NEUTRINOS FROM PROTONEUTRON STARS
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Abstract
We study the diffusive transport of neutrinos in a newly born neutron star to explore its sensitivity to dense matter properties. Energy and lepton number which are trapped during the catastrophic implosion diffuse out on the time scale of a few tens of seconds. Results for different dense matter models are presented.

1 Introduction
The core of a massive star implodes when its mass exceeds the Chandrashekar mass. The hot and dense remnant formed subsequent to the implosion is a protoneutron star. Numerical simulations of the implosion (and the subsequent formation of a shock wave at core bounce) indicate that, due to the high densities and temperatures, most of the star’s gravitational binding energy and lepton number released remains trapped in the star as neutrinos. The general features of the early evolution have been discussed in prior work \cite{1, 2}. The object of this work is to elucidate the role played by the microphysical inputs (equation of state (EOS) and neutrino opacities) on the macrophysical evolution of the protoneutron star.

2 The Basic Equations
The structure of the star is assumed to be in quasi-static equilibrium, and is described by the general relativistic equation for hydrostatic equilibrium. The loss of lepton number and energy due to neutrino flows is treated in the diffusion approximation. The equations governing the early evolution may be found in \cite{1, 2}. To solve the structure equations we need to specify the finite temperature EOS discussed in \S3. Other microphysical inputs required to solve the transport equations are the neutrino mean free paths and bulk properties such as the specific heat and the nuclear symmetry energy.
2.1 Deleptonization

To illustrate how microphysical inputs influence lepton number transport, we examine the Newtonian diffusion equation \[ \frac{n}{Y_L} \frac{\partial Y_L}{\partial t} \approx \frac{1}{r^2} \frac{\partial}{\partial r} \left[ r^2 \left( (D_2 + D_2) \frac{\partial (\mu_\nu / T)}{\partial r} - (D_3 - D_3) \frac{\partial (1/T)}{\partial r} \right) \right]. \]

(1)

Here \( Y_L = Y_e + Y_\nu \) is the total lepton fraction and \( \mu_\nu \) is the local neutrino chemical potential. The neutrino mean free path \( \lambda(E_\nu) \) enters Eq. (1) via the unnormalized diffusion coefficients \( D_n \) (and \( D_\bar{n} \) for anti-neutrinos) defined by \( D_n = \int_0^\infty dE_\nu E_\nu \lambda_\nu(E_\nu) f_\nu(E_\nu)(1 - f_\nu(E_\nu)) \). The time scales crucially depend on the magnitude of \( \lambda(E_\nu) \) and its energy dependence. For electron neutrinos, the dominant contributions to \( \lambda(E_\nu) \) arise from the charged current reaction \( \nu + n \rightarrow e^- + p \). The rate of this reaction is sensitive to both temperature and the composition of the ambient matter [3-6]. Under degenerate conditions, the phase space for this reaction is proportional to \( \mu_n T^2 (\hat{\mu} + E_\nu) \), where \( \mu_n \) is the neutron chemical potential and \( \hat{\mu} = \mu_n - \mu_p \). The left hand side of Eq. (1) illustrates one way the EOS directly influences the lepton number flows. Note that \( \frac{\partial Y_L}{\partial t} = \frac{\partial Y_L}{\partial Y_\nu} \frac{\partial Y_\nu}{\partial t} \), and that \( \frac{\partial Y_L}{\partial Y_\nu} \) is directly related to the nuclear symmetry energy \( S(n_B) \). Since \( \hat{\mu} = 4S(n_B)(1 - 2Y_p) \), where \( Y_p \) is the proton fraction, the nuclear symmetry energy will play a crucial role in the deleptonization phase. Further, the possible presence of hyperons at high density affects both \( \frac{\partial Y_L}{\partial Y_\nu} \) and the neutrino mean free path \( \lambda \) will be altered [3, 4].

2.2 Cooling

At early times, the flow of electron neutrinos due to chemical potential gradients results in net heating rather than cooling. This Joule heating and negative temperature gradients warm the central regions until the center reaches the maximum temperature. At this stage, the center begins to cool as the thermal gradients force all six neutrino species radially outwards. Due to the high densities and temperatures present, the pair production processes are sufficiently rapid to ensure that \( \mu \) and \( \tau \) neutrinos are in thermal equilibrium. Energy transport is governed by

\[ nT \frac{\partial s}{\partial t} = \frac{c}{6\pi(\hbar c)^3 r^2} \frac{1}{\partial r} \left[ r^2 \sum_\ell \frac{D_\ell}{T^2} \frac{\partial T}{\partial r} \right]. \]

(2)

