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# PARAMETRIZED SPHERICALLY SYMMETRIC CORE-COLLAPSE SUPERNOVA SIMULATIONS: PUSH

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We report on a method, PUSH, for artificially triggering core-collapse supernova explosions of massive stars in spherically symmetric simulations. Our simulations are based on the general relativistic hydrodynamics code Agile and the detailed neutrino transport scheme IDSA. To trigger explosions in the otherwise non-exploding simulations, we rely on the neutrino-driven mechanism. The PUSH method taps the energy reservoir provided by the heavy neutrino flavours to locally increase the energy deposition in the gain region, mimicking in spherically symmetric simulations the effects of large multi-dimensional hydrodynamical instabilities. We analyze the feedback of the neutrinos on the evolution of the system, including the explosion dynamics, the electron fraction and the resulting nucleosynthesis. In this work we calibrate the PUSH method by using observed properties of SN 1987A. We found that fallback is necessary to reproduce the observations of nucleosynthesis yields, in agreement with other works. Our 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.

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## 1. Introduction

We report on a new method, PUSH, for artificially triggering core-collapse supernova explosions of massive stars in spherically symmetric simulations, which takes into account the effect of neutrino interactions with matter and its impact on $Y_e$ and the abundance composition. Here we only give a brief description and discuss some first preliminary results, further details will be reported in a separate forthcoming article. Our 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. We will show that our method reproduces the known properties of SN 1987A (e.g., [1]). We analyse the mass range between 18 and 21 $M_\odot$, which corresponds to the typical values of the progenitor mass of SN1987A reported in the literature (e.g., [2]). For this study, we use the non-rotating, solar-metallicity progenitors of Woosley et al. [3]. The simulations were performed making use of the general relativistic hydrodynamics code Agile [4]. The tabulated microphysical equation of state of Hempel & Schaffner-Bielich [5], whereas the DD2 parametrization for the nucleon interactions has been used. We employ the Isotropic Diffusion Source Approximation [6] for the electron flavour and an advanced energy-dependent leakage scheme [7] for the heavy-lepton flavour neutrino transport.

## 2. The PUSH method

To trigger explosions in the otherwise non-exploding simulations, we rely on the neutrino-driven mechanism. The PUSH method taps the energy reservoir provided by the heavy neutrino flavours to locally increase the energy deposition in the gain region, mimicking in spherically symmetric simulations the effects of large multi-dimensional hydrodynamical instabilities. This energy deposition is achieved by introducing a local heating term (energy per unit mass and time) given by

$$Q^+_{\mathrm{push}}(t,r) = 4\mathcal{G}(t)\int_0^\infty q^+_{\mathrm{push}}(r,E)\,dE, \tag{2.1}$$

where $\mathcal{G}(t)$ (Fig. 1) determines the temporal behaviour of $Q^+_{\mathrm{push}}$ and

$$q^+_{\mathrm{push}}(r,E) \equiv \sigma_0\,\frac{1}{4m_b}\left(\frac{E}{m_e c^2}\right)^2\frac{1}{4\pi r^2}\left(\frac{dL_{\nu_x}}{dE}\right)\mathcal{F}(r,E), \tag{2.2}$$

with

$$\sigma_0 = \frac{4G_F^2\left(m_e c^2\right)^2}{\pi(\hbar c)^4} \approx 1.759\times 10^{-44}\mathrm{cm}^2 \tag{2.3}$$

being a typical neutrino cross-section, $m_b \approx 1.674\times10^{-24}$g an average baryon mass, and $(dL_{\nu_x}/dE)/(4\pi r^2)$ the spectral energy flux for any single $\nu_x$ neutrino species ($\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$) with energy $E$. Note that all four heavy neutrino flavors are treated identically by the ASL scheme, and contribute equally to $Q^+_{\mathrm{push}}$. The term $\mathcal{F}(r,E)$ in Equation 2.2 defines the spatial location where $Q^+_{\mathrm{push}}(t,r)$ is active:

$$\mathcal{F}(r,E) = \begin{cases} 0 & \text{if} \quad ds/dr > 0 \quad \text{or} \quad \dot{e}_{\nu_e,\bar{\nu}_e} < 0 \\ \exp(-\tau_{\nu_e}(r,E)) & \text{otherwise} \end{cases}, \tag{2.4}$$

