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Evolution of Proto-neutron star and the structure near the surface

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Abstract: In the discussion of the evolution of PNS, neutrinos play a crucial role. The general understanding is that the emission of neutrinos leads to the cooling of the PNS. As neutrino detecting technology advances, an extended period for neutrino observation is expected. To comprehend the prolonged evolution of the PNS, we employed a quasi-static evolution code for numerical simulations and calculated a 50-second evolution for two different nuclear equation of state(EOS) for comparison. Additionally, we provide a discussion of the thermal structure near the surface where the crust is considered to form.

Introduction

After a supernova explosion(SN), the new-born neutron star left in the central region called proto-neutron star(PNS) evolves while emitting neutrinos. This process, known as PNS cooling(PNSC), occurs after the PNS contracts and the temperature decreases. In recent years, with the improvement in the observational sensitivity of SN neutrino detectors, an extended period($\lesssim 100$ sec.) for detecting SN neutrinos is anticipated when a Galactic supernova occurs. Conducting long-term simulations of PNSC is crucial to accurately estimate the emitted neutrinos.

In previous studies(Nakazato et al., 2018), the impact of neutrino reactions and evolutionary calculations due to the distribution of heavy atomic nuclei near the surface of PNS, using different EOS for nuclear matter, was discussed. Our focus has been on the late thermal evolution of the outer layers of PNS, revealing the presence of a local maximum temperature (**T-peak**) through evolutionary calculations.

Objective

Through PNS evolutionary calculations, we analyze energy exchange through neutrinos and the thermodynamic profiles of the constituent matter, exploring the causes behind the formation of T-peak in the outer layers of PNS.

Method

Code: quasi-static evolution code under spherical symmetry with general relativity

neutrino transfer: multi-energy flux limited diffusion scheme

Flux limiter: Mayle & Wilson(1987)

Nuclear equation of state(EOS): Shen(1998) & Togashi(2017)

Neutrino reactions:

Absorption and emission (AE)	$e^- + A \leftrightarrow \nu_e + A'$ $e^- + p \leftrightarrow \nu_e + n$ $e^+ + n \leftrightarrow \bar{\nu}_e + p$
Electron scattering (ES)	$\nu + e^{\pm} \leftrightarrow \nu + e^{\pm}$
Thermal pair (TP)	$e^- + e^+ \leftrightarrow \nu + \bar{\nu}$ $\quad \tilde{\gamma} \leftrightarrow \nu + \bar{\nu}$ $N + N \leftrightarrow N + N + \nu + \bar{\nu}$
Isoenergetic scattering off nucleon (IS)	$\nu + n \leftrightarrow \nu + n$ $\nu + A \leftrightarrow \nu + A$ $\nu + p \leftrightarrow \nu + p$

Result

We calculated the PNSC process up to 50 seconds. The density of the PNS increases with evolution, while the temperature continues to decrease.

Simulation results with different EOS are shown in Figure 1. The neutrino reactions exchanging the energy at a specific position induce entropy changes there. The contributions to the entropy change rate for each reaction are illustrated in (a), (d) of Figure 2. Furthermore, (b), (c), (d), (e) in Figure 2 depict the radial distribution of physical quantities in the outer layers of the PNS, such as mass ratio and specific heat. Additionally, the mass ratio and the temperature derivative of entropy(ds/dT) were determined based on the EOS, and the specific heat was calculated using the following formula.

$$ds = \frac{dQ}{T} \qquad C = \frac{dQ}{dT} \qquad C = T\frac{ds}{dt}\frac{dt}{dT}$$

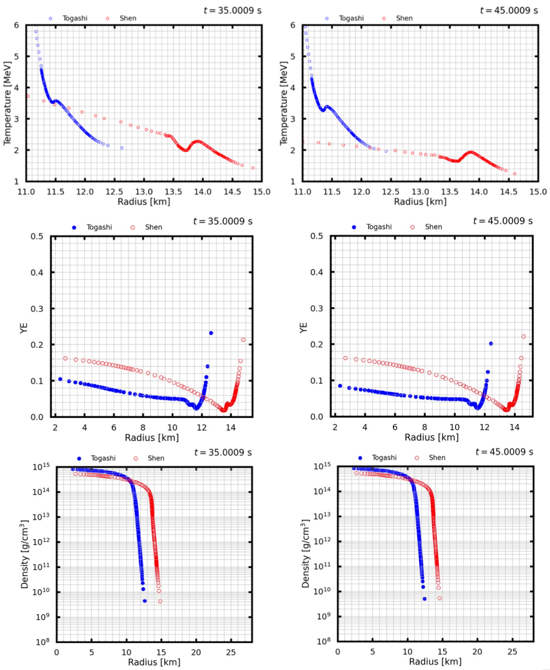

Figure 1. The simulation results at 35 s and 45 s using the Shen EOS(red) and Togashi EOS(blue) are shown. The plots depict the temperature, electron fraction(Ye), and density profiles from top to bottom.

