User's Guide for Supernova Neutrino Database

Ken'ichiro Nakazato* (Kyushu University)

May 14, 2016

Abstract

This is a guide for users of Supernova Neutrino Database for neutrino astronomy.

1 Introduction

Supernova Neutrino Database contains light curves and spectra of supernova neutrinos from the onset of collapse to 20 s after the core bounce for the following progenitors

- initial mass: $M_{\rm init} = 13$, 20, 30 and $50 M_\odot$
- metallicity: $Z = 0.02$ (solar) and 0.004 (Small Magellanic Cloud)

except the model with $M_{\rm init} = 30 M_\odot$ and $Z = 0.004$ which forms black hole after the core bounce.

Here, we performed both of neutrino-radiation hydrodynamic (νRHD) simulations for the early phase and quasi-static evolutionary calculations of proto-neutron star cooling (PNSC) with neutrino diffusion for the late phase. Assuming the shock revival time $t_{\rm revive}$ which corresponds to the explosion mechanism, we combine the results of neutrino signals for the early and late phases. For details on the computations, please see in our original paper [1]. **Please reference it when you publish scientific articles using this database.**

*e-mail: nakazato@artsci.kyushu-u.ac.jp

For the computations, we utilized the nuclear equation of state (EOS) constructed by Shen et al. [Prog. Theor. Phys. 100 (1998) 1013]. However, we provide also the result obtained with EOS constructed by Lattimer & Swesty [Nucl. Phys. A535 (1991) 331] for the black-hole-forming progenitor ($M_{\rm init} = 30M_\odot$ and $Z = 0.004$), because the neutrino signal from black hole formation considerably depends on nuclear EOS. While the Lattimer & Swesty EOS has three choices with different values of incompressibility, we adopt the set with incompressibility of 220 MeV (hereafter, LS220). For the details of the neutrino emission from black hole formation of LS220 model, please see in another paper [2].

2 Original Data for the Early and Late Phases

2.1 νRHD

The results of νRHD simulations are given from the onset of collapse to 550 ms after the core bounce except for the black-hole-forming model ($M_{\rm init} = 30M_\odot$ and $Z = 0.004$), for which the data is given to the time of black hole formation. The data files are named `spectobAAB0.data` with

- `AA` is an initial mass
- `B` represents a metallicity: `0` for $Z = 0.02$ and `1` for $Z = 0.004$

For instance, `spectob3000.data` is a data for $M_{\rm init} = 30M_\odot$ and $Z = 0.02$. Nevertheless, for the black-hole-forming progenitor ($M_{\rm init} = 30M_\odot$ and $Z = 0.004$), `spectob3010.data` is a data obtained with Shen EOS and `spectob301L.data` is a data obtained with LS220 EOS. The time to black hole formation measured from the core bounce is different between them, 842 ms for Shen EOS and 342 ms for LS220 EOS.

The data are arranged as follows:

t_0

$$E_0 \quad E_1 \quad \frac{\Delta N_{1,\nu_e}(t_0)}{\Delta E_1} \quad \frac{\Delta N_{1,\bar{\nu}_e}(t_0)}{\Delta E_1} \quad \frac{\Delta N_{1,\nu_x}(t_0)}{\Delta E_1} \quad \frac{\Delta L_{1,\nu_e}(t_0)}{\Delta E_1} \quad \frac{\Delta L_{1,\bar{\nu}_e}(t_0)}{\Delta E_1} \quad \frac{\Delta L_{1,\nu_x}(t_0)}{\Delta E_1}$$

$$E_1 \quad E_2 \quad \frac{\Delta N_{2,\nu_e}(t_0)}{\Delta E_2} \quad \frac{\Delta N_{2,\bar{\nu}_e}(t_0)}{\Delta E_2} \quad \frac{\Delta N_{2,\nu_x}(t_0)}{\Delta E_2} \quad \frac{\Delta L_{2,\nu_e}(t_0)}{\Delta E_2} \quad \frac{\Delta L_{2,\bar{\nu}_e}(t_0)}{\Delta E_2} \quad \frac{\Delta L_{2,\nu_x}(t_0)}{\Delta E_2}$$

$\dots$

$$E_{19} \quad E_{20} \quad \frac{\Delta N_{20,\nu_e}(t_0)}{\Delta E_{20}} \quad \frac{\Delta N_{20,\bar{\nu}_e}(t_0)}{\Delta E_{20}} \quad \frac{\Delta N_{20,\nu_x}(t_0)}{\Delta E_{20}} \quad \frac{\Delta L_{20,\nu_e}(t_0)}{\Delta E_{20}} \quad \frac{\Delta L_{20,\bar{\nu}_e}(t_0)}{\Delta E_{20}} \quad \frac{\Delta L_{20,\nu_x}(t_0)}{\Delta E_{20}}$$

t_1

$$E_1 \quad \frac{\Delta N_{1,\nu_e}(t_1)}{\Delta E_1} \quad \frac{\Delta N_{1,\bar{\nu}_e}(t_1)}{\Delta E_1} \quad \frac{\Delta N_{1,\nu_x}(t_1)}{\Delta E_1} \quad \frac{\Delta L_{1,\nu_e}(t_1)}{\Delta E_1} \quad \frac{\Delta L_{1,\bar{\nu}_e}(t_1)}{\Delta E_1} \quad \frac{\Delta L_{1,\nu_x}(t_1)}{\Delta E_1}$$