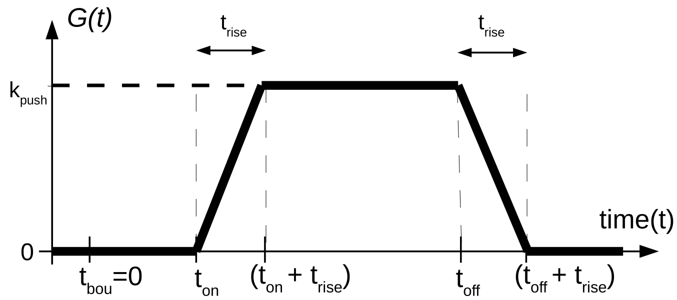



Figure 1: The function $\mathcal{G}(t)$ determining the temporal behavior of the heating due to PUSH.

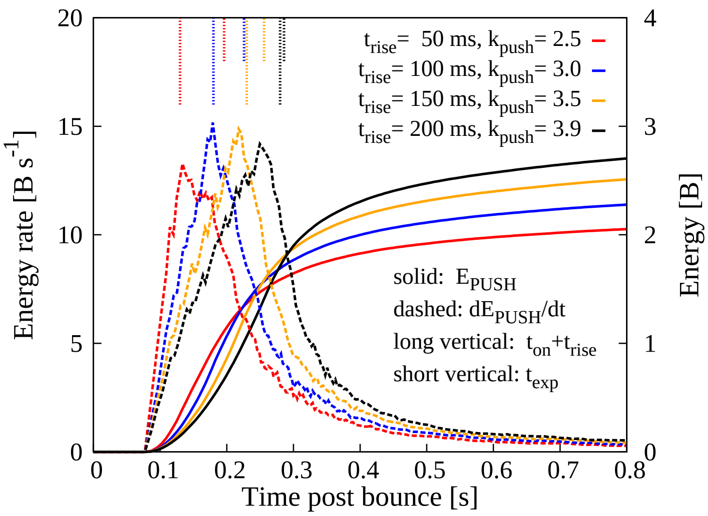
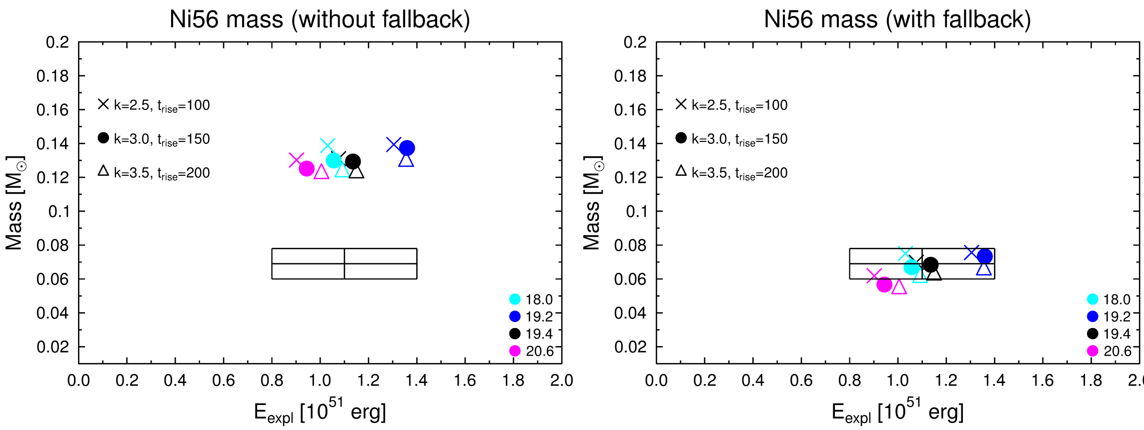



