The First Hours of a Core Collapse Supernova

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Abstract

New two-dimensional, high-resolution calculations of a core collapse supernova in a $15 M_\odot$ blue supergiant are presented, which cover the entire evolution from shock revival until the first few hours of the explosion. Explosive nucleosynthesis, its dependence upon convective mixing during the first second of the evolution and the growth of Rayleigh-Taylor instabilities at the composition interfaces of the progenitor star are all modeled consistently and allow for a comparison with observational data. We confirm our earlier findings, that the perturbations induced by neutrino driven convection are sufficiently strong to seed large-scale Rayleigh-Taylor mixing and to destroy the onion-shell structure of the stellar He-core. As in our earlier calculations, the strong deceleration of the nickel clumps in the layers adjacent to the He/H interface suggests that the high velocities of iron-group elements observed in SN 1987 A cannot be explained on the basis of currently favored progenitor models. Possible solutions to this dilemma and the implications of the mixing for type Ib explosions are briefly discussed.

1.1 Introduction

Recent observations of the Cas A remnant by NASA’s Chandra X-ray observatory [3] appear to directly disclose for the first time the nature of the violent processes which are responsible for the synthesis of heavy and intermediate mass elements in core collapse supernovae. The spatial separation of silicon and iron emission observed by Hughes et al. [3] has been interpreted as the result of a large-scale overturn during the earliest phases of the explosion of the Cas A progenitor. Together with the numerous indications of strong mixing in e.g. SN 1987 A [1] and SN 1993 J [7] these new observations begin to assemble into a picture in which hydrodynamic instabilities in supernova explosions are inevitable and must be regarded as a key to an understanding of these events. Thus multidimensional hydrodynamic simulations are urgently required which must cover the entire evolution from shock formation until shock breakout through the stellar photosphere.

In [5] we have reported on first preliminary results of such calculations and found that neutrino driven convection is able to seed strong Rayleigh-Taylor mixing at the Si/O and (C+O)/He interfaces of the SN 1987 A progenitor model of [8] within only about a minute after core bounce. The stellar metal core was found to have been completely shredded only five minutes after bounce and high-velocity clumps of newly synthesized elements were observed to be ejected up to the outer edge of the helium core. However, these were substantially decelerated in a dense shell that formed at the He/H interface after the supernova shock entered the hydrogen envelope of the star. In this contribution we present more refined calculations for the same presupernova star, which cover a longer period of the evolution and which are used to test the numerical sensitivity of our earlier results.
1.2 Models

In our new calculations we have accomplished to overcome the numerical problems due to “odd-even decoupling” that were observed in [5], to increase the spatial resolution and to include gravity into the adaptive mesh refinement (AMR) calculations of the Rayleigh-Taylor growth phase, which now cover the time span from 820 ms up to more than 20 000 s after bounce. Different from [5] we have also used a new, somewhat more energetic explosion model ($E_{\text{expl}} = 1.8 \times 10^{53}$ ergs as compared to $E_{\text{expl}} = 1.5 \times 10^{51}$ ergs). Note, however, that since gravity was neglected in our old AMR calculations, the old model resulted in a kinetic energy at infinity of $E_{\text{expl}} \approx 1.8 \times 10^{51}$ ergs which is by about 20% larger than in the new simulations. This, of course, resulted in a slower overall expansion in our new calculations, giving the Rayleigh-Taylor instability somewhat more time to grow before the clumps reached the outer edge of the He core.

Not being affected by noise due to odd-even decoupling, our new simulations show qualitative differences in the growth of the Rayleigh-Taylor instability. Seeded by neutrino driven convection in the deeper layers of complete silicon burning, the instability starts to grow about 50 s after bounce at the Si/O interface on much smaller angular scales (of the order of $\leq 1^\circ$) than found in [5]. Superposed upon the resulting mushrooms, which grow out of the highest frequency perturbations that can still be resolved on our grid, are long-wavelength perturbations of the entire interface which are caused by the convective blobs beneath it. From these perturbations evolve initially cusps and subsequently fully-grown fingers, which start to perturb also the unstable O/He interface. Fig. 1 shows the situation 1170 s after core bounce when the instabilities at both interfaces are already fully developed. Depicted are the spatial distribution of the mass density as well as the partial densities of oxygen, silicon and nickel. Fine-grained filaments of dense material which includes silicon as well as newly synthesized $^{56}\text{Ni}$ (and other nuclides) are visible, which are embedded in broader oxygen fingers that penetrate through the He-core. However, no overturn of the $^{28}\text{Si}$ and $^{56}\text{Ni}$ rich layers as suggested by [5] is found in which the $^{56}\text{Ni}$ is mixed much farther out than the silicon. Both elements are rather evenly distributed throughout the He-core.

We find maximum $^{56}\text{Ni}$ velocities around 3000 km/s before the clumps penetrate into the dense shell at the He/H interface (see Fig. 1) 1600 s after bounce, and their velocities decrease to about 1000 km/s at the end of our calculations. Both of the quoted values are substantially lower than in our earlier simulations. The dense shell is caused by the compression of the post-shock matter behind the decelerating shock, which encounters a flatter slope of the density profile once it crosses the He/H interface and enters the hydrogen envelope. The strong flattening of the density gradient is a generic feature in all presupernova models proposed for SN 1987 A and makes dense shell formation inevitable during the explosion. Thus our new calculations underline that on the basis of presently favored progenitor and current multidimensional explosion models, it is not possible to explain the high nickel velocities in two-dimensional calculations.

1.3 Conclusions

Though in detail differences as compared to [5] are found, the main results and conclusions of our earlier work remain unchanged. We confirm that neutrino driven convection succeeds in seeding large-scale mixing processes in the exploding star which destroy its onion-shell structure on a time-scale of minutes. Although our calculations do not yield the kind of
Figure 1: Spatial distribution of the density (left) and the partial densities (right) of $^{16}$O (blue), $^{28}$Si (green, turquoise, white), and $^{56}$Ni (red, pink) in the inner He-core of the exploding star 1700 seconds after bounce. At this time, the supernova shock is already propagating through the hydrogen envelope. The onion shell structure of the core has been completely shredded by Rayleigh-Taylor instabilities at the Si/O and (C+O)/He interfaces. $^{28}$Si, $^{56}$Ni and all other products of explosive oxygen and silicon burning are localized in dense, rapidly expanding clumps which are propelled through the He core.

The overturn of iron and silicon-rich layers claimed to be present in Cas A by [3], they appear to yield a natural explanation for the mixing occurring in type Ib supernovae (see also [3]).

The situation is much more unclear in case of SN 1987 A. Definitely, a reliable modeling of the deceleration of the nickel clumps in the dense shell at the He/H interface has to take into account the different drag that genuinely three-dimensional “mushrooms” experience as compared to two-dimensional tori [4]. Thus three-dimensional calculations are required before one will be able to draw definite conclusions. However, the present calculations indicate that standard stellar evolution models for the progenitor of this supernova might have to be abandoned in favor of merger models, which appear to be the most likely explanation for such large differences of the hydrogen-envelope structure as our hydrodynamic simulations require.

An alternative explanation might, however, be sought in “missing physics” in the modeling of the explosion itself. Large-scale asymmetries, e.g. produced by jets [3], [6], may accelerate the products of complete silicon burning to velocities that might be sufficient to propel these elements up to the stellar hydrogen envelope.

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