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Explosion dynamics of parametrized spherically symmetric core-collapse supernova simulations

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Abstract. We analyze the explosion properties and dynamics of spherically symmetric, parametrized core-collapse supernovae derived with the new PUSH method. To this end, we explore the progenitor mass range between 18 and 21 $M_\odot$. We find that it is possible to suggest a distinction between low and high compactness progenitors. We discuss the differences on the example of two reference runs.

1. Introduction

We discuss explosion dynamics of spherically symmetric core-collapse supernova simulations obtained with the recently presented PUSH method ([1], Fröhlich et al., and Eichler et al., this volume). The PUSH method provides a framework to study many important aspects of core-collapse supernovae: the effects of the shock passage through the star, explosive supernova nucleosynthesis and the progenitor-remnant connection. To trigger explosions in the otherwise non-exploding simulations, the PUSH method relies on the neutrino-driven mechanism. It taps the energy reservoir provided by the heavy neutrino flavours to locally increase the energy deposition in the gain region, mimicking the net effects of large multi-dimensional instabilities in spherically symmetric framework. This extra energy deposition is achieved by introducing a local heating term, which is only active where electron-neutrinos are heating and where neutrino-driven convection can occur. For the neutrino transport, we employ IDSA [2] for the electron flavour neutrinos, and ASL [3] for the heavy-lepton flavour neutrinos. We analyze the progenitor mass range between 18 and 21 $M_\odot$ [4], which corresponds to typical values for the progenitor of SN 1987A [5].

2. Explosion Dynamics

Contrary to traditional artificial methods such as pistons (e.g., [6],[7]) or thermal bombs (e.g., [8], [9]), now with PUSH, it is possible to analyze the feedback of the evolution of the system on the neutrino heating and hence the explosion dynamics. Furthermore, in our simulations the mass cut emerges naturally. In our models, the explosion energy is mostly generated by the energy deposition of neutrinos in the eventually ejected layers, especially within the first second after bounce. Neutrinos are required to deposit a cumulative energy ($E_{idsa}+E_{push}$) much larger than the actual explosion energy E_{expl} (see Table 1) to revive the shock and to generate

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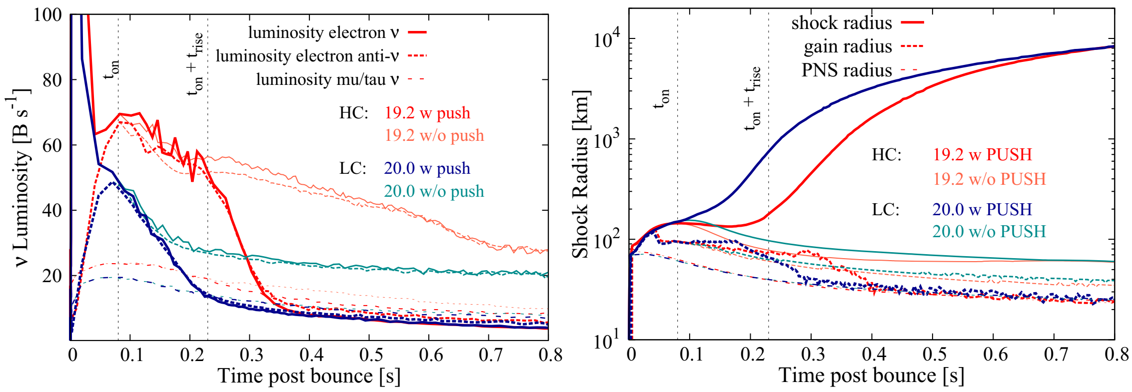
a successful explosion that matches the expected energy range.This is mainly due to the fact that the advection timescale is much shorter than the explosion timescale. A large fraction of the energy deposited in the gain region is advected onto the PNS surface by the accreting mass before an explosion sets in.

By investigating typical values of explosion energies and explosion times obtained with PUSH, as well as the response of the simulations to variations of the PUSH parameters, it is possible to suggest a distinction between low compactness (LC) and high compactness (HC) progenitors. This was also suggested by the work of Nakamura et al. in two-dimensional supernova simulations [10]. We evaluate the compactness parameter [11] at an enclosed mass of 1.75 $M_\odot$ and we employ a value of 0.4 to discriminate between HC and LC models. Below, we compare the 19.2 and 20.0 $M_\odot$ ZAMS progenitor models [4] as representatives for HC and LC models (see Table 1 for the explosion properties of the two reference runs).