Figure 2: Temporal evolution of the cumulative energy deposited by PUSH, $E_{\text{push}}$, and of its derivative, for four models with progenitor mass 18 $M_{\odot}$ and an explosion energy of approximately 1.05 Bethe, but different combinations of PUSH parameters.

where $\tau_{\nu_e}$ denotes the (radial) optical depth of the electron neutrinos, $s$ is the matter entropy per baryon and $\dot{e}_{\nu_e,\bar{\nu}_e}$ the net specific energy deposition rate due to electron neutrinos and anti-neutrinos. The two criteria above are a crucial ingredient in our description of artificially exploding CCSNe: PUSH is only active, where electron-neutrinos are heating ($\dot{e}_{\nu_e,\bar{\nu}_e} > 0$) and where neutrino-driven convection can occur ($ds/dr < 0$).

## 3. Fitting of SN1987 A

We calibrate the PUSH method by reproducing the observed properties of SN 1987A. The quantities $t_{\text{on}}$ and $t_{\text{off}}$ are set by multi-dimensional models and also by estimates for the different involved timescales (e.g. [13], [12]). We use values of $t_{\text{on}} = 0.08$, which we relate to the time when deviations from spherically symmetric behavior appear in multi-dimensional simulations. $t_{\text{off}}$ is the time after which the PUSH contribution starts to be switched off. Due to the fast decrease of the luminosities during the first second after core bounce, we expect neutrino driven explosions to develop for $t \lesssim 1\,\text{s}$. We fix $t_{\text{off}} = 1\,\text{s}$. Once the explosion has been launched, the energy deposition

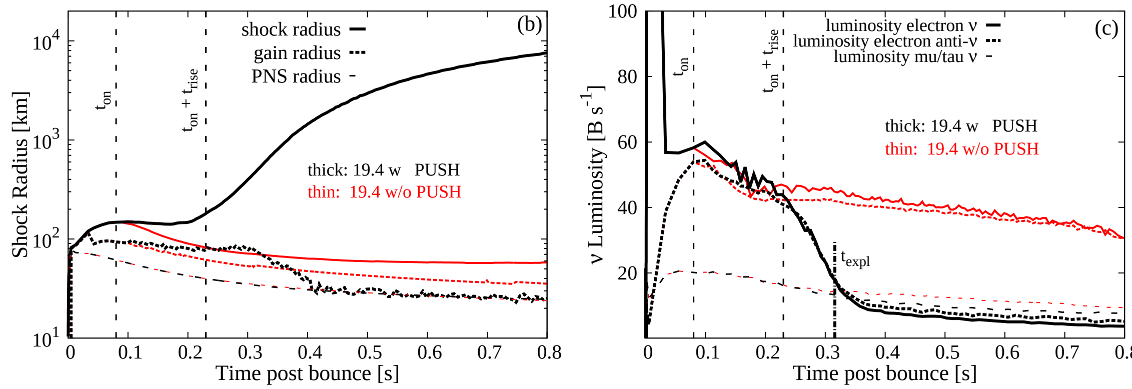



(a) (b)

Figure 3: Subplot (a) shows the ejected mass of $^{56}$Ni. Subplot (b) shows the ejected mass of $^{56}$Ni with fallback. The error bar box represents the observational values from [1], [9]

