PUSHing core-collapse simulations to explosion

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Abstract. We report on the PUSH method for artificially triggering core-collapse supernova explosions of massive stars in spherical symmetry. The PUSH method increases the energy deposition in the gain region proportionally to the heavy flavor neutrino fluxes.We summarize the parameter dependence of the method and calibrate PUSH to reproduce SN 1987A observables. We identify a best-fit progenitor and set of parameters that fit the explosion properties of SN 1987A, assuming 0.1 $M_\odot$ of fallback. For the explored progenitor range of 18-21 $M_\odot$, we find correlations between explosion properties and the compactness of the progenitor model.

1. Introduction

At the end of the life of a massive star ($M_{\mathrm{ZAMS}} \gtrsim 8 M_\odot$), the iron core collapses. In this process, a proto-neutron star is formed and an outgoing shock wave is triggered. However, this shock wave looses energy to the dissociation of nuclei and neutrino emission, and thus stalls. It is thought that the shock is revived by fluid instabilities such as convection, turbulence, and the standing accretion shock instability and by the resulting more efficient neutrino-energy deposition. Core-collapse supernova simulations in spherical symmetry even with detailed neutrino-transport and general relativity fail to explode self-consistently. There are many ongoing efforts using multi-dimensional simulations. While such models are needed to fully investigate and understand the explosion mechanism, they are currently computationally too expensive for investigations that naturally require large numbers of simulations, such as "What are the explosive nucleosynthesis yields of massive stars?" or "What is the connection between the progenitor and the compact remnant?". For these questions, a large number of simulations is required. Hence, computationally feasible, exploding models in spherical symmetry are of key importance. Such models have evolved from adding energy to a pre-collapse star either via a piston or via thermal energy to physically motivated models [1, 2, 3, 4, 5, 6, 7, 8]. Here, we describe a new approach, PUSH, to artificially trigger explosions in massive stars in spherical symmetry [9]. The PUSH method captures the relevant physics and is computationally efficient to allow for large and systematic parameter variations.

2. Method

For our simulations, we use the general relativistic, spherically symmetric hydrodynamics code AGILE [10]. We employ spectral neutrino transport [11, 12], a microphysics nuclear equation of state (EOS) [13], and a simplified α-network. We use the solar-metallicity, non-rotating stellar
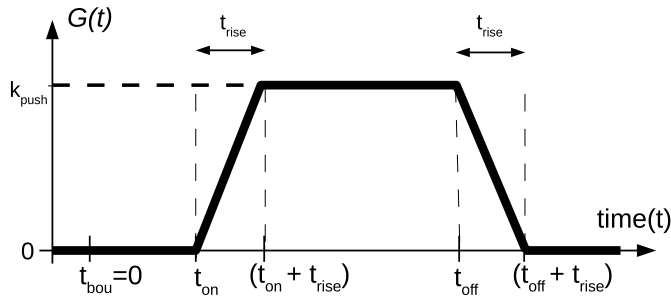
Figure 1. Function $\mathcal{G}(t)$ determines the temporal behavior of the PUSH heating. Two parameters are robustly set from multi-dimensional simulations: $t_{\mathrm{on}} = 80$ ms and $t_{\mathrm{off}} = 1$ s. The free parameters are k_{PUSH} and t_{rise}.

models from [14]. All our models include the progenitor star up to the helium shell. We simulate the collapse, bounce, and onset of the explosion for a total time of 5 s.

To trigger explosions in otherwise non-exploding models, we rely on the neutrino-driven mechanism where energy deposition from neutrinos inside the gain region is thought to revive the stalled shock. The PUSH method mimics this increased net neutrino heating which is expected in multi-dimensional simulations. PUSH provides additional neutrino heating in the gain region by depositing a fraction of the luminosity of heavy flavor neutrinos behind the shock. The rationale for using the heavy flavor neutrinos is that they are one of the largest energy reservoirs available and they do not directly change the electron faction (unlike the electron flavor neutrinos). In addition, all the neutrino luminosities are calculated consistently within the model and do not have to be modified. As such, they include dynamical feedback from the history of the model and change between different progenitor models. The enhanced neutrino-heating is achieved through a local heating term which is proportional to the spectral $\nu_{\mu,\tau}$ flux and which is applied only inside the gain region (i.e. if $\dot{e}_{\nu_e,\bar{\nu}_e} > 0$). The temporal dependence of the additional heating is given by the function $\mathcal{G}(t)$, as shown in Figure 1. The two free parameters are k_{PUSH} and t_{rise}. The former directly controls the amount of extra heating provided by PUSH. The latter sets the time scale over which $\mathcal{G}(t)$ increases from zero to k_{PUSH}.