$\dots$

where t_n [s] is a time measured from the bounce and E_k [MeV] is a neutrino energy. Note that, E_k is defined on the interface between k-th and $(k+1)$-th energy bins. For k-th energy bin, $\frac{\Delta N_{k,\nu_i}(t_n)}{\Delta E_k}$ [/s/MeV] and $\frac{\Delta L_{k,\nu_i}(t_n)}{\Delta E_k}$ [erg/s/MeV] are differential neutrino number flux and differential neutrino luminosity, respectively, where $\nu_x = (\nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau)/4$. Thus, the number luminosity of $\bar{\nu}_e$ is given by

$$N_{\bar{\nu}_e}(t_n) = \sum_{k=1}^{20} (E_k - E_{k-1}) \times \frac{\Delta N_{k,\bar{\nu}_e}(t_n)}{\Delta E_k}, \tag{1}$$

where $E_0 = 0$ MeV. The total emission energy of ν_e up to 550 ms is given by

$$\mathcal{E}_{550\,\mathrm{ms},\nu_e} = \sum_{n=1}^{n_{\max}} (t_n - t_{n-1}) \times \left\{ \sum_{k=1}^{20} (E_k - E_{k-1}) \times \frac{\Delta L_{k,\nu_e}(t_n)}{\Delta E_k} \right\}. \tag{2}$$

2.2 PNSC

For the PNSC simulations, we assume three cases of the shock revival time t_{revive} and νRHD profiles at t_{revive} are used as the initial conditions. The results of PNSC simulations are given from the shock revival to 20 s after the core bounce. The data files are named `spectobAABC.data` with

- `AA` is an initial mass

- `B` represents a metallicity: `0` for $Z = 0.02$ and `1` for $Z = 0.004$

- `C` represents a shock revival time: `1`, `2` and `3` for $t_{\rm revive} = 100$, 200 and 300 ms, respectively

For instance, `spectob2013.data` is a data for $M_{\rm init} = 20 M_\odot$, $Z = 0.004$ and $t_{\rm revive} = 300$. Since the model with $M_{\rm init} = 30 M_\odot$ and $Z = 0.004$ forms a black hole, its PNSC data is not prepared.

The data format is the same with that of the νRHD data. Note that, the time does not start with $t_{\rm revive}$. We evaluate the neutrino flux on the outer boundary of our νRHD simulation (in the stellar envelope), which is different from the outer boundary of our PNSC simulation (proto-neutron star surface). The light traveling time of the distance between the outer boundary and proto-neutron star surface is corrected.

3 Full Data from Core Collapse to Neutron Star Cooling Phase (Interpolated Data)

To combine νRHD data and PNSC data, we recommend an interpolation

$$F_{\nu_i}(E,t) = f(t)\, F_{\nu_i}^{\nu\rm RHD}(E,t) + (1 - f(t))\, F_{\nu_i}^{\rm PNSC}(E,t), \tag{3}$$

with

$$f(t) = \begin{cases} 1, & t \leq t_{\rm revive} + t_{\rm shift}, \\ \exp\left(-\frac{t-(t_{\rm revive}+t_{\rm shift})}{\tau_{\rm decay}} \right), & t_{\rm revive} + t_{\rm shift} < t < t_{\rm revive} + t_{\rm shift} + t_{\rm cutoff}, \\ 0, & t \geq t_{\rm revive} + t_{\rm shift} + t_{\rm cutoff}, \end{cases} \tag{4}$$

where $\tau_{\rm decay} = 30$ ms, $t_{\rm shift} = 50$ ms and $t_{\rm cutoff} = 200$ ms. For details of there parameters, please see in our original paper [1].

Assuming this interpolation, we construct spectral data from the onset of collapse to 20 s after the core bounce. The data files are named `intpAABC.data` and the notation of `AABC` is the same with that of PNSC data. The data format is the same with that of the νRHD data and PNSC data.

4 Time Integrated Data

We also prepare the spectral data integrated from the onset of collapse to 20 s after the core bounce with the interpolation. The data files are named `integAABC.data`. The notation of `AABC` is the same with that of PNSC data except for `integ3010.data` and `integ301L.data`, which gives the integrated data till the black hole formation for the progenitor with the initial mass $M_{\mathrm{init}} = 30M_{\odot}$ and the metallicity $Z = 0.004$. Here, `integ3010.data` is a data obtained with Shen EOS and `integ301L.data` is a data obtained with LS220 EOS.

