Non-spherical core collapse supernovae and nucleosynthesis

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Motivated by observations of supernova SN 1987A, various authors have simulated Rayleigh–Taylor (RT) instabilities in the envelopes of core collapse supernovae (for a review, see [1]). The non-radial motion found in these simulations qualitatively agreed with observations in SN 1987A, but failed to explain the extent of mixing of newly synthesized \( ^{56}\text{Ni} \) quantitatively. Here we present results of a 2D hydrodynamic simulation which re-addresses this failure and covers the entire evolution of the first 5 hours after core bounce.

1. Model description and numerical setup

Our simulation is split into two stages. The early evolution \((t < 1\text{s})\) is computed with the HERAKLES code (Plewa & Müller, in preparation) which solves the multi-dimensional hydrodynamic equations using the direct Eulerian version of the Piecewise Parabolic Method [2] and which incorporates the physics (equation of state, neutrino source terms and light bulb) described in the simulations of neutrino driven supernovae by [3] with the following modifications. General relativistic corrections are added to the gravitational potential. A 14-isotope network is implemented to compute the explosive nucleosynthesis including the 13 \(\alpha\)-nuclei from \(^{4}\text{He}\) to \(^{56}\text{Ni}\) and a tracer nucleus which is used to keep track of the neutronization of the material. The 2D spherical grid consists of 400 radial zones \((3.17 \times 10^{6}\text{cm} \leq r \leq 1.7 \times 10^{9}\text{cm})\) and 192 angular zones \((0 \leq \theta \leq \pi)\). The initial data is a 15\(M_{\odot}\) progenitor model [4] which has been collapsed [5]. The following set of neutrino parameters is adopted (cf. [3]): \(L_{\nu_{e}}^{0} = 3.094 \times 10^{52}\text{erg/s}, L_{\nu_{x}}^{0} = 2.613 \times 10^{52}\text{erg/s}, \Delta Y_{l} = 0.0963, \Delta \varepsilon = 0.0688\). The neutrino spectra and the functional form of the luminosity decay are the same as in [3]. A random initial seed perturbation is added to the velocity field with a modulus of \(10^{-3}\) of the (radial) velocity of the post–collapse model. The computation begins 20\(\text{ms}\) after core bounce and is carried up to 800\(\text{ms}\) when the explosion energy has saturated at \(E_{\text{expl}} = 1.77 \times 10^{51}\text{erg}\).

The subsequent propagation of the shock through the stellar envelope and the growth of RT instabilities is simulated with the adaptive mesh refinement code AMRA (Plewa & Müller, in preparation). Neutrino physics is not included in AMRA because it does influence the explosion dynamics only within the first few seconds. Newtonian self-gravity

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is taken into account by solving Poisson’s equation in one spatial dimension with an angular average of the density, which is an adequate approximation once the shock has left the iron core. The equation of state includes contributions from photons, non-degenerate electrons, $e^+e^-$-pairs, $^1$H, and the nuclei included in the reaction network.

The AMR calculations are started with the inner and outer boundaries located at $r_{\text{in}} = 10^8 \text{ cm}$ and $r_{\text{out}} = 4.8 \times 10^{10} \text{ cm}$. No further seed perturbations are added. The maximum resolution is equivalent to that of a uniform grid of $3072 \times 768$ zones. The radial extent of the base grid is extended whenever the supernova shock approaches the outer grid boundary, which attains a maximum value of $r_{\text{out}} = 3.9 \times 10^{12} \text{ cm}$ at $t = 2095 \text{ s}$. Reflecting (outflow) boundary conditions are imposed in angular (radial) direction. The initial data for the AMR simulation consists of three different parts. Interior to $17000 \text{ km} (1.63 \text{ M}_\odot)$ data from the simulations of the first stage of the explosion, and exterior to that radius data from Bruenn’s 1D post-collapse model are used. Matched to Bruenn’s model (covering only parts of the He core) is a new progenitor model of Woosley (private communication; data for the 1988 model are no longer available).

2. Results and discussion

The simulation of the early evolution shows, in accordance with [3], that neutrino driven convection leads to the formation of a roughly spherical but very inhomogeneous post-shock shell containing dense $^{56}$Ni–rich regions and low–density, deleptonized bubbles. These inhomogeneities provide the seed for RT mixing in the stellar envelope at the Si/O and (C+O)/He interfaces of the SN 1987A progenitor model within only about a minute after core bounce [3].

The stellar metal core is completely shredded only 5 minutes after bounce and high velocity clumps of newly synthesized elements are observed to be ejected up to the outer edge of the He–core. While the instability is turning the inner core of the star inside out, a dense shell forms at the He/H interface as a result of the deceleration of the main shock in the H–envelope. The subsequent interaction of the metal–enriched clumps with this dense He–shell leads to their strong deceleration. After entering the shell the clumps reach transonic speeds and dissipate a large fraction of their kinetic energy. As a result the entire dense shell and the H–envelope are pervaded by bow-shocks and strong acoustic waves from 3000 to 10 000 s after core bounce. During this interaction, which has not been reported in any previous calculation of RT instabilities in SNeII progenitors, the composition within the clumps themselves is almost entirely homogenized. Furthermore, acting like a wall the shell shields the H–envelope of the star from becoming enriched with freshly synthesized elements.