3. Results
3.1. Parameter studies
In order to test the PUSH method and to investigate the impact of the free parameters on the explosion properties, we performed a large number of runs for a wide range of parameter values. We include 16 progenitor models in the mass range of 18–21 $M_\odot$, corresponding to the typical progenitor mass of SN 1987A. In the following, we characterize these models by their compactness at $M = 1.75$, defined as

$$\xi_M \equiv \frac{M/M_\odot}{R(M)/1000\mathrm{km}}. \tag{1}$$

As expected intuitively, k_{PUSH} has a strong and direct impact on the explosion: Larger values of k_{PUSH} result in more energetic and faster explosions and as a consequence, a lower remnant mass (assuming all other parameters are fixed). The detailed behavior also depends on the compactness of the progenitor models. We found different behaviors for the low-compactness (LC; $\xi_{1.75} < 0.45$) and the high-compactness (HC) models in our sample ($\xi_{1.75} > 0.45$). For different values of k_{PUSH}, the LC models explode slightly weaker and faster, with less variability in the explosion energy and explosion time. The HC models explode stronger and later, with larger variations in the explosion properties. We find explosion energies of $\gtrsim 1$ Bethe only for the HC models in our sample. These trends do not depend on the choice of t_{rise}. Figure 2 shows the explosion energy as function of progenitor compactness for $t_{\mathrm{rise}} = 150$ ms and different values of k_{PUSH}. A fixed explosion energy, e.g. 1 Bethe for the HC models, can be achieve by several

parameter combinations in the $k_{\rm PUSH}$-$t_{\rm rise}$ plane. Generally, a longer $t_{\rm rise}$ requires a larger $k_{\rm PUSH}$. This can be understood from the function $\mathcal{G}(t)$: with a longer $t_{\rm rise}$, PUSH takes longer to reach its maximum, at which time the neutrino luminosities have already decreased. To compensate for this, a larger $k_{\rm PUSH}$ is required. A detailed discussion of the contributions to the explosion energy can be found in Ebinger et al (this volume) and in [9].
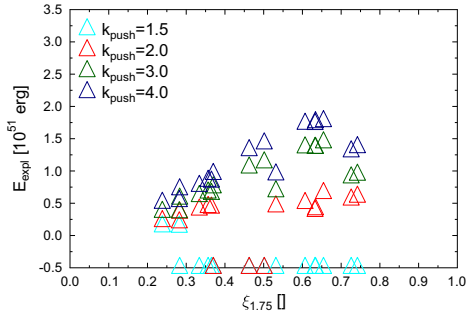
Figure 2. Explosion energies as function of compactness for $k_{\rm PUSH}$ of 1.5, 2.0, 3.0, and 4.0 and $t_{\rm rise}$ fixed at 150 ms.
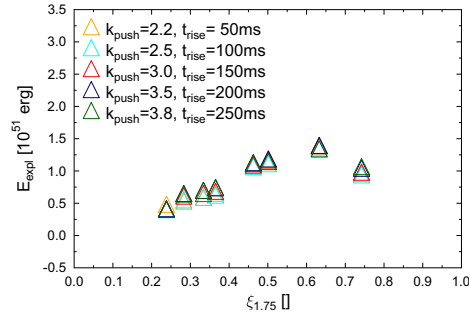

Figure 3. Explosion energies as function of compactness for pairs of $k_{\rm PUSH}$ and $t_{\rm rise}$ for select progenitor models.

