Neutrino Processes in Supernovae and the Physics of Protoneutron Star Winds

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In preparation for a set of hydrodynamical simulations of core-collapse supernovae and protoneutron star winds, we investigate the rates of production and thermalization of $\nu_\mu$ and $\nu_\tau$ neutrinos in dense nuclear matter. Included are contributions from electron scattering, electron-positron annihilation, nucleon-nucleon bremsstrahlung, and nucleon scattering. We find that nucleon scattering dominates electron scattering as a thermalization process at neutrino energies greater than $\sim 15$ MeV. In addition, nucleon-nucleon bremsstrahlung dominates electron-positron annihilation as a production mechanism at low neutrino energies, near and below the $\nu_\mu$ and $\nu_\tau$ neutrinosphere.

Furthermore, we have begun a study of steady-state general relativistic protoneutron star winds employing simple neutrino heating and cooling terms. From this analysis we obtain acceleration profiles as well as asymptotic lepton fractions and baryon entropies essential in assessing the wind as a potential site for $r$-process nucleosynthesis.

1. Introduction

The cores of protoneutron stars and core-collapse supernovae are unique environments in nature. They are characterized by mass densities of order $\sim 10^{11} - 10^{15}$ g cm$^{-3}$ and temperatures that range from $\sim 1$ to 50 MeV. At these temperatures and densities neutrinos of all species are produced in proliferation via electron-positron annihilation ($e^+e^- \leftrightarrow \nu\bar{\nu}$), nucleon-nucleon bremsstrahlung, and plasmon decay ($\gamma_{pl} \leftrightarrow \nu\bar{\nu}$). While these processes contribute for the electron types ($\nu_e$s and $\bar{\nu}_e$s), for them the charged-current absorption and emission processes $\nu_en \leftrightarrow pe^-$ and $\bar{\nu}_ep \leftrightarrow ne^+$ dominate. Neutrino-electron and neutrino-nucleon scattering also contribute to the total opacity. All of these interactions combine to couple the neutrinos to dense nuclear matter, affecting energy transport from the core where the neutrinos are diffusive to the more tenuous outer layers where the neutrinos begin to free-stream. Indeed, the neutrino heating in the semi-transparent region behind the shock is now thought to be an essential ingredient in igniting the supernova explosion itself [1–3]. Furthermore, a neutrino-driven protoneutron star wind is thought to be a general feature of the core-collapse phenomenon and has been proposed as a site for $r$-process nucleosynthesis.

Essential in understanding the mechanism of Type-II supernovae is an accurate prediction of the production spectrum for each neutrino species. To this end, in §2 we present results of a thermalization and equilibration study of $\mu$ and $\tau$ neutrinos in dense matter.

Separately, in §3 we present preliminary results from calculations of steady-state protoneutron star winds in general relativity. We include velocity profiles, asymptotic entropies, and expansion timescales central in assessing this site as a candidate for $r$-process nucleosynthesis.

2. Thermalization and Production

For $\nu_\mu$ and $\nu_\tau$ neutrino types (collectively $\nu_\mu$s'), which carry away 50–60% of the $\sim 2 - 3 \times 10^{53}$ ergs liberated during collapse and explosion, the prevailing opacity and production sources are $\nu_\mu$-electron scattering, $\nu_\mu$-nucleon scattering, $e^+e^-$ annihilation, and nucleon-nucleon bremsstrahlung. The charged-current reactions dominate the electron-type transport so completely that we do not consider them here.

