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Stellar Core-collapse Simulations with the Boltzmann-radiation-hydrodynamics code under axisymmetry

Akira Harada[1], Hiroki Nagakura[2], Wakana Iwakami[3,4], Hirotada Okawa[5], Shun Furusawa[6], Hideo Matsufuru[7], Kohsuke Sumiyoshi[8], and Shoichi Yamada[4]

[1]*Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwa-no-ha, Kashiwa, Chiba, 277-8582, Japan*
[2]*Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*
[3]*Yukawa Institute for Theoretical Physics, Kyoto University, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto, 606-8502, Japan*
[4]*Advanced Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo 169-8555, Japan*
[5]*Waseda Institute for Advanced Study, Waseda University, 1-6-1 Nishi-Waseda, Shinjuku-ku, Tokyo, 169-8050, Japan*
[6]*Department of Physics, Tokyo University of Science, Shinjuku, Tokyo, 162-8601, Japan*
[7]*High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[8]*Numazu College of Technology, Ooka 3600, Numazu, Shizuoka 410-8501, Japan*

E-mail: harada@icrr.u-tokyo.ac.jp

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We report the stellar core-collapse simulations of the 11.2 $M_\odot$ progenitor under axisymmetry with varying the nuclear equations of state (EOSs) and the rotational velocities by using the Boltzmann-radiation-hydrodynamics code. The problem of the explosion mechanism of core-collapse supernovae involves a variety of physical processes such as neutrino transport and the nuclear force. Such a complicated phenomenon requires numerical simulations to be examined. The Boltzmann-Radiation-Hydrodynamics code developed by us solves the hydrodynamics and the Boltzmann equations for neutrino transport. The employed models are the non-rotating models with the Lattimer & Swesty (LS) EOS and the Furusawa & Shen (FS) EOS, and the rotating model with the FS EOS. The shock in the non-rotating LS model seems to revive, while those in both the non-rotating and rotating FS model do not revive because of the difference in the nuclear compositions and the slow rotational velocity. The momentum distributions of neutrinos are also examined. Especially, the Eddington tensors are investigated. The Eddington tensor is the key quantity in the M1-closure method, a commonly used approximation for neutrino transport. We report the accuracy of the approximation, and this evaluation offers useful insight into the calibration of the M1-closure scheme.

KEYWORDS: computational astrophysics, core-collapse supernova, nuclear equation of state

1. Introduction

The core-collapse supernova is the explosive death of a massive star. Its explosion energy is $\sim 10^{51}$ erg and the energy source is the released gravitational energy when the star collapses to form a neutron star (NS). A massive star forms an iron core at its center at the end of its evolution. This iron core eventually starts the gravitational collapse. Then the collapse stops by the nuclear repulsive force, and the bounce shock is launched. This bounce shock finally stalls due to the energy loss by the photodissociation of accreting heavy nuclei. The question is how to revive this stalled shock.

The leading hypothesis for the shock revival is the neutrino heating mechanism. After the core bounce, a proto-neutron star (PNS), which evolves into an NS, is formed. This PNS emits energetic neutrinos, and these neutrinos are absorbed by matter behind the shock. With this energy supply, shock revives. However, this mechanism does not work under spherical symmetry. This is concluded by the simulations which solve the Boltzmann equation for neutrino transport under that symmetry. After that, supernova modelers ran axisymmetric simulations with approximate neutrino transport and found that the shock revives with the help of the multi-dimensional effects such as turbulence. However, the simulated explosion energy is $\sim 10^{50}$ erg, much smaller than the observed explosion energy. Next, simulations without any spatial symmetry have been performed, but the same problem remains.

Since the conclusion in spherically symmetric simulations was obtained with the Boltzmann-neutrino-transport simulations, we think that performing the Boltzmann-neutrino-transport is necessary to obtain robust results in multi-dimensions. Therefore we developed the multi-dimensional Boltzmann-radiation-hydrodynamics code for CCSN simulations. In this article, we report the results of stellar core-collapse simulations with different nuclear equations of state (EOSs) and initial rotation under axisymmetry.

2. Numerical Setup

The equations to be solved and the numerical techniques of the Boltzmann-radiation-hydrodynamics code are described in [1–3]. The progenitor model is the $11.2\,M_\odot$ model, which is a commonly used progenitor. The employed neutrino reactions are the electron and positron capture reaction on nucleon, the electron capture on nuclei, the neutrino-nucleon scattering and the coherent scattering on nuclei, the neutrino-electron scattering, the pair-annihilation and production reaction, and the nucleon bremsstrahlung. The grid numbers are $(N_r, N_\theta, N_\epsilon, N_{\theta_\nu}, N_{\phi_\nu}) = (384, 128, 20, 10, 6)$.