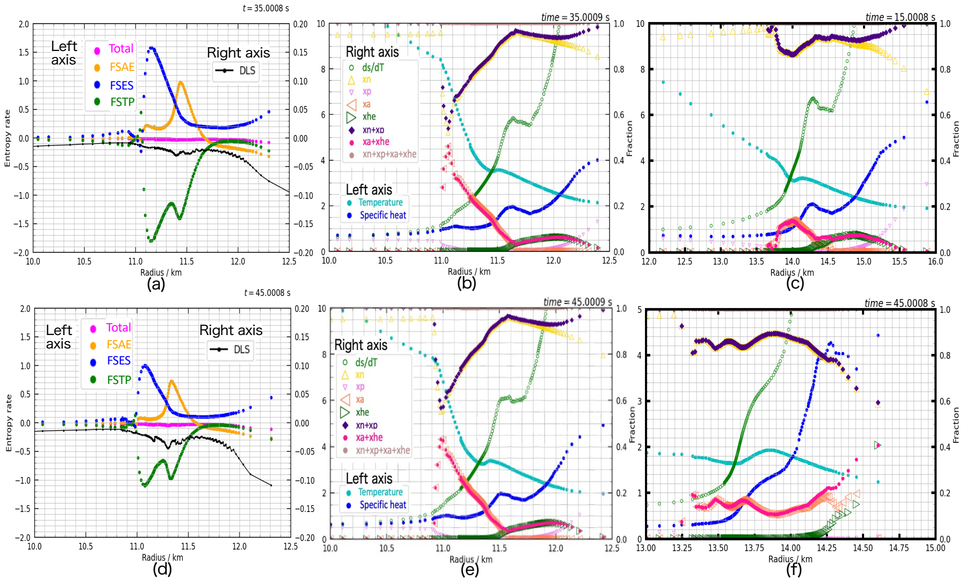

Figure 2. (a),(d) represent the radial distribution of time derivative of entropy($\dot{s}$) due to AE, ES, TP reactions at 35 s and 45 s. Total and DLS denote the total change rates, with DLS corresponding to the right axis. Values below zero indicate the emission of neutrinos and cooling. (b), (c), (e), (f) illustrate the radial distribution of mass ratios for neutrons(n), protons(p), heavy nuclei(a), and helium(he) per nucleon, as well as the temperature and specific heat of the PNS as 35 s and 45 s. However, (c), (f) present results based on the Shen EOS calculation, while the others use the Togashi EOS

Discussion

Over time, the PNS emits neutrinos and cools down. To understand the formation of T-peak, we analyzed locations in the outer layers of the PNS that are less prone to cooling than their surroundings.

From the distribution of $\dot{s}$, it was confirmed that the outer layers of the PNS release neutrinos and experience cooling. However, the $\dot{s}$ does not exhibit a distribution structure like the T-peak around the location where the T-peak exists.

From Figure 2 (b), (e), when examining the time evolution of temperature, it is observed that the temperature changes in the outer regions where heavy nuclei exist are smaller than in the inner regions. Furthermore, beyond the location of the T-peak(at 11.6 km and 11.5 km at 35 s and 45 s, respectively), there exists a local maximum value of specific heat. This location corresponds to the boundary region where heavy nuclei and helium are generated. Places with high specific heat capacity are less susceptible to temperature changes.

Additionally, the results based on the Shen EOS calculation have a difference in T-peak formation time. This is attributed to the difference in the transition temperatures of nuclei in different EOS.

Conclusion

In the late thermal evolution of the outer layers of the PNS up to 50 seconds, the appearance of T-peak is attributed to the occurrence of heavy nuclei and helium, resulting in a maximum value of specific heat in the outer layers of the PNS. In those locations, it acts to impede cooling, making them less prone to cooling than the inner regions.