Core-Collapse Supernova Neutrinos

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Overview

• NuLib
  • Motivation
  • Current Status

• Core-Collapse Supernovae: Models and Observable Signals: From the Neutrino Sector
  • Transport
  • Motivate our Study
  • Look at Progenitor Dependence of Neutrino Signal
NuLib

- NuLib is an open-source neutrino microphysics library
- Intention is to create a one-stop-shop for everything neutrino
- inspired by ReacLib, a collection of reaction rates for astrophysical models.
- used for benchmarking current codes, validating and developing new codes
- provide venue for nuclear theorists to provide new/improved interaction rates
- github repository for easy distribution and collaborative efforts

http://www.nulib.org
NuLib

- NuLib provides routines for calculating neutrino cross sections, opacities, emissivities, kernels, Fermi functions/integrals, ...

- Ideally, routines are optimized for on the fly evaluation of neutrino interaction rates

- Also provides routines for developing tables for fast on-the-fly interpolation of rates

- Currently includes a base set of neutrino interactions: Bruenn ’85; Burrows, Reddy, Thompson ‘06
• NuLib will ultimately include many more neutrino interactions:
  • inelastic interactions of neutrinos with electrons, nucleons, ions
  • kernels for pair-processes
  • detailed electron capture rates

• covering all high energy astrophysical systems:
  • Core-Collapse Supernovae
  • Protoneutron star cooling
  • Neutron star—Black Hole mergers
  • Neutron star—Neutron star mergers

• and neutrino transport techniques:
  • full transport
  • moment scheme
  • grey schemes
  • leakage schemes

Anyone interested, in contribution, developing, using, or commenting please do
Core-Collapse Supernova Neutrinos

- We are using NuLib in our new neutrino transport code nuGR1D

- nuGR1D, is the combination of a new two-moment neutrino transport code and GR1D

- GR1D is a spherically-symmetric general relativistic Eulerian hydrodynamics code for studying stellar collapse. Open source, www.stellarcollapse.org

- nuGR1D is a general relativistic M1 scheme based on Shibata et al. 2011, Audit et al. 2002. It is coupled to GR1D. Will be open source when complete.
• Define the neutrino moment tensor as follows Shibata et al. (2011):

\[ M_{(\nu)}^{\alpha\beta} = E_{(\nu)} n^\alpha n^\beta + F_{(\nu)}^{\alpha} n^\beta + F_{(\nu)}^{\beta} n^\alpha + P_{(\nu)}^{\alpha\beta} \]

\[ n^\alpha = (1/\alpha, -\beta^i/\alpha) \]
\[ n^\alpha = (1/\alpha, 0) \]

• Here \( E, F^\alpha, P^{\alpha\beta} \) are the moments in the laboratory frame
• Thorne’s (1981) moment formalism gives evolution equations for the moment tensor:

\[ \nabla_\beta M_{(\nu)}^{\alpha\beta} - \frac{\partial}{\partial \nu} \left( \nu M_{(\nu)}^{\alpha\beta\gamma} \nabla_\gamma u_\beta \right) = S_{(\nu)}^{\alpha} \]

• For simplicity we ignore the energy-coupling term and velocity dependence. Generally bad, but will show it is acceptable for this study
• For GR1D, evolution equations become

\[ \partial_t E_{(\nu)} + \frac{1}{r^2} \partial_r \left( \frac{\alpha r^2}{X^2} F_{r,(\nu)} \right) = \alpha^2 S_{(\nu)}^t \]

\[ \partial_t F_{r,(\nu)} + \frac{1}{r^2} \partial_r \left( \frac{\alpha r^2}{X^2} P_{rr,(\nu)} \right) = \alpha X^2 S_{(\nu)}^r + \alpha \frac{E_{(\nu)}(1 - p_{(\nu)})}{r} \]

• Source terms are calculated using NuLib and tabulate in \( \rho, T, Y_e, E \) space

\[ S^t = \left( \eta_{(\nu)} - \kappa_{a,(\nu)} E_{(\nu)} \right) / \alpha, \]

\[ S^r = - \left( \kappa_{a,(\nu)} + \kappa_{s,(\nu)} \right) F_{r,(\nu)} / X^2 \]

• Flux equation uses analytic closure and solved via Audit et al. (2002)

\[ P_{ii,(\nu)} = \frac{3p_{(\nu)} - 1}{2} P_{ii,(\nu),\text{thin}} + \frac{3(1 - p_{(\nu)})}{2} P_{ii,(\nu),\text{thick}} \]

where \( p_{(\nu)} = \frac{1}{3} + \frac{f_{(\nu)}^2}{15} (6 - 2f_{(\nu)} + 6f_{(\nu)}^2) \)
We compare nuGR1D to Liebendoerfer et al. (2005) “Supernova Simulations with Boltzmann Neutrino Transport: A Comparison of Methods”