The employed nuclear EOSs are the Lattimer-Swesty (LS) EOS [4] and the Furusawa-Shen (FS) EOS [5]. For the nuclear interaction model, the LS EOS uses the Skyrm-type interaction while the FS EOS uses the relativistic mean-field theory. For the nuclear composition at sub-nuclear densities, the LS EOS employs the single-nuclear-approximation, while the FS EOS considers the nuclear statistical equilibrium. For the rotational model, the nuclear EOS is fixed to the FS EOS. We impose so-called the shellular rotational profile $\Omega(r) = 1\,\mathrm{rad/s}/(1 + (r/1000\,\mathrm{km})^2)$ on the non-rotating progenitor.

3. EOS Results

First, we examined the effect of the nuclear EOSs [6]. The simulations with the different EOS models show a significant difference: the LS model shows shock revival while the FS model not (the left panel of figure 1). A useful quantity to understand the difference is the timescale ratio, which is defined as $\tau_{\mathrm{adv}}/\tau_{\mathrm{heat}}$, where $\tau_{\mathrm{adv}} := M_{\mathrm{gain}}/\dot{M}$ and $\tau_{\mathrm{heat}} := E_{\mathrm{gain}}/Q_{\mathrm{gain}}$ are the advection timescale with which a fluid element flows through the gain region and the heating timescale with which a fluid element is heated and become gravitationally unbound, respectively. The gain region is the region where the neutrino heating exceeds cooling. The symbols M_{gain}, $\dot{M}$, E_{gain}, and Q_{gain} are the mass in the gain region, the mass accretion rate, the total energy including the gravitational binding energy in the gain region, and the net neutrino heating rate in the gain region, respectively. If the timescale ratio exceeds unity, the neutrino heating proceeds sufficiently fast and the explosion succeeds. The right panel of figure 1 shows that the timescale ratio of the LS model exceeds unity, while that of the FS model not. Although $\dot{M}$, E_{gain}, and Q_{gain} are similar between the LS and FS models, M_{gain} for the LS model is larger than that of the FS model. This is because the turbulence is stronger for the LS model. Indeed, the prompt convection is stronger for the LS model, and it enhances the neutrino driven convection at the later stage. The stronger prompt convection in the LS model is originated

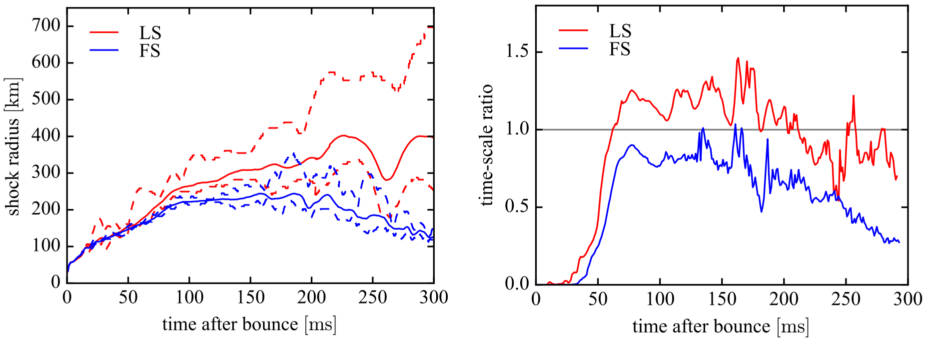

Fig. 1. (Left) The time evolution of the shock radii for the LS (red) and FS (blue) models. The thick solid lines are the angular averaged shock radii, and the dashed lines show the ranges between the minimum and the maximum shock radii. (Right) The time evolution of the timescale ratio for the LS (red) and FS (blue) models.

from the stronger photodissociation of the accreting nuclei: the accretion flow outside the shock in the LS model contains more heavy nuclei, and hence the energy consumed by the photodissociation of these nuclei is larger for the LS model. Therefore the proper treatment of the nuclear composition of an EOS at low densities is important to assess the influence of EOSs on the CCSNe.