(a) Temporal evolution of the neutrino luminosities.

(b) Temporal evolution of the shock, the gain, and the PNS radii. t_{on} sets the time post bounce when PUSH starts to act. At $t=t_{on}+t_{rise}$ the temporal tuning prefactor of PUSH reaches its maximum.

Figure 1. Temporal evolution of the neutrino luminosities, the shock, the gain, and the PNS radii of the HC (red lines) and the LC (blue lines) progenitor with (thick lines) and without PUSH (thin lines).

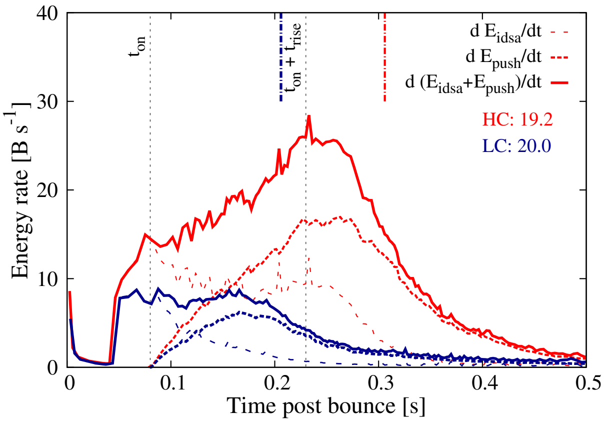


Figure 2. Temporal evolution of the neutrino energy deposition inside the gain region. The short colored vertical lines mark the times of explosion.

Quantity		HC	LC
ZAMS	($M_\odot$)	19.2	20.0
$\xi_{1.75}$	(-)	0.637	0.283
$t_{\rm expl}$	(ms)	307	206
$M_{\rm remn}$	($M_\odot$)	1.713	1.469
$E_{\rm expl}$ ($t_{\rm final}$)	(B)	1.36	0.57
$E_{\rm push}$ ($t_{\rm off} + t_{\rm rise}$)	(B)	3.51	1.08
$E_{\rm idsa}$ ($t_{\rm off} + t_{\rm rise}$)	(B)	2.76	1.01

Table 1. Explosion properties for the reference HC and LC runs. The compactness parameter evaluated at at an enclosed mass of 1.75 $M_\odot$ is denoted by $\xi_{1.75}$. Here, the explosion time $t_{\rm expl}$ is defined as the time when the shock reaches 500km, measured with respect to core bounce. Our final simulation time $t_{\rm final} \gtrsim 4.6$ s is much larger than the explosion time and allows the explosion energy $E_{\rm expl}$ to saturate. The value $E_{\rm push}$ denotes the cumulative energy deposited by PUSH and $E_{\rm idsa}$ represents the cumulative energy deposited by IDSA. Thereby, $t_{\rm off}$ stands for the time after bounce when PUSH is turned off ($t_{\rm off} = 1$ s).

Initially, the infalling velocities of unshocked matter are almost identical. However, the different density profiles of HC and LC models affect the evolution of the shock (see Figure 1b). For instance, $\rho_{19.2}/\rho_{20.0} \gtrsim 1.2$ outside the shock up to a radius of 2×10^8cm. The mass accretion rates start to differ between the two models around 30ms after the bounce. Immediate consequences of the difference in the accretion rates are that the neutrino luminosities are higher (Figure 1a), and that the shock stalling happens earlier and at a smaller radius (Figure 1b, visible in the case without PUSH) in the HC case. In the LC case, due to a lower accretion rate, the relatively small energy deposition rate of PUSH in the gain region (see Figure 2) is able to revive the shock a few milliseconds after PUSH is initiated (Figure 1b). As a result, the LC case explodes faster and with a lower explosion energy than the HC case (see Table 1).

3. Summary & Outlook

We have discussed the qualitative difference between a high and a low compactness explosion scenario in the progenitor mass range between 18 and 21 $M_\odot$ ZAMS that was investigated in [1] in order to reproduce observed properties of SN 1987A. In a next step we plan to conduct a broad progenitor study in the mass range between 15 and 75 $M_\odot$.

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