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Proto-neutron star evolution with convection

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Introduction

- **Motivation**: After a supernova explosion (SN), the new-born neutron star left in the central region is called proto-neutron star (PNS). The general understanding is that the emission of neutrinos leads to the cooling of the PNS. In the discussion of PNS evolution, neutrinos play a crucial role. With upcoming neutrino detectors such as upgraded water-Cherenkov observatories and the liquid scintillator detector JUNO, the observable duration is expected to extend to several tens of seconds during a Galactic supernova event. Thus, conducting long-term simulations of PNS cooling is necessary to accurately estimate the emitted neutrinos.

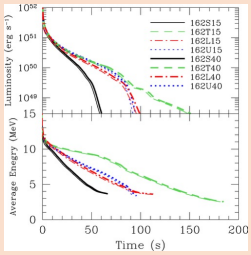

Figure 1. Luminosity and average energy of ν_e as a function of time after the bounce for PNS models with a baryon mass of $M_b = 1.62$ solar mass.
(Ken'ichiro Nakazato *et al* 2022 *ApJ* **925** 98)

- **Limitation**: Considering the calculation cost and complexity, using spherical symmetry is a reasonable choice for a systematic study of the PNS cooling. However, it is known that multi-dimensional effects play important roles in the process.
  - Convection
  - Hydrodynamical instabilities
- **Purpose:** The effects above can lead to variation in the observed neutrino signal. Therefore, to provide a more accurate understanding of PNS cooling and neutrino emission from Supernova, a diffusion-based convective treatment inspired by mixing-length theory is implemented in our code. Partial results from convective models are presented for comparison in the early 4 seconds.

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 state (EOS):** Togashi(2017)
- **Neutrino reactions:**

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

- **Convection:** mixing length theory
  - Unstable criterion: Ledoux $C_L = \frac{\partial \rho}{\partial s}\Big|_{P,Y_e} \frac{ds}{dr} + \frac{\partial \rho}{\partial Y_e}\Big|_{P,s} \frac{dY_e}{dr} < 0$
  - Diffusion equations: $N_B \frac{dY_e}{dt} = \oint_{S'} (n_B D \nabla Y_e) \cdot d\boldsymbol{s'}$ $\quad N_B \frac{ds}{dt} = \oint_{S'} (n_B D \nabla s) \cdot d\boldsymbol{s'}$

(D: diffusion coefficient, n_B: baryon number density, N_B: baryon number within the closed surface S', Y_e: electron fraction, s: entropy, $\boldsymbol{s'}$: infinitesimal surface element)

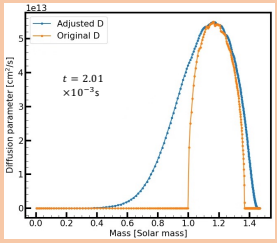

Figure 2. Overshooting of Diffusion parameter.

When the convective boundary is treated with such a simple on/off threshold criterion, the solution can exhibit numerical oscillations. To address this issue, we adopted a smoothing scheme for the diffusion coefficient D using a Gaussian function.

$$D'_{i\to k} = D_i \exp\left(-\frac{(r_k - r_i)^2}{\lambda_\beta^2}\right) \qquad i \in [1, i_{max}]$$

We adopt the maximum value of $D'_{i\to k}$ as our final diffusion coefficient at mesh point k.

Results

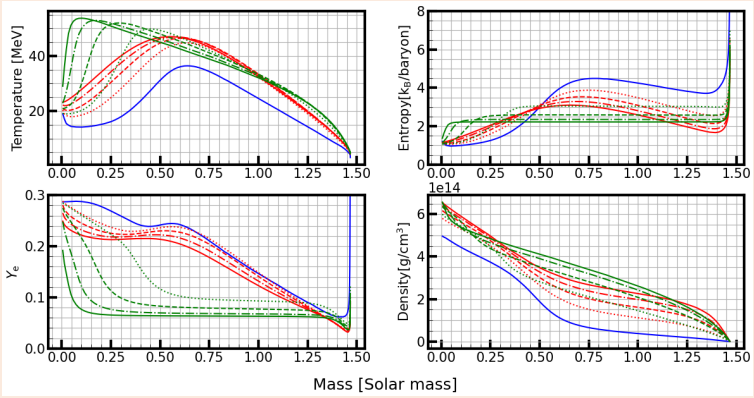

Figure 3. T, s, Y_e , ρ on mass. Dotted, dashed, dash dot, solid line represent time = 1s, 2s, 3s, 4s in the simulation. Red, green, blue lines are non-convection model, convection model and initial distributions.

Figure 3 shows a comparation between convection model with non-convection model. A convection region exist at the early phase during PNS evolution. The range of the region changed in time, which make the entropy and Y_e profiles in the convective layer become flatter. These distributions show qualitative agreement with earlier work (Pascal 2022)

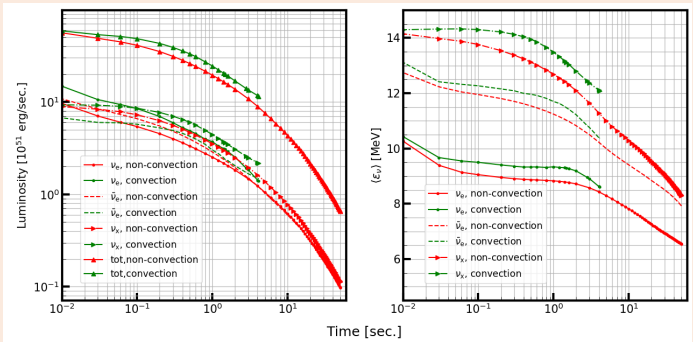

Figure 4. Mean energy of emitted neutrinos (right) and neutrino energy luminosity (left) as a function of time, for each neutrinos flavor, with and without convection.

- $\langle \varepsilon_{\nu_{e,con.}} \rangle > \langle \varepsilon_{\nu_{e,non-con.}} \rangle$
- $\langle \varepsilon_{\bar{\nu}_{e,con.}} \rangle > \langle \varepsilon_{\bar{\nu}_{e,non-con.}} \rangle$
- $\langle \varepsilon_{\nu_{x,con.}} \rangle > \langle \varepsilon_{\nu_{x,non-con.}} \rangle$

$$L_{tot,con.} > L_{tot,non-con.}$$

As shown in Figure 4, convection increases the mean energy and luminosity of emitted neutrinos at the early phase.

Conclusion

A diffusion-based treatment of convection, inspired by mixing-length theory, is implemented to examine its early influence on neutrino transport. The results are consistent with previous studies, supporting the view that convection enhances early neutrino emission. This is because convection transports internal energy from the inner region to the outer region of PNS, which raises the temperature near the neutrino sphere. Although, under our treatment of convection(diffusion of Y_e and s), both the mean energy and luminosity of emitted neutrinos increase, for a more accurate assessment of this process, it necessitates a treatment of neutrino diffusion. We therefore plan to integrate these considerations into long-term simulations of various progenitors and EOS to study supernova neutrino signals.