4. Rotation Results

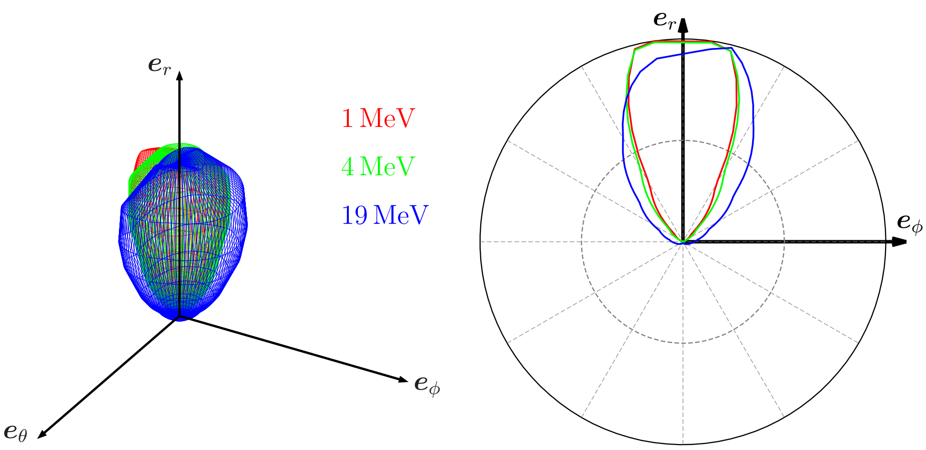

Fig. 2. The angular distributions of neutrinos outside the shock on the equator at 12 ms after bounce. The left panel shows the 3D distributions, and the right panel shows the sections by the r-ϕ plane. The different colors correspond to the different energies as indicated in the left panel.

Next, we investigated the effect of rotation [8]. However, the employed rotational velocity is too slow to affect the postbounce dynamics even though the velocity is almost the highest according to the current stellar evolution theory [7]: the shock radii and other dynamical features are similar between the rotating and non-rotating models. What is more interesting here is the momentum space distributions of neutrinos. Figure 2 shows the neutrino angular distributions in the laboratory frame outside the shock on the equator. Especially, the distribution of the high-energy neutrinos is tilted to the ϕ-direction. This is because matter rotates and drags the neutrino distribution to the rotational

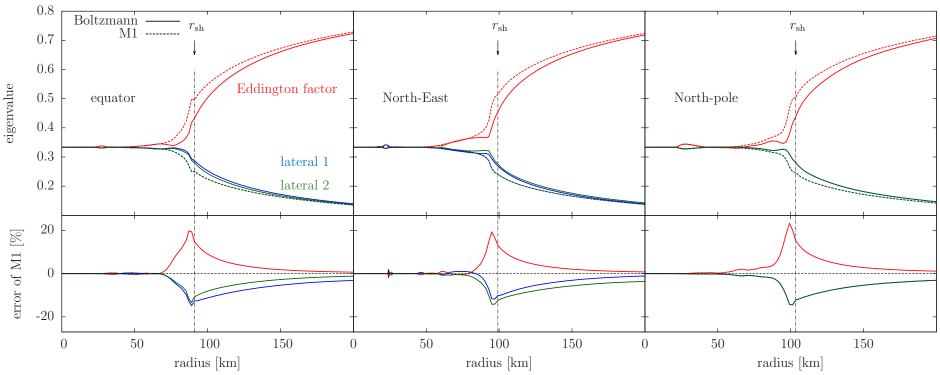

Fig. 3. The eigenvalues of the Eddington tensors calculated from the distribution function (solid) and the M1-closure scheme (dashed) in different directions at 12 ms after bounce. The largest eigenvalue is called the Eddington factor (red), and the other eigenvalues are named lateral 1 and 2 (blue and green). The upper row shows the eigenvalues itself, while the lower row displays the fractional difference between the solid and dashed lines.

direction. This detailed angular distribution is only accessible by the Boltzmann solver. Since we have such information, we can assess the accuracy of the M1-closure scheme, one of the approximate neutrino transport method. The second angular moment of the distribution divided by the zero-th moment is called the Eddington tensor. The M1-closure scheme estimates the Eddington tensor from the energy flux and density of neutrinos. In figure 3, we compare the eigenvalues of the Eddington tensor calculated from the distribution function directly and the M1-closure scheme. The largest eigenvalue, or the Eddington factor, is $\sim$ 20% larger for the M1-closure scheme. This difference originates from so-called ray-collision between outward and inward rays. If we can get some information about these rays from neighboring matter, we may improve the accuracy of the M1-closure scheme.

5. Conclusion

With the Boltzmann-radiation-hydrodynamics code, we simulated the stellar core-collapse of the 11.2 $M_\odot$ progenitor with the different nuclear EOSs and the different initial rotation. From the EOS comparison, the treatment of nuclear composition seems to play an important role. From the rotational calculation, even the almost fastest rotation does not affect the explodability. Besides, thanks to the Boltzmann solver, we can access the neutrino angular distributions and estimate the accuracy of the M1-closure scheme. In addition, we are improving the code further. With the highly sophisticated simulation code, the robust conclusion about the explosion mechanism of the CCSNe would be obtained.

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