Core-collapse Supernova Simulations from a 3D Progenitor Model

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Abstract

Theoretical and observational studies of core-collapse supernova (CCSN) have been discovered that in general CCSNe have aspherical matter distribution. Furthermore, recent numerical simulations of stellar evolution find that massive stars involve strong convective motions driven by nuclear shell burning, which causes aspherical structure of CCSN progenitors (Couch et al. 2015; Mueller et al. 2016,2018). These aspehricity would not only produce aspherical matter distribution in CCSN ejecta, but also aid a stalled shock to revive and expand outward, which would result in a large explosion energy (Couch & Ott 2013; Burrows et al. 2018). In this poster we report our first attempt to simulate CCSN from 3D progenitor model. We employ m25M model from Yoshida et al. (2019) which has a convective structure in Si/O layer (2500 < R < 11300 km). We find that this progenitor revives the shock before the perturbation falls onto the shock, so that its contribution to explosion is controversial.

3D CCSN Progenitor

Yoshida et al. (2019):
- **25M** model (M_{ZAMS} = **25** $M_\odot$, calibrated to **M**ilky Way Galaxy stars).
- Solar metallicity, no rotation.
- 3D simulation of convective O-shell burning until the onset of collapse.

3DnSEV:
- A derivative stellar-evolution code from CCSN code ***3DnSNe*** (Takiwaki+'16; Nakamura+'16)
- Spherical coordinate with n_r x n_θ x n_φ = 512 x 64 x 128.
- Newtonian gravity.
- Helmholtz EoS.
- 21-isotope network

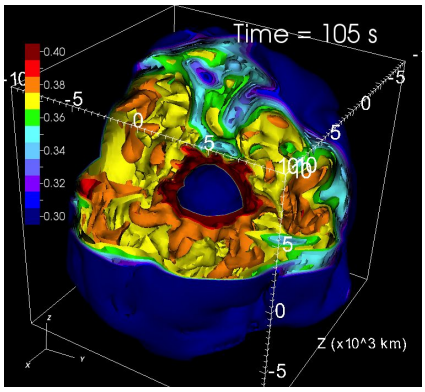


Fig.1. A snapshot of ^{28}Si mass fraction of model 25M at the simulation time of 105 s (from Figure 7 in Yoshida et al. 2019).

Numerical Scheme

Initial condition:
- 25M progenitor model from Yoshida. et al. (2019) @ t = 117 s.
- Strong convective motions in Si/O layer (2,500-11,400 km).

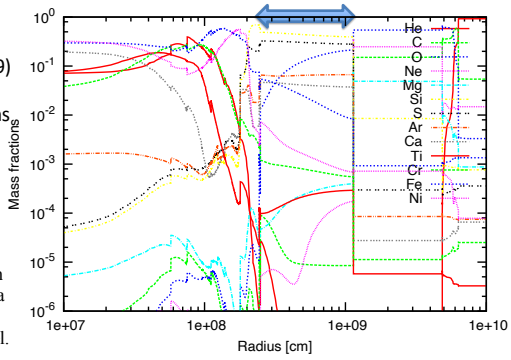


Fig.2. The radial distribution of chemical composition in a 1D spherical progenitor corresponding to 25M model.

Numerical code and setups:
- ***3DnSNe*** (Takiwaki+,'16; Nakamura+'16).
- 2D spherical coordinate with n_r x n_θ = 630 x 64 (R < 20,000 km).
- Perturbation of radial velocity in ϕ=0 is initially imposed.
- LS220 + Boltzmann gas EoS.
- 13-α nuclear network.