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Our focus is on (1) the role of $\nu_\mu$-nucleon scattering relative to $\nu_\mu$-electron scattering in thermalizing $\nu_\mu$ neutrinos and (2) the importance of bremsstrahlung as compared with $\nu_\mu$ of thermalizer of $\nu_\mu$ calculations were [8–11]. These efforts reveal that the average energy transfer in $\nu_\mu$ nucleon degeneracy, at the temperatures and densities encountered in the core of a core-collapse supernova $\nu$, a re-evaluation of these processes in the supernova context. In the last few years, analytic formulae for $\nu_\mu$-nucleon have been derived that include the full kinematics and final-state Pauli blocking, at arbitrary nucleon degeneracy, at the temperatures and densities encountered in the core of a core-collapse supernova $\nu$. These efforts reveal that the average energy transfer in $\nu_\mu$-nucleon scattering may surpass previous estimates by an order of magnitude and, hence, that this process may compete with $\nu_\mu$-electron scattering as an equilibration mechanism $\nu$ $\nu$. Similarly, estimates of the nucleon-nucleon bremsstrahlung rate have been obtained $\nu$ $\nu$ $\nu$ $\nu$ which indicate that this process can compete with $e^+e^-$ annihilation in the dense core.

In order to compare these scattering and production processes directly, we solve the Boltzmann equation for the time evolution of the neutrino phase-space distribution function ($F_\nu$) in an idealized system with no spatial or angular gradients. We consider an isotropic homogeneous thermal bath of scatterers and absorbers held at constant temperature, density, and electron fraction. For the scattering processes, we begin the equilibration calculation at $t = 0$ with a $\nu_\mu$ distribution function with a characteristic temperature of twice that of the surrounding matter. We then evolve this distribution function using the full collision integral of the Boltzmann equation, with the structure function formalism of Burrows and Sawyer (1998) $\nu$ and Reddy et al. (1998) $\nu$. When equilibrium is reached the final distribution is Fermi-Dirac, at the temperature of the surrounding matter, with chemical potential set by the initial neutrino number density ($n_\nu$), conserved to better than 0.0001% throughout the calculation. For the production and absorption processes we begin with zero phase-space occupancy for both $\nu_\mu$ and $\bar{\nu}_\mu$ at all energies and let bremsstrahlung and $e^+e^-$ annihilation each build an equilibrium distribution of neutrinos and anti-neutrinos. $e^+e^-$ annihilation is calculated in a Legendre polynomial expansion $\nu$. The production rate via nucleon-nucleon bremsstrahlung is calculated in a one-pion exchange model with arbitrary nucleon degeneracy $\nu$ $\nu$ $\nu$. As a check to the calculation, the final distribution should have a characteristic temperature of the ambient matter with zero neutrino chemical potential.

The left panel of Fig. 1 shows the thermalization rates for $\nu_\mu n$ and $\nu_\mu e^-$ scattering, defined in terms of the average energy transfer ($\omega$) at that energy, in equilibrium. The calculation was performed with $T \simeq 6.1$ MeV and $\rho \simeq 1.1 \times 10^{12}$ g cm$^{-3}$. These thermodynamic conditions are representative of the $\nu_\mu$ neutrinosphere, the semi-transparent regime where the neutrinos begin to decouple from the matter and free-stream to infinity. Most noticeable in this graph is the fact that while $\nu_\mu e^-$ scattering dominates at low energies ($< 10$ MeV), at modest and high energies $\nu_\mu n$ scattering competes with or dominates thermalization. Throughout our calculations, at a variety of densities, temperatures, and compositions, we find this behavior to be generic for the two scattering processes. Indeed, the point where $\nu_\mu n$ scattering begins to overwhelm $\nu_\mu e^-$ scattering seems always to fall between approximately 10 and 20 MeV.

The right panel of Fig. 1 reveals the same type of systematics for the production and absorption processes. In this case, however, we plot the total differential emissivity for nucleon-nucleon bremsstrahlung and $e^+e^-$ annihilation in equilibrium for two different thermodynamic points taken from a one-dimensional core-collapse simulation $\nu$ $\nu$ $\nu$. Bremsstrahlung is clearly the dominant production mechanism at low neutrino energies. In the interior, at densities of order $10^{13}$ g cm$^{-3}$, $e^+e^-$ annihilation begins to compete only at neutrino energies above 50 MeV. In our time-dependent calculations, we find that bremsstrahlung always dominates production below 10-20 MeV at all points in a representative collapse profile.

