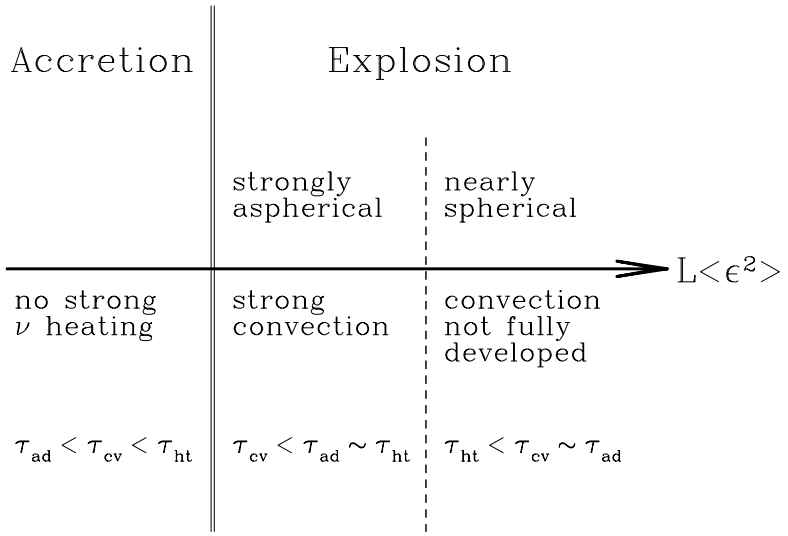

Figure 3. Order scheme for the dependence of the post-collapse dynamics on the strength of the neutrino heating as a function of $L_\nu \langle \epsilon_\nu^2 \rangle$.

in the neutrino-heated region outside the gain radius has absorbed roughly its gravitational binding energy from the neutrino fluxes, it starts to expand outward (see Eq. (3)) and moves away from the region of strongest heating. Since the onset of the explosion shuts off the re-supply of the heating region with cool gas, the curves in Fig. 2 approach a saturation level as soon as the expansion gains momentum and the density in the heating region decreases. Thus the explosion energy depends on the strength of the neutrino heating, which scales with the ν_e and $\bar{\nu}_e$ luminosities and mean energies, and it is limited by the amount of matter ΔM in the heating region and by the duration of the heating (see Eq. (2)), both of which decrease when the heating is strong and expansion happens fast.

This also implies that neutrino-driven explosions can be "delayed" (up to a few 100 ms after core bounce) but are *not* "late" (after a few seconds) explosions. The density between the gain radius and the shock decreases with time because the proto-neutron star contracts and the mass infall onto the collapsed core declines steeply with time. Therefore the mass ΔM in the heated region drops rapidly and energetic explosions by the neutrino-heating mechanism become less favored at late times.

Moreover, Fig. 2 tells us that convection is *not necessary* to get an explosion and convective overturn is *no guarantee* for strong explosions. Therefore one must suspect that neutrino-driven type-II explosions should reveal a considerable spread in the explosion energies, even for similar progenitor stars. Rotation in the stellar core, small differences of the core mass or statistical variations in the dynamical events that precede and accompany the explosion may lead to some variability.

The role of convective overturn and its importance for the explosion can be further illuminated by considering the three timescales of neutrino heating, $\tau_{\rm ht}$,

advection of accreted matter through the gain radius into the cooling region and onto the neutron star (compare Fig. 1), $\tau_{\rm ad}$, and growth of convective overturn, $\tau_{\rm cv}$. The evolution of the shock — accretion or explosion — is determined by the relative sizes of these three timescales. Straightforward considerations show that they are of the same order and the destiny of the star is therefore a result of a tight competition between the different processes (see Fig. 3).

The heating timescale is estimated from the initial entropy $s_{\rm i}$, the critical entropy $s_{\rm c}$ (Eq. (4)), and the heating rate per nucleon (Eq. (1)) as

$$\tau_{\rm ht} \approx \frac{s_{\rm c}-s_{\rm i}}{Q_\nu^+/(k_{\rm B}T)} \approx 45\,{\rm ms}\cdot\frac{s_{\rm c}-s_{\rm i}}{5k_{\rm B}/N}\,\frac{R_{\rm g,7}^2(T/2{\rm MeV})\,f}{(L_\nu/2\cdot10^{52}{\rm erg/s})\langle\epsilon_{\nu,15}^2\rangle}\,. \tag{7}$$

