

# On the importance of the equation of state for the neutrino-driven supernova explosion mechanism

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**Abstract.** We present two-dimensional numerical simulations of core-collapse supernova including multi-energy neutrino radiative transfer. We aim to examine the influence of the equation of state (EOS) for the dense nuclear matter. We employ four sets of EOSs, namely, those by Lattimer and Swesty (LS) and Shen *et al.*, which became standard EOSs in the core-collapse supernova community. We reconfirm that not every EOS produces an explosion in spherical symmetry, which is consistent with previous works. In two-dimensional simulations, we find that the structure of the accretion flow is significantly different between LS EOS and Shen EOS, inducing an even qualitatively different evolution of the shock wave, namely, the LS EOS leads to shock propagation beyond 2000 km from the center, while the Shen EOS shows only oscillations within 500 km. The possible origins of the difference are discussed.

**Keywords.** equation of state — hydrodynamics — neutrinos — stars: neutron — supernovae: general

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## 1. Introduction

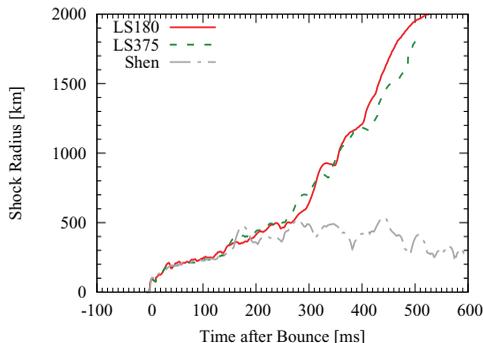
Core-collapse supernova explosions are triggered by the gravitational energy released during the transition from a stellar core into a protoneutron star (PNS), which has a temperature on the order of tens of MeV and densities on the order of normal nuclear matter density ( $3 \times 10^{14}$  g cm<sup>-3</sup>). There are only few equations of state (EOS) valid for these conditions. The most commonly used nuclear EOS in supernova simulations are the EOS from Lattimer & Swesty (1991) (hereafter LS), based on the incompressible liquid-drop model including surface effects, and from Shen *et al.* (1998) (SHEN). The latter is based on relativistic mean field (RMF) theory and Thomas-Fermi approximation.

There are several studies, which investigated EOS dependences on the hydrodynamical features in spherical symmetry, while a similar study in multi-dimensional simulation is not performed so far. Recently, several simulations that successfully produced the explosion are reported (Marek & Janka (2009), Suwa *et al.* (2010)). Therefore, we can now investigate how the EOS could affect the supernova dynamics.

In this paper we present results of numerical simulation of core-collapse supernovae of massive iron-core progenitors. Our model is based on neutrino radiation hydrodynamics and includes multi-energy radiative transfer. We employ four EOS, LS (with three values of incompressibility) and SHEN. We focus on the shock formation and evolution on a long timescale (more than 500 ms after core bounce) and investigate whether the shock finally obtains enough energy via neutrino heating to expand outward.

## 2. Numerical Method and Results

*Methods.* Our 2D simulations are performed using a code which is based on the spectral neutrino transport scheme IDSA, developed by Liebendörfer *et al.* (2009), and the



**Figure 1.** The time evolution of the maximum radius of shock wave.

ZEUS-2D code (Stone & Norman (1992), Suwa *et al.* (2010), Suwa *et al.* (2011)). In this study, we employ the two standard EOS for matter in NSE, LS and SHEN, in supernova simulations. As for the LS, there are three different versions available, for three different values of the incompressibility,  $K = 180$  MeV (LS180), 220 MeV (LS200), and 375 MeV (LS375). Here we present results of LS180 and LS375 because LS220 is similar to LS180 in our simulation. We use the  $15 M_{\odot}$  progenitor from Woosley & Weaver (1995).

*Results.* We compare the results obtained in core-collapse supernova simulations of the  $15 M_{\odot}$  progenitor using the different EOS, i.e., LS180, LS375, and SHEN. Fig. 1 shows the shock-radius evolution for each model. Each of them has three lines, corresponding to maximum, angular average and minimum shock radii (from top to bottom). From Fig. 1, we can see that LS180 and LS375 (red solid lines and green dotted lines) show similar trajectories. There is a gradual expanding phase for the postbounce time  $t_{\text{pb}} \lesssim 200$ –300 ms where the maximum shock radii reach about 500 km, after which the shock radii start to grow more rapidly for both models. Later, no further contraction is observed. The maximum shock radii reach about 2000 km for LS180 and 1800 km for LS375 at 500 ms post bounce. On the other hand, for the 2D simulation using SHEN the shock wave does not continue to grow to increasingly larger radii, even at late times. Although conclusions about possible explosions using LS180 and LS375 are still weak at the post bounce times when the 2D simulations were stopped (the explosion energy remains  $\sim 10^{50}$  erg in both cases), explosions for the 2D simulations using SHEN are highly unlikely to occur.

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