3. Neutrino-Driven Protoneutron Star Winds

A complete and self-consistent theory of the origin of all the elements has been the grand program of nuclear astrophysics since the field’s inception. The $r$-process, or rapid neutron capture process, is
a mechanism for nucleosynthesis by which seed nuclei neutron capture on timescales shorter than those for $\beta^-$ decay. With a sufficient neutron flux, capture continues to very neutron-rich isotopes and to the heaviest elements (e.g., Eu, Dy, Th, and U) producing unique abundance peaks at $A \sim 80, 130,$ and $195$ \cite{20-22}. The $r$-process is only quelled when photodisintegration timescales approach those for neutron capture. After the intense neutron flux lessens, $\beta^-$ decay populates the primary stable isobar for a given atomic number. While the relevant nuclear physics is fairly well understood, the astrophysical site, which must exist in order to produce the elemental abundances we find in nature, is not known. The viability of a site for $r$-process nucleosynthesis hinges on three characteristics: the asymptotic entropy per baryon ($s_f$), the electron fraction ($Y_e$), and the dynamical timescale ($\tau_{\text{dyn}}$). One proposed site is the protoneutron star wind that emerges after core collapse and shock reheating during a supernova \cite{18-21, 20-22}.

Both numerical and analytic studies of the conditions in this neutrino-driven wind have been carried out previously \cite{20-22}. Early calculations based on realistic supernova models produced interesting nucleosynthesis and appreciable $r$-process yields, but overproduced nuclei near $N = 50$ ($^{88}$Sr, $^{89}$Y, and $^{90}$Zr) \cite{20-22}. This problem was overcome by fine-tuning $Y_e$ in these simulations \cite{21}, but no consensus on the other parameters (particularly, $s_f$) has yet been reached. The pioneering analytic work of ref. \cite{20-22} using simple wind models showed that entropies fell short by a factor of $\sim 2 - 3$ of those needed for the $r$-process. The dynamic timescales and lepton fractions achieved. In other studies $s_f$ was artificially enhanced by a factor of $\sim 5$ to achieve proper solar $r$-process abundances \cite{23}. The fact that these calculations indicate an $s_f$ too low for the $r$-process nucleosynthesis does not exclude the wind as a potential site. A slight increase in energy deposition after the wind’s acceleration phase \cite{20-22} or the effects of general relativity have been shown to decrease $\tau_{\text{dyn}}$ and increase $s_f$ \cite{20-22}, both favorable to nucleosynthesis. Recent general relativistic steady-state and hydrodynamical studies indicate that winds can generate all three $r$-process abundance peaks only when the protoneutron star is quite massive $\sim 2$ $M_\odot$ \cite{21, 22} and the total neutrino luminosity large ($\sim 10^{52}$ erg s$^{-1}$). These condition produce modest entropies ($\sim 130$ baryon$^{-1}$ k$^B_{\text{B}}$), but short $\tau_{\text{dyn}} \sim 6$ ms.

The wind equations can be reduced to three ordinary coupled, critical differential equations for the evolution of temperature ($T$), mass density ($\rho$), and velocity ($v$) in radius. $Y_e$ is held constant. Solving these equations constitutes an eigenvalue problem. The eigenvalue sought is the mass outflow rate $M = 4\pi r^2 \rho c_s$, or, alternatively, the critical radius ($R_c$) where $v(R_c) = c_s$, the local speed of sound. In practice, we impose two boundary conditions at the protoneutron star surface ($R_o$), which we take to be the neutrinosphere: (1) $T(R_o) = T_{\nu_e}$ and (2) $\tau_\nu(R_o) = -\int \kappa_\nu \rho \, dr = 2/3$, where $\tau_\nu$ is the neutrino optical depth. A third constraint must be imposed if we are to close the system of equations. This we take to be the critical condition, $v(R_c) = c_s$, which defines the outer radial boundary. The system, now well-posed, can be solved using a relaxation technique on an adaptive radial grid \cite{23}. The code then adjusts the radial mesh in a Newton-Raphson sense in order to fulfill all boundary conditions simultaneously. Once the critical point is determined, we use l’Hospital’s rule to bridge it and then integrate to infinity using a simple Runge-Kutta scheme.