3.2. Calibration to SN 1987A

We have calibrated the PUSH method to reproduce the observed properties (explosion energy and Ni ejecta mass) of SN 1987A. The observational properties that we use are summarized in Table 1, including the references. Figure 4 shows the mass of ^{56}Ni as function of explosion energy for different parameter combinations and progenitor models. The error box indicates the observational uncertainties. In order to fit both the explosion energy and the ejecta nickel masses, a fallback of 0.1 $M_\odot$ is required. Our best fit model for SN 1987A is obtained for the 18.0 $M_\odot$ progenitor model, $k_{\rm PUSH} = 3.5$ and $t_{\rm rise} = 150$ ms. The yields of ^{57}Ni and ^{58}Ni strongly depend on the location of the mass cut within the progenitor structure. All our models underproduce ^{44}Ti. For a detailed discussion of the nucleosynthesis yields, see Eichler et al (this volume) and also [9].

| Quantity	Value	Ref.
$E_{\rm expl}$	$(1.1 \pm 0.3) \times 10^{51}$ erg	[15]
$m_{\rm prog}$	18-21 $M_\odot$	[16]
$m(^{56}{\rm Ni})$	(0.071 ± 0.003) $M_\odot$	[17]
$m(^{57}{\rm Ni})$	(0.0041 ± 0.0018) $M_\odot$	[17]
$m(^{58}{\rm Ni})$	0.006 $M_\odot$	[18]
$m(^{44}{\rm Ti})$	$(0.55 \pm 0.17) \times 10^{-4}$ $M_\odot$	[17]

**Table 1.** Observational properties of SN 1987A. For details, see text.
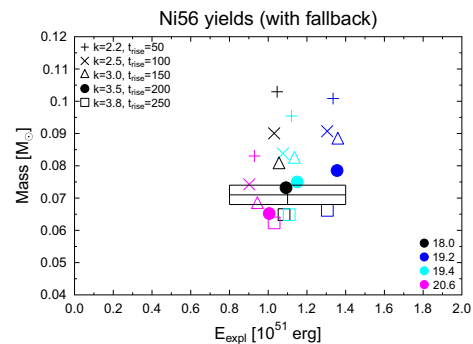
Figure 4. Ejected ^{56}Ni mass and explosion energy for representative HC models.

3.3. Progenitor explorations

From our investigations of the 18-21 $M_\odot$ progenitor models we found interesting correlations between different quantities. For these investigations, we use the parameters of our best-fit model ($k_{\text{PUSH}} = 3.5$ and $t_{\text{rise}} = 150$ ms). Even within this relatively narrow mass range of progenitor models we find a large diversity of explosion properties. However, we find indications of at least a weak correlation with the compactness parameters $\xi_{1.75}$. While there are significant deviations, one can identify general trends: For example, the explosion energy increases with larger progenitor compactness, see Figure 5. The explosion times are relatively constant within each of the sub-samples (LC models and HC models). As expected, the remnant mass increases with compactness, see Figure 6.
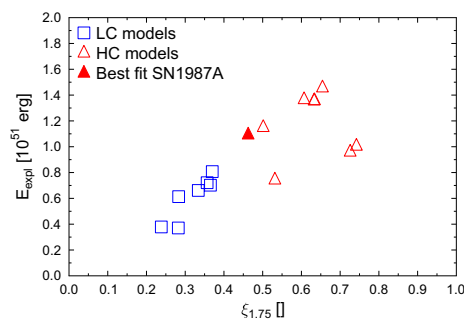
Figure 5. Explosion energies as function of compactness for PUSH parameters of our best-fit model.
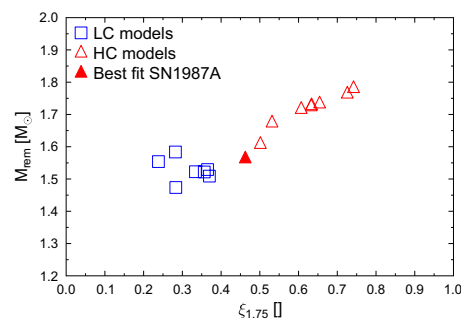
Figure 6. Remnant masses as function of compactness for PUSH parameters of our best-fit model.

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