All general relativistic corrections and terms arising due to lepton number gradients have been dropped to highlight the essential role of the microphysics. The dominant opacity for \( \mu \) and \( \tau \) pairs is that due to scattering on baryons and
electrons, as the charged current reactions are kinematically inaccessible. The charged current reactions are still the dominant source of opacity for electron neutrinos; thus, relative to the $\mu$ and $\tau$ pairs their contribution to energy transport is significantly suppressed. Under partially degenerate conditions, the phase space for scattering reactions is roughly proportional to $M^2 T^3$ (note that the ambient temperature determines the average $E_\nu$); $M^*$ arises since it determines the density of states at the Fermi surface. The left hand side of Eq. (2) is directly related to the specific heat since $T ds = C_v dT$, and is strongly dependent on the effective baryon mass $M^*$. Neutrino mean free paths depend on the same physics, since they are proportional to the number of target particles which do not suffer significant Pauli blocking.

3 Microphysics
3.1 The Equation of State (EOS)

The dense matter EOS is an important ingredient in protoneutron star simulations. For a detailed discussion of a variety of dense matter models see [4]. In this work, we have explored four different models (see Table) to study the early evolution. We broadly classify them as soft (GM3) and stiff (GM1) models [3], and models can contain (GM1-H, GM3-H) or not contain (GM1-N, GM3-N) hyperons. Hyperons begin to appear only towards the late stages of the deleptonization [7]. This results in these models having significantly lower maximum masses for $Y_\nu=0$ ($4^{th}$ column) and the existence of a range ($3^{rd}$ & $4^{th}$ columns) of initial masses that become unstable upon deleptonization.

| Model   | Composition          | $M_{Y_\nu=0.4}^{\text{MAX}}$ ($T = 0$) | $M_{Y_\nu=0}^{\text{MAX}}$ ($T = 0$) |
|---------|----------------------|----------------------------------------|-------------------------------------|
| GM1-N   | n,p + leptons        | 2.52                                   | 2.76                                |
| GM1-H   | n,p,H + leptons      | 2.25                                   | 1.96                                |
| GM3-N   | n,p + leptons        | 2.16                                   | 2.35                                |
| GM3-H   | n,p,H + leptons      | 1.95                                   | 1.74                                |

3.2 Neutrino Interactions

Neutrino interactions are significantly modified in a hot and dense medium. The effects of Pauli blocking and strong interactions on the weak interaction rates have been investigated in Refs. [3-6] which showed that density and temperature dependence of the neutrino mean free path are significantly different from those employed in earlier proto-neutron star simulations [1, 2]. Strong interaction effects may be incorporated by employing appropriate dispersion relations and effects of Pauli blocking may be incorporated exactly. In addition, Ref. [3] shows that the neutrino mean free path also depends on the composition of the ambient matter. In particular, the appearance of hyperons leads to significant reduction in $\lambda_\nu$ during the cooling phase.
4 Results

Figure 1: Central temperature and neutrino chemical potential vs time (model GM3). Right (left) panels: matter with (without) hyperons. Curves are labelled by the initial baryon masses. Models \( M_B \geq M_{\nu_\alpha=0}^{M_{\rm MAX}} = 1.74 M_\odot \) are unstable and collapse as they deletonize (denoted by an asterix). Note, however, that if the baryon mass does not significantly exceed this value the meta-stable state lasts for a very long time.

We turn now to results of simulations which include the full effects of general relativity. In Fig. 1, the time evolution of the central temperatures are shown for models with (right top) and without (left top) hyperons for different initial masses. The deletonization times are related to the time evolution of the neutrino chemical potential, which are shown for models with (right bottom) and without (left bottom) hyperons. The identification of time scales associated with deletonization and cooling depend on their precise definition. Here, we opt to define the deletonization time \( \tau_D \) as the time it takes for the central value of \( \mu_{\nu_e} \) to drop below 10 MeV, and the cooling time \( \tau_C \) as the time it takes for the central temperature \( T_c \) to drop below 5 MeV. Fig. 2 clearly shows the generic trends; (1) Softening leads to higher central densities, and thus higher temperatures, both of which act to decrease \( \lambda_\nu \), (2) Hyperons decrease the baryon degeneracy in the central regions, and since the neutrinos couple quite strongly to the hyperons [4], \( \lambda_\nu \) is reduced; and (3) Hyperonization is accompanied by compressional heating and neutrino production, both of which delay the cooling and deletonization times. Hyperons thus always act to
increase the deleptonization and cooling times. Fig. 2 also shows that a softer EOS favors longer diffusion times due to higher temperatures and densities in the inner regions of the star. To discriminate observationally between these different dense matter scenarios, the neutrino luminosities must be folded with the response of terrestrial detectors.

Figure 2: Deleptonization and cooling times. Left panel: $\tau_D$ for various models as a function of the initial baryon mass. Right Panel: $\tau_C$ for the different models.

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