With a postshock velocity of $u_1 = u_0/\beta \approx (\gamma-1)\sqrt{GM/R_{\rm s}}/(\gamma+1)$ the advection timescale is

$$\tau_{\rm ad} \approx \frac{R_{\rm s}-R_{\rm g}}{u_1} \approx 52\,{\rm ms}\cdot\left(1-\frac{R_{\rm g}}{R_{\rm s}}\right)\frac{R_{\rm s,200}^{3/2}}{\sqrt{M_{1.1}}}\,, \tag{8}$$

where the gain radius can be determined as

$$R_{\rm g,7} \cong 0.4\left(\frac{L_\nu}{2\cdot10^{52}{\rm erg/s}}\right)^{-1/4}\langle\epsilon_{\nu,15}^2\rangle^{-1/4}f^{1/4}\left(\frac{R_{\rm ns}}{25{\rm km}}\right)^{3/2} \tag{9}$$

from the requirement that the heating rate, Eq. (1), is equal to the cooling rate per nucleon, $Q_\nu^- \approx 288(T/2{\rm MeV})^6$, when use is made of the power-law behavior of the temperature according to $T(r) \approx 4\,{\rm MeV}\,(R_{\rm ns}/r)$ with $R_{\rm ns}$ being the proto-neutron star radius (roughly equal to the neutrinosphere radius). The growth timescale of convective instabilities in the neutrino-heated region depends on the gradients of entropy and lepton number through the growth rate of Ledoux convection, $\sigma_{\rm L}$ (g is the gravitational acceleration):

$$\tau_{\rm cv} \approx \frac{\ln(100)}{\sigma_{\rm L}} \approx 4.6\left\{\frac{g}{\rho}\left[\left(\frac{\partial\rho}{\partial s}\right)_{Y_e,P}\frac{{\rm d}s}{{\rm d}r}+\left(\frac{\partial\rho}{\partial Y_e}\right)_{s,P}\frac{{\rm d}Y_e}{{\rm d}r}\right]\right\}^{-1/2} \gtrsim 50\,{\rm ms}\,. \tag{10}$$

The numerical value is representative for those obtained in hydrodynamical simulations (e.g., Janka & Müller 1996). $\tau_{\rm cv}$ of Eq. (10) is sensitive to the detailed conditions between neutrinosphere (where Y_e has typically a minimum), gain radius (where s develops a maximum), and the shock. The neutrino heating timescale is shorter for larger values of the neutrino luminosity L_ν and mean squared neutrino energy $\langle\epsilon_\nu^2\rangle$, while both $\tau_{\rm ht}$ and $\tau_{\rm ad}$ depend strongly on the gain radius, $\tau_{\rm ad}$ also on the shock position.

3. Convection inside the nascent neutron star

Convective energy transport inside the newly formed neutron star can increase the neutrino luminosities considerably (Burrows 1987). This could be crucial for energizing the stalled supernova shock (Mayle & Wilson 1988; Wilson & Mayle 1988, 1993; see also Sect. 2.).

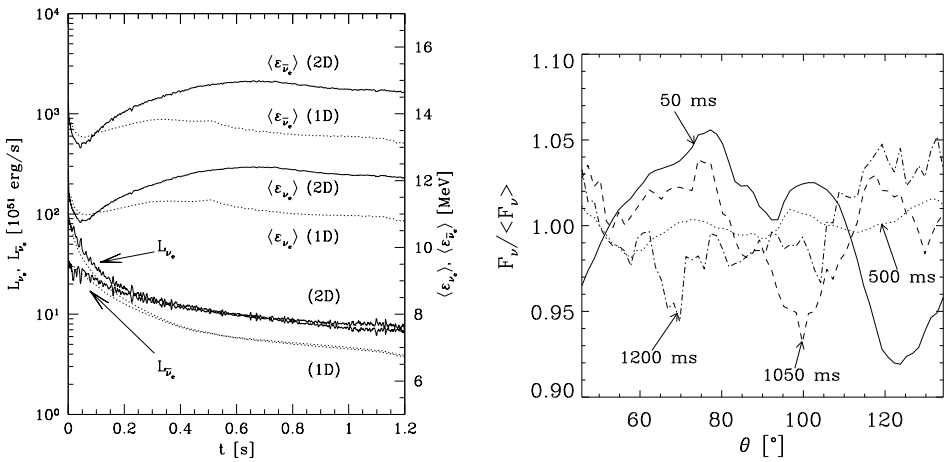

Figure 4. Left: Luminosities $L_\nu(t)$ and mean energies $\langle\epsilon_\nu\rangle(t)$ of ν_e and $\bar{\nu}_e$ for a $1.1\,M_\odot$ proto-neutron star without ("1D"; dotted) and with convection ("2D"; solid). Time is measured from core bounce. Right: Angular variations of the neutrino flux at different times for the 2D simulation.

Recent two-dimensional simulations by Keil et al. (1996, 1997) and Keil (1997) have followed the evolution of the proto-neutron star formed in the core collapse of a $15\,M_\odot$ star for a period of more than 1.2 seconds. The simulations were performed with the hydrodynamics code *Prometheus*. A general relativistic 1D gravitational potential with Newtonian corrections for asphericities was used, $\Phi \equiv \Phi^{\rm GR}_{\rm 1D} + (\Phi^{\rm N}_{\rm 2D} - \Phi^{\rm N}_{\rm 1D})$, and a flux-limited (equilibrium) neutrino diffusion scheme was applied for each angular bin separately ("$1\frac{1}{2}$D").