rate $\mathrm{d}E_{\mathrm{push}}/\mathrm{d}t$ decreases fast (see Fig. 2). This behavior makes our results practically inpedendent of $t_{\mathrm{off}}$. The parameters $t_{\mathrm{rise}}$ and $k_{\mathrm{push}}$ are set by our calibration procedure. $t_{\mathrm{rise}}$ defines the time scale over which $\mathcal{G}(t)$ increases from zero to $k_{\mathrm{push}}$. We connect $t_{\mathrm{rise}}$ with the time scale that characterizes the growth of the largest multi-dimensional perturbations between the shock radius and the gain radius. We use values of $0.05\,\mathrm{s} \lesssim t_{\mathrm{rise}} \lesssim (0.30\,\mathrm{s} - t_{\mathrm{on}})$. $k_{\mathrm{push}}$ is a global multiplication factor that controls directly the amount of extra heating provided by PUSH. The calibration is done by finding a combination of progenitor mass, $k_{\mathrm{push}}$, and $t_{\mathrm{rise}}$ which provides the best fit to the observational quantities of SN 1987A, i.e., explosion energy and ejected masses of $^{56}$Ni, $^{57}$Ni, $^{58}$Ni, and $^{44}$Ti. To compute the explosion energy, we assume that the total energy of the ejecta with rest-masses subtracted converts into kinetic energy of the expanding supernova remnant. Our final simulation time is always much larger than the explosion time, which allows the explosion energy to saturate. The explosion time $t_{\mathrm{expl}}$ is defined by the time the shock reaches a radial extension of 500 km. We find a roughly linear correlation between the explosion energy and the amount of synthesized $^{56}$Ni (Fig. 3 (a)). This correlation is not directly compatible with the observational values, since the ejected nickel mass is systematically larger than expected. By imposing fallback of the innermost ejecta we can match the explosion energy and the ejected nickel mass (Fig. 3 (b)). Using also the yields of $^{57}$Ni and $^{58}$Ni we can narrow down the relatively broad progenitor sample. The $^{44}$Ti yields are underproduced in all our simulations compared to the observed value.

In our analysis we obtained the best fit to SN 1987A with the 19.4 $\mathrm{M}_{\odot}$ progenitor model with $k_{\mathrm{push}}$=3, $t_{\mathrm{rise}}$=150 ms and a fallback of 0.1 $\mathrm{M}_{\odot}$. Fig. 4 shows the temporal evolution during the first 0.8 sec after core bounce of the shock radius, the gain radius, the PNS radius and neutrino luminosities (with and without the inclusion of PUSH). After the initial stalling phase, the shock starts to expand due to the influence of PUSH around 200 ms and reaches a radial extension of 500 km at $t_{\mathrm{expl}}$=316ms. One sees in Fig. 2 that the PUSH energy deposition rate $dE_{\mathrm{push}}/dt$ reaches its maximum a few tens of milliseconds before $t_{\mathrm{expl}}$. Once the explosion has been launched and the accretion rate on the PNS has diminished due to the shock expansion, the luminosities drop. Only the contribution coming from the cooling PNS remains and the energy deposition rate of PUSH




(a) (b)

Figure 4: (a):Temporal evolution of the shock radius and the gain radius for the SN 1987A fitting model: 19.4 $M_\odot$ progenitor, with $t_{on}$= 80 ms, $t_{rise}$= 150 ms and $k_{push}$= 3. (b): Temporal evolution of the neutrino luminosities for the SN 1987A fitting model

decreases significantly (Fig. 2).

## 4. Conclusion

Our simulations are based on a detailed neutrino transport scheme, and the artificial explosions are induced via a neutrino mechanism. In comparison to traditional artificial methods as pistons or thermal bombs (e.g., [10], [11]) we can analyze the feedback of the neutrinos on the evolution of the system, including the electron fraction which is crucial for nucleosynthesis. Furthermore, the PUSH method has the advantage that the mass cut emerges naturally from our simulations. Differently from Ugliano et al. [14], who also used neutrinos to trigger explosions in spherically symmetric models, we don't need to impose any inner boundary conditions, but we model consistently the evolution and the cooling of the whole PNS. We could reproduce the observed properties of SN 1987A using PUSH and found that fallback is necessary to reproduce the observations of nucleosynthesis yields. The amount of fallback we find to be necessary is in agreement with other works (e.g. [8]). In a next step we will identify general trends and systematics of our explosion models, for example the distinct behavior of high and low compactness models (see also [15],[16]).

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