The data are arranged as follows:

$$\mathcal{N}_{\nu_e} \quad \mathcal{N}_{\bar{\nu}_e} \quad \mathcal{N}_{\nu_x} \quad \mathcal{E}_{\nu_e} \quad \mathcal{E}_{\bar{\nu}_e} \quad \mathcal{E}_{\nu_x}$$

$$\begin{array}{llcccccc}
E_0 & E_1 & \frac{\Delta\mathcal{N}_{1,\nu_e}}{\Delta E_1} & \frac{\Delta\mathcal{N}_{1,\bar{\nu}_e}}{\Delta E_1} & \frac{\Delta\mathcal{N}_{1,\nu_x}}{\Delta E_1} & \frac{\Delta\mathcal{E}_{1,\nu_e}}{\Delta E_1} & \frac{\Delta\mathcal{E}_{1,\bar{\nu}_e}}{\Delta E_1} & \frac{\Delta\mathcal{E}_{1,\nu_x}}{\Delta E_1} \\
E_1 & E_2 & \frac{\Delta\mathcal{N}_{2,\nu_e}}{\Delta E_2} & \frac{\Delta\mathcal{N}_{2,\bar{\nu}_e}}{\Delta E_2} & \frac{\Delta\mathcal{N}_{2,\nu_x}}{\Delta E_2} & \frac{\Delta\mathcal{E}_{2,\nu_e}}{\Delta E_2} & \frac{\Delta\mathcal{E}_{2,\bar{\nu}_e}}{\Delta E_2} & \frac{\Delta\mathcal{E}_{2,\nu_x}}{\Delta E_2} \\
\dots & & & & & & & \\
E_{19} & E_{20} & \frac{\Delta\mathcal{N}_{20,\nu_e}}{\Delta E_{20}} & \frac{\Delta\mathcal{N}_{20,\bar{\nu}_e}}{\Delta E_{20}} & \frac{\Delta\mathcal{N}_{20,\nu_x}}{\Delta E_{20}} & \frac{\Delta\mathcal{E}_{20,\nu_e}}{\Delta E_{20}} & \frac{\Delta\mathcal{E}_{20,\bar{\nu}_e}}{\Delta E_{20}} & \frac{\Delta\mathcal{E}_{20,\nu_x}}{\Delta E_{20}}
\end{array}$$

where E_k [MeV] is a neutrino energy. Note that, E_k is defined on the interface between k-th and $(k+1)$-th energy bins. For k-th energy bin, $\frac{\Delta\mathcal{N}_{k,\nu_i}}{\Delta E_k}$ [/MeV] and $\frac{\Delta\mathcal{E}_{k,\nu_i}}{\Delta E_k}$ [erg/MeV] are differential number and differential energy of total neutrino emission, respectively, which are computed as

$$\frac{\Delta\mathcal{N}_{k,\nu_i}}{\Delta E_k} = \int_{t_0}^{20\,\mathrm{s}} \frac{\Delta N_{k,\nu_i}(t)}{\Delta E_k}\, dt, \tag{5}$$

$$\frac{\Delta\mathcal{E}_{k,\nu_i}}{\Delta E_k} = \int_{t_0}^{20\,\mathrm{s}} \frac{\Delta L_{k,\nu_i}(t)}{\Delta E_k}\, dt. \tag{6}$$

$\mathcal{N}_{\nu_i}$ and $\mathcal{E}_{\nu_i}$ [erg] are total emission number and energy of ν_i, respectively, which are computed as

$$\mathcal{N}_{\nu_i} = \sum_{k=1}^{20} (E_k - E_{k-1}) \times \frac{\Delta\mathcal{N}_{k,\nu_i}}{\Delta E_k}, \tag{7}$$

$$\mathcal{E}_{\nu_i} = \sum_{k=1}^{20} (E_k - E_{k-1}) \times \frac{\Delta\mathcal{E}_{k,\nu_i}}{\Delta E_k}, \tag{8}$$

where $E_0 = 0$ MeV. Therefore the mean energy of emitted ν_x is given by

$$\langle E_{\nu_x} \rangle = \frac{\mathcal{E}_{\nu_i}}{\mathcal{N}_{\nu_i}} \times \frac{\mathrm{MeV}}{1.6022 \times 10^{-6}\ \mathrm{erg}}. \tag{9}$$

5 Contact

If you find some strange problem, please contact us. We would appreciate it very much if you could give us comments or suggestions on the database. The correspondence address is

- Ken'ichiro Nakazato

  Faculty of Arts and Science, Kyushu University

  744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

  E-mail: nakazato@artsci.kyushu-u.ac.jp

References

[1] K. Nakazato, K. Sumiyoshi, H. Suzuki, T. Totani, H. Umeda, and S. Yamada, Astrophys. J. Supp. 205 (2013) 2, arXiv:1210.6841 [astro-ph.HE]

[2] K. Nakazato, E. Mochida, Y. Niino, and H. Suzuki, Astrophys. J. 804 (2015) 75, arXiv:1503.01236 [astro-ph.HE]