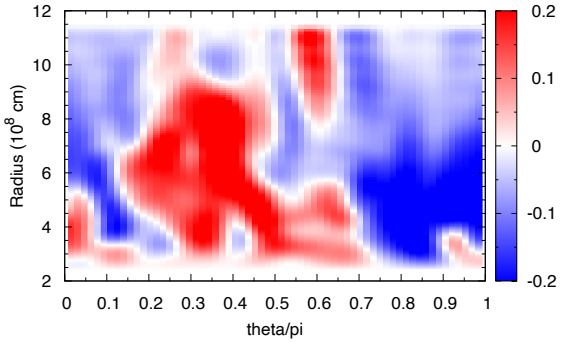


Fig.3. The radial and angle distribution of the convective Mach number. Adopted in the 2D simulation here is from 3D 25M model (φ=0).

1D Simulation

The bottom of the convective region touches the stalling shock at 320 ms after bounce.

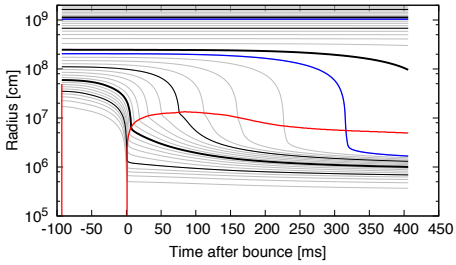


Fig.4. The mass shell diagram of 1D model. Two blue lines correspond to the top and bottom of the convective Si/O layer. Also shown by red line is the shock radius.

2D Simulation

Both of the models with/without perturbations successfully revive the shock once stalled. The shock evolution (shock revival time and expansion rate) is very similar, but explosion energy and synthesized Ni mass show different evolution later (t_pb > ~350 ms).

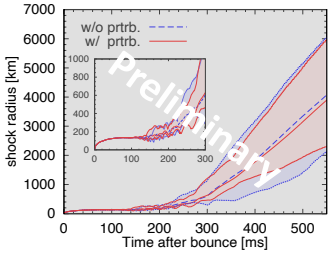
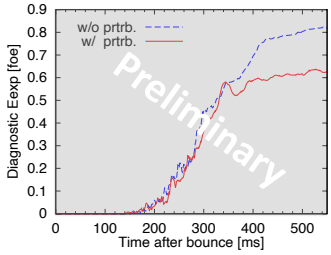
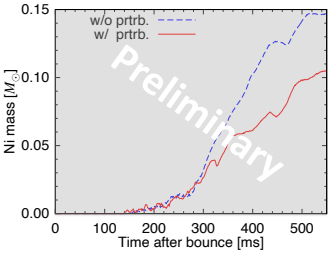


Fig.5. The time evolution of angle-averaged shock radius (top-right panel), diagnostic explosion energy (bottom-left), and Ni mass in ejecta (bottom-right). Shown are the cases of 2D simulation with perturbation by red line, and without perturbation by blue dashed line.





Note: We rely on the neutrino heating mechanism and neutrino properties (luminosity and average energy of each neutrino flavor) are very similar between our models with/without perturbations.

The expanding shock touches the perturbed region at ~ 350 ms, which is the time the explosion energies bifurcate.

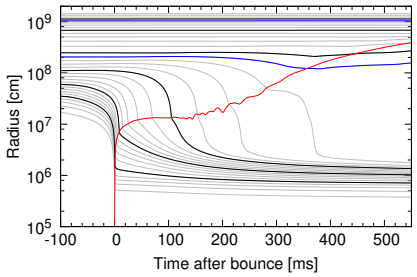


Fig.5. Same as Fig. 4, but for 2D model with initial perturbation.

Taking account of stochastic behaviors of hydrodynamics in explosion, we can not conclude that the aspherical structures of the supernova progenitor play a negative role in explosion. Our models revive the stalled shock before the shock encounter the perturbation, which is different from previous works. We need more case studies to investigate the role of the perturbation in CCSN explosion.

References

Yoshida, Takiwaki, Kotake, Takahashi, Nakamura, & Umeda "One-, Two-, and Three-dimensional Simulations of Oxygen-shell Burning Just before the Core Collapse of Massive Stars" ApJ, 881, id.16 (2019)