The simulations show that convectively unstable surface-near regions (i.e., around the neutrinosphere and below an initial density of about $10^{12}\,{\rm g/cm^3}$) exist only for a short period of a few ten milliseconds after bounce, in agreement with the findings of Bruenn & Mezzacappa (1994), Bruenn et al. (1995), and Mezzacappa et al. (1997). Due to a flat entropy profile and a negative lepton number gradient, convection, however, also starts in a layer deeper inside the star, between an enclosed mass of $0.7\,M_\odot$ and $0.9\,M_\odot$, at densities above several $10^{12}\,{\rm g/cm^3}$. From there the convective region digs into the star and reaches the center after about one second. Convective velocities as high as $5 \cdot 10^8\,{\rm cm/s}$ are reached (about 10–20% of the local sound speed), corresponding to kinetic energies of up to $1\text{–}2 \cdot 10^{50}\,{\rm erg}$. Because of these high velocities and rather flat entropy and composition profiles in the star, the overshoot (and undershoot) regions are large.

The coherence lengths of convective structures are of the order of 20–40 degrees (in 2D!) and coherence times are of the order of 10 ms which corresponds to only one or two overturns. The convective pattern is therefore very time-dependent and nonstationary. Convective motions lead to considerable variations of the composition. The lepton fraction (and thus the abundance of protons) shows relative fluctuations of several 10%. The entropy differences in

rising and sinking convective bubbles are much smaller, only a few per cent, while temperature and density fluctuations are typically less than one per cent.

The energy transport in the neutron star is dominated by neutrino diffusion near the center, whereas convective transport plays the major role in a thick intermediate layer where the convective activity is strongest, and radiative transport takes over again when the neutrino mean free path becomes large near the surface of the star. But even in the convective layer the convective energy flux is only a few times larger than the diffusive flux. This means that neutrino diffusion can never be neglected.

There is an important consequence of this latter statement. The convective activity in the neutron star cannot be described and explained as Ledoux convection. Applying the Ledoux criterion for local instability, $C_{\rm L}(r) = (\rho/g)\sigma_{\rm L}^2 > 0$ with $\sigma_{\rm L}$ from Eq. (10) and Y_e replaced by the total lepton fraction $Y_{\rm lep}$ in the neutrino-opaque interior of the neutron star, one finds that the convecting region should actually be stable, despite of slightly negative entropy *and* lepton number gradients. In fact, below a critical value of the lepton fraction (e.g., $Y_{\rm lep,c} = 0.148$ for $\rho = 10^{13}\,{\rm g/cm^3}$ and $T = 10.7\,{\rm MeV}$) the thermodynamical derivative $(\partial\rho/\partial Y_{\rm lep})_{s,P}$ changes sign and becomes positive because of nuclear and Coulomb forces in the high-density equation of state. Therefore negative lepton number gradients should stabilize against convection in this regime. However, an idealized assumption of Ledoux convection is not fulfilled in the situations considered here: Because of neutrino diffusion energy exchange and, in particular, lepton number exchange between convective elements and their surroundings are *not* negligible. Taking the neutrino transport effects on $Y_{\rm lep}$ into account in a modified *Quasi-Ledoux criterion* (Keil 1997 and Keil et al. 1997) one predicts instability exactly where convective action happens in the two-dimensional simulation.

4. Conclusions

Convection inside the proto-neutron star can raise the neutrino luminosities within a few hundred ms after core bounce (Fig. 4). In the considered collapsed core of a $15\,M_\odot$ star L_{ν_e} and $L_{\bar{\nu}_e}$ increase by up to 50% and the mean neutrino energies by about 15% at times later than 200–300 ms post bounce. This favors neutrino-driven explosions on timescales of a few hundred milliseconds after shock formation. Also, the deleptonization of the nascent neutron star is strongly accelerated, raising the ν_e luminosities relative to the $\bar{\nu}_e$ luminosities during this time. This helps to increase the electron fraction Y_e in the neutrino-heated ejecta and might solve the overproduction problem of $N = 50$ nuclei during the early epochs of the explosion (Keil et al. 1996). Anisotropic mass motions due to convection in the neutron star lead to gravitational wave emission and anisotropic radiation of neutrinos. The angular variations of the neutrino flux determined by the 2D simulations are of the order of 5–10% (Fig. 4). With the typical size and short coherence times of the convective structures, however, the global anisotropy of the neutrino emission from the cooling proto-neutron star is certainly less than 1% (more likely only 0.1%, since in 3D the structures tend to be smaller) and kick velocities in excess of 300 km/s can definitely not be explained.

In more recent simulations, mass accretion and rotation of the forming neutron star were included. Rotation has very interesting consequences, e.g., leads to a suppression of convective motions near the rotation axis because of a stabilizing stratification of the specific angular momentum, an effect which can be understood by applying the Solberg-Høiland criterion for instabilities in rotating, self-gravitating objects. Future simulations will have to clarify the influence of the nuclear equation of state on the presence of convection in nascent neutron stars. Also, a more accurate treatment of the neutrino transport in combination with a state-of-the-art description of the neutrino opacities of the nuclear medium is needed to confirm the existence of a convective episode during neutron star formation and to study its importance for the explosion mechanism of type-II supernovae.

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