Agile-BOLTZTRAN (Liebendoerfer et al. 2001, ...) & VERTEX* (Rampp & Janka 2002)

due to lack of inelastic scattering
Motivation:

- In O’Connor and Ott (2011) we studied progenitor dependence of black hole formation.
- Black hole formation properties of massive stars do not correlate with ZAMS mass.
Motivation:

- $\xi_M$ is a measure of the compactness of the progenitor’s inner $M$ solar masses:

$$\xi_M = \frac{M}{M_{\odot}} \frac{R_M}{1000 \text{km}}$$

- In OC&O’11, we chose 2.5 solar masses as this is the relevant mass scale for black hole formation.
Motivation:

- BH formation time set by progenitor structure and EOS
- Of course, many will explode in nature...
- Free fall time of a test particle is half the orbital period

\[ t_{\text{ff}} = \frac{1}{2} \sqrt{\frac{4\pi^2 a^3}{GM^*}} = \pi \sqrt{\frac{r^3_*}{8GM^*}} \]

\[ t_{\text{ff}}^{2.5M_\odot} = \pi \sqrt{\frac{(2.5M_\odot)^2}{8G(\xi_{2.5})^3}} \]
Models

- We use the 32 solar metallicity models from Woosley & Heger (2007) ranging is ZAMS mass from 12 to 120 $M_{\text{sun}}$.
- We use 2 EOS: LS220, Hshen.
- Perform core collapse and 450ms of postbounce preexplosion evolution with nuGR1D.
- We look for trends with the compactness, $\xi_{1.75}$.
- Chose 1.75$M_{\text{sun}}$ as this is relevant mass scale for early phase.
Luminosities of all species increase with $\xi_{1.75}$ in a predictable way: low $\xi_{1.75}$ have small accretion rates and low protoneutron star temperatures.
- Luminosities of all species increase with $\xi_{1.75}$ in a predictable way: low $\xi_{1.75}$ have small accretion rates and low protoneutron star temperatures.

- There is a slight EOS dependence, the HShen EOS gives lower luminosities—the neutrinosphere radii are large than the LS220 case.
• Average energies of all species also increase with $\xi_{1.75}$ in a predictable way: low $\xi_{1.75}$ models have lower temperature and less compact protoneutron stars.
Results – Average Energies

- Average energies of all species also increase with $\xi_{1.75}$ in a predictable way: low $\xi_{1.75}$ models have lower temperatures and less compact protoneutron stars.

- There is a stronger EOS dependence, the HShen EOS can give up to 5MeV lower average energies.

- At late times, high $\xi_{1.75}$ models are close to black hole formation---very high average energies.
• Cumulative emitted electron antineutrino energy also is proportional to $\xi_{1.75}$

• electron antineutrinos are the predominate neutrino detected on Earth from a core-collapse supernova

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
More Quantitative

- Cumulative emitted electron antineutrino energy also is proportional to $\xi_{1.75}$

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Detection on Earth

- We use SNOwGLOBES (Scholberg 2012) to reconstruct the number of events in a Super-K-like \( \nu \) detector for a 10 kpc supernova.

- Same trends as cumulative \( \nu \) energy.

- Stronger EOS dependence as cross sections are very sensitive to energies.

- The early postbounce preexplosion \( \nu \) signal will tell us the compactness of the progenitor star!
Detection on Earth

• Another method of probing the progenitor star’s structure is through the total emitted neutrino energy

• Assume explosion is launched at postbounce time $t$

• Convert baryonic mass into total emitted $\nu$ energy

• Estimate of explosion time and total $\nu$ energy gives compactness and remnant mass!

$$E_{\text{binding}} \sim 1.12 \times 10^{53} \left(\frac{M_{\text{bary}}}{M_\odot}\right)^2 \text{ergs}$$
Degeneracies 😞

• Nuclear equation of state is not completely degenerate with progenitor compactness.

Accurate observations will allow EOS to be probed, otherwise it will cloud $\xi_{1.75}$ determination.
Degeneracies 😞

**Distance**
- If distance is uncertain, one cannot nail down total emitted energy.
- The energy spectrum would not be changed

**Rotation**
- 1.5D rotation simulations show that significant rotation will alter ν signal

**Neutrino Oscillations**
- both MSW and collective will complicate picture
We use SNOwGLOBES to predict the neutrino signal of our models for K-II at 51.47kpc.

- We overlay 1987A’s first four events.

- Very small number statistics so not much can be said.

- 1987A progenitor was not a high $\xi_{1.75}$ progenitor that exploded late.
Summary

• Next galactic core-collapse supernova will be well observed in neutrinos

• Early postbounce, preexplosion rates of inverse beta decay interactions will relay direct information on the progenitor structure of the core

• Will allow us to connect inner core structure with presupernova structure of the rest of the star

• Several theoretical hurdles to overcome before precise quantitative conclusions can be reached

• Use NuLib!