According to a linear stability analysis the He/H interface should be RT unstable. However, we do not find a strong growth of the instability at this interface. Since the supernova shock is almost perfectly spherically symmetric when it emerges from the He–core the evolution in these layers proceeds basically one-dimensional. Only when the metal–enriched clumps reach the inner boundary of the dense shell behind the He/H interface and start to dissipate their energy about 3000 s after bounce, are perturbations from spherical symmetry induced by the waves which are thereby excited. However, as the interface is only moderately unstable at this time, only small scale variations are
Figure 1. Mass of $^{56}$Ni which is contained within the velocity interval $[v_r, v_r + dv_r]$ as a function of the radial velocity $v_r$ at various epochs. The resolution is $dv_r \approx 130$ km s$^{-1}$.

observed. If this result also holds for other progenitor models, it indicates that neutrino driven convection alone is not able to provide the perturbations which are needed to induce strong mixing of the helium core and the H–envelope as observed in SN 1987A.

Already within the first 300 s of the explosion elements like $^{16}$O and $^{32}$Si that made up the original metal core as well as the newly synthesized $^{56}$Ni have been mixed almost homogeneously throughout the inner 2.0$M_\odot$, i.e., throughout about the inner half of the He–core. The extent of mixing increases up to 3.2$M_\odot$ at 10 000 s. Species which are not mixed this far out in mass are $^{44}$Ti and our neutronization tracer. These nuclei were synthesized in the innermost layers of the ejecta which were located very close to the collapsed core.

The dynamics of the explosion is reflected in the distribution of the mass of $^{56}$Ni in velocity space (Fig. 1). The most conspicuous feature which can be seen in this plot is the bulk deceleration of the material from velocities as large as $\sim 5000$ km/s at a time of 50 s after bounce to less than 1500 km/s after 10 000 s. At 50 s the average $^{56}$Ni velocity is $\sim 3500$ km/s with a spread of about $\pm 1400$ km/s. At 10 000 s the corresponding values are $\sim 900$ km/s and $\pm 500$ km/s. The maximum velocities are significantly smaller than the ones which have been observed in SN 1987A. During no phase of the evolution we do see an acceleration of material from the former metal core of the star. This is in contrast to the results of Herant & Benz (1992) who report to have obtained nickel velocities comparable to those observed in SN 1987A provided that they premixed the $^{56}$Ni in their SPH calculations throughout 75% (in mass) of the metal core ($\sim 2M_\odot$) of their 20$M_\odot$ progenitor.

The occurrence of conditions which could give rise to the development of an instability at the He/H interface is harmful for the propagation of the clumps. Even if very strong
perturbations are imposed upon the dense unstable shell which forms at this interface the
instability is growing too slowly in order to shred this “wall” before the clumps will reach
it. On the other hand, with a smoother density profile between the He–core and the H–
envelope, the dense shell might either not form at all or become at least less pronounced
which might help the clumps to preserve most of their energy. Such a smoother density
profile could be envisaged when the progenitor star of SN 1987A was not the result of
the evolution of a single star but a merger of two smaller stars [9]. The dimensionality
of our simulations may also be a possible cause of the problem. The fingers found in 2D
calculations are in fact axially symmetric tori which also experience a larger drag when
propagating outwards than genuinely 3D mushroom structures.

Finally, “missing physics” in the explosion models itself might be responsible for the
small maximum nickel velocities that we obtain. Effects like rotation or anisotropic neu-
trino emission might have to be considered for the explosion mechanism. These may
result in an additional large scale asphericity of the shock or even in jet-like outflows of
the ejecta. In that case it has been claimed [8] that it is possible to reproduce nickel
velocities in excess of 3000 km/s. However, these simulations suffer from coarse resolution
and from rather unrealistic parameterized initial conditions.

3. Summary

Our calculations prove for the first time that convective instabilities which develop
during the first second of the explosion are able to provide the seed for significant RT
mixing at the Si/O and (C+O)/He interfaces. This might offer an explanation for the
mixing observed in the explosions of SNe Ib/Ic [6].

During the first $\sim 30$ minutes of the explosion our $^{56}\text{Ni}$ velocities are as high as those
measured in the Type II SN 1987A and the Type IIb SN 1993J. The main reason for this
agreement is the subsonic ballistic motion of the clumps relative to the mean background
flow. The concordance with observations is, however, destroyed, when the clumps enter
the outer helium core and encounter a dense (RT unstable) shell which is left behind by
the shock at the He/H interface. The clumps are decelerated to velocities $< 2000$ km/s
because their propagation in this new environment is transonic. Hence, the main difficulty
for future simulations is how to avoid to decelerate the initially fast $^{56}\text{Ni}$ clumps.

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