The results of a preliminary and representative general relativistic calculation are shown in Fig. 2. The left panel shows velocity profiles for a variety of $\tilde{\nu}_e$ luminosities, for a protoneutron star mass $M = 1.4M_\odot$ and radius $R_o = 10$ km. This range of neutrino luminosities is indicative of the first $\sim 8 - 10$ seconds of the protoneutron star’s life. The right panel is a plot of the asymptotic entropy per baryon per Boltzmann constant versus $\tau_{\text{dyn}}$ for the same protoneutron star. Note that these calculations were carried out with constant $Y_e = 0.302$.

In general, we find that higher entropies and shorter dynamical timescales result from the use of general relativity instead of Newtonian gravity. For the 1.4 $M_\odot$ object we consider here, however, we do not achieve entropies and timescales appropriate for $r$-process nucleosynthesis \cite{21, 22, 23}.

4. Summary and Conclusions

Our results for equilibration via $\nu_{\mu}$-$e$ scattering and $\nu_{\mu}$-nucleon scattering demonstrate that the latter competes with or dominates the former as a thermalizer for neutrino energies $> 10$ MeV for $\rho > 1 \times 10^{11}$ g cm$^{-3}$ at all temperatures. At neutrino energies $> 30$ MeV, the difference at all densities and temperatures is approximately an order of magnitude. For the production and absorption processes, we find that nucleon-nucleon bremsstrahlung, at the average energy of an equilibrium Fermi-Dirac distribution at the local temperature, is 2 orders of magnitude faster than $e^+e^-$ annihilation at
$T \sim 15$ MeV and $\rho \sim 10^{13}$ g cm$^{-3}$. Only for $\rho \sim 10^{12}$ g cm$^{-3}$ and $T \sim 6$ MeV does $e^+e^- \leftrightarrow \nu_\mu \bar{\nu}_\mu$ begin to compete with bremsstrahlung at all energies. We conclude from this study that the emergent $\nu_\mu$ and $\nu_\tau$ spectrum is (1) brighter and (2) softer than previously estimated \cite{16}. The former results from the inclusion of the new pair emission process, nucleon-nucleon bremsstrahlung. The latter is a consequence of both the increased energy coupling between the nuclear and neutrino fluids through $\nu_\mu$-nucleon scattering and the fact that bremsstrahlung dominates $e^+e^-$ annihilation near the neutrinospheres at the lowest neutrino energies.

In addition, our first step in the calculation of realistic protoneutron star wind models has been successful; we have created a robust technique for solving the steady-state eigenvalue problem and have confirmed the results of other researchers qualitatively. We plan to explore the parameter space of protoneutron star winds exhaustively with an eye toward implementing full neutrino transport in a hydrodynamic simulation of wind emergence and evolution.

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Figure 1. Left panel: the thermalization rate $\Gamma$ (s$^{-1}$) for both $\nu_\mu$-electron and $\nu_\mu$-neutron scattering as a function of neutrino energy $\varepsilon_\nu$ (MeV) in equilibrium. Right panel: the differential emissivity versus $\varepsilon_\nu$ for both nucleon-nucleon bremsstrahlung and $e^+e^-$ annihilation for two thermodynamic points taken from a representative one-dimension core-collapse simulation [3].
Figure 2. Left panel: general relativistic protoneutron star wind velocity $v$ (cm s$^{-1}$) profiles for six $\bar{\nu}_e$ luminosities: (A) 4.5, (B) 3.5, (C) 2.5, (D) 1.5, and (E) $1 \times 10^{51}$ erg s$^{-1}$. The mass and radius of the central neutron star are $M = 1.4 M_\odot$ and $R_o = 10$ km, respectively. The electron fraction ($Y_e$) is held constant at 0.302. The dots denote the critical point where the velocity of the wind is equal to the local speed of sound. Right panel: asymptotic entropy ($s_f$) versus dynamical timescale ($\tau_{dyn}$) for constant protoneutron star mass and radius, but as a function of $\bar{\nu}_e$ luminosity.