README for Angle-Dependent and Angle-Averaged Neutrino Emission Files for 3D FORNAX Supernova Models

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1 Introduction

We provide here lab-frame neutrino data for 9 progenitors (9-, 10-, 12-, 13-, 14-, 15-, 19-, 25-, 60-$M_\odot$) simulated by FORNAX in our recent publications. The data are based on 1D FORNAX simulations from the bounce to 10 ms, which is then connected to many of the 3D models found in Burrows et al. (2020, MNRAS, 491, 2227) for the rest of their respective postbounce phases. In the 3D simulations, we employ an angular resolution of 128 cells (in θ) and 256 cells (in ϕ), and 12 energy bins to study the neutrino transport (logarithmically spaced from 1-300 MeV for electron-neutrinos, and 1-100 MeV for the electron anti-neutrinos and "heavy"-neutrinos). The data are calculated at 250 km and redshifted (with velocity and GR corrections) to the lab-frame.

2 Angle-averaged and Energy-integrated quantities

We provide the angle-averaged energy-luminosity, number-luminosity, and average energy for each of the progenitor models and for each neutrino species in files of the format "d()M_spec_inu().time.lumi_spec_lm0.Num_spec_lm0.eave_spec_lm0.dat". The first column is time (in seconds), the second is energy-luminosity (10^{50}ergs^{-1}), the third is number-luminosity (10^{50}s^{-1}) and the fourth is average neutrino energy (MeV).

3 Angle-averaged Luminosity Spectra

We also provide the angle-averaged luminosity spectra for each progenitor model for each neutrino species (27 files in total) in files of the format "lum_spec_()M_inu()_byHN.dat", e.g. "lum_spec_10M_inu0_byHN.dat." The first column is time (in seconds), columns 2−13 are the bin center energy (in MeV) for each of the twelve bins, and columns 14−25 are the spectra in each bin (in 10^{50} erg s^{-1} MeV^{-1}) for each time.

4 Luminosity and Angular Moments

Lab-frame neutrino luminosities, integrated over the energy bins, for all the eleven 3D progenitors in this set (33 text files, three per progenitor, corresponding to one file for each neutrino species) are to be found in files with the format "**lum_()M_inu().dat**". For instance, "lum_10M_inu0.dat" contains data for the electron-neutrino species for the $10M_\odot$ progenitor.

Each file has 10 columns. The first is post-bounce time (in s), and the remaining nine are the spherical harmonic decomposition moments, labeled as $A_{l,m}$ in Eq. 1, of the total neutrino-luminosity (in 10^{50} erg s^{-1}). We decompose up to the quadrupole moment l=2 for each azimuthal moment m (see below).

The energy luminosities to be found in these files are redundant with the same quantity in the "d()M_spec_inu().time.lumi_spec_lm0.Num_spec_lm0.eave_spec_lm0.dat" files discussed above, which nevertheless contains other quantities as well.

5 Angle-Dependence

As additional data, we provide angle-dependent neutrino quantities. The data are in eleven HDF5 files, one for each of the progenitors studied, of the form "**lum_spec_()M.h5**". For example, "lum_spec_10M.h5" contains data for the 10 $M_\odot$ progenitor. We calculate the angle-dependent quantities, such as the neutrino luminosity, through spherical harmonic decomposition up to order $l = 2$ for the corresponding azimuthal moments m as follows:

$$L_{\nu_i}(\theta,\phi,t) = A_{00}\,Y_{00} + \sum_{m=-1}^{1} A_{1m}\,Y_{1m}(\theta,\phi) + \sum_{m=-2}^{2} A_{2m}\,Y_{2m}(\theta,\phi)\,,$$

where

$$A_{ij}(t) = \int_\Omega r^2 F_r[t,r,\theta,\phi] \times Y_{ij}[\theta,\phi]\,d\Omega\,, \tag{1}$$

where the terms on the right-hand-side correspond to the monopole, dipole, and quadrupole terms, respectively, for each neutrino species i $\in \{\nu_e, \bar{\nu}_e, \nu_\mu\}$. F_r is the radial flux outwards at a given radius, here taken to be 250 km. $Y_{l,m}$ is the spherical harmonic decomposition with order l and azimuthal moment m.

These HDF5 files contain data for the three neutrino species studied, nu0, nu1, and nu2, and one attribute, time. nu0 corresponds to electron-neutrinos, nu1 to anti-electron neutrinos, and nu2 to the bundled "heavy"-species (mu & tau neutrinos and their antiparticles). Simulation time (in seconds) is measured post-core-bounce, and begins at 10 ms (0.01 seconds after bounce).

For each neutrino species, we include 1) the lab-frame neutrino bin energy at each time for each of the 12 neutrino energy bins (*egroup*, in MeV), and 2) the lab-frame neutrino bin energy group width at each time for each of the 12 bins (*degroup*, in MeV), 3) the average neutrino energy (eave, in MeV) over all bins at each time, and the 4) RMS neutrino energy (*erms*, in MeV) over all bins at each time.

Additionally, these files include the luminosity spectra (in units of 10^{50} erg s^{-1} MeV^{-1}) in each of the twelve energy bins (labeled *g0...g12*). The energy bin width (*degroup*) allows one to independently calculate the bin-integrated luminosity for the luminosity spectra.

The average and RMS neutrino energies, as well as the luminosity spectra, each have 9 values, labeled "l=, m=", corresponding to the spherical harmonic decomposition up to the quadrupole (l=2) term with azimuthal ("m") dependence for each time, analogous to A_{00}, A_{1m}, and A_{2m} in Eq. 1. These include the monopole term (l=0, m=0), the dipole terms (l=1, m=-1; l=1, m=0; l=1; m =1), and the quadrupole terms (l=2, m=-2; l=2, m=-1; l=2, m=0; l=2, m=1; l=2, m=2). The l=0, m=0 component corresponds to the solid-angle averaged value of the given quantity.

We provide the grid file, **grid.h5**, which contains the central values of phi and theta on our simulation grid, as well as the solid angles in each grid cell, to allow the user to reconstruct angle-dependent neutrino quantities.

6 Sample Script

A sample python script is provided to illustrate how to read and visualize the data. There, we define the spherical harmonic basis (real_sph_harm) to reconstruct the angle-dependent neutrino quantities from the data.

To execute:

python spectra_reader.py --mass {} --neutrino {}

e.g., for a 10-$M_\odot$ progenitor and for the electron-neutrino species (0)

python spectra_reader.py -- mass 10 --neutrino 0

For help, contact David Vartanyan: dvartany@berkeley.edu