The physics of collective neutrino–plasma interactions

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Abstract. A review of recent work on collective neutrino–plasma interactions is presented. The basic physical concepts of this new field as well as some possible astrophysical problems where the physics of collective neutrino–plasma interactions can have a radical impact, are discussed.

1. Introduction

Neutrinos are produced in violent processes following the big bang leading to what we call the relic neutrinos-equivalent to the microwave background. Copious amounts of neutrinos are created during supernova explosions as well as from fusion reactions in the Sun. Even though neutrinos are among the most abundant elementary particles in the universe, they are also the most elusive. Some important questions about their properties (mass and helicity, for instance) remain to be answered in a definite way. Recent results from the superkamiokande experiment in Japan suggest that neutrinos have a mass of 0.1 eV or greater. Yet, neutrinos play a fundamental role in some of the most extraordinary events in the universe; from the big bang to the solar neutrino problem, from supernova explosions to the dark matter problem, the systematic presence of neutrinos has lead the physics community to devote a considerable effort to studies of the neutrino properties (Bahcall 1989, Bahcall and Ostriker 1996).

The strongest effort towards the understanding of the neutrino properties has been made by the particle physicists: the interaction of the neutrinos with matter is well understood from a single-particle non-self-consistent point of view (see, for example, Kuo and Pantaleone 1989). However, at several scales of the universe, very intense neutrino fluxes are present. The fluxes can be so intense that the background matter is disturbed, which in turn affects the neutrino propagation. For example the gravitational binding energy of massive stars, of the order of 10^{53} ergs s^{-1}, is released in the form of neutrinos during a supernova explosion. Therefore, we are in the presence of a scenario requiring a self-consistent description of neutrino propagation in matter, eventually leading to several types of instabilities. An electron beam, or a photon beam, propagating through a plasma generates plasma waves, which perturb and eventually break up the electron or photon beam; a similar scenario (a two-stream instability) should also be observed for intense neutrino bursts in plasmas. From a conceptual point of view, this is not surprising, since the weak interaction force and the electromagnetic force have been unified by the standard electroweak model. Thus, the behaviour of neutrinos and electrons must, in a way, reflect this unification, and a similar phenomenology must be present for equivalent scenarios with electrons and neutrinos.

The possibility of neutrino driven instabilities was proposed for the first time by Bingham *et al* (1994), where it was shown that a considerable amount of the energy released as neutrinos in a supernova explosion could be deposited in the plasma due to Landau damping of nonlinearly excited electron plasma waves. This result can have significant consequences for supernova dynamics and it can explain the revival of the stalled shock. The neutrino anomalous energy absorption would heat up the plasma, allowing for the propagation of the shock out of the star, leading to the supernova explosion (Wilson 1985, Bethe and Wilson 1985). Other conditions where neutrino driven instabilities can be of significant importance are those existing in the early stages of the big bang, where a neutrino filamentation instability can influence the large scale structure of the universe.

In this paper, we review the properties of neutrinos propagating in plasmas from a plasma physics point of view. We show that a strong flux of neutrinos can drive two-stream instabilities, create inhomogeneities and generate magnetic fields in plasmas. The consequences of this fundamental result to several pending astrophysical puzzles is presented. The paper is organized in the following fashion: in section 2, we briefly describe the single neutrino dynamics in a dense background. This is the fundamental building block of our formulation. We emphasize that our formulation can be easily applied to several species of background matter such as electrons, neutrons, photons or other neutrinos, thus providing a general description of the self-consistent processes involved in neutrino matter interactions. In section 3, we consider how the presence of an intense neutrino flux affects the plasma electrons. In a fashion similar to photons, the electron neutrinos exert a long range force (or ponderomotive force) which pushes the electrons to regions of lower neutrino number density. A kinetic theory for the electrons and the electron-neutrinos is then developed, from which the dispersion relation of longitudinal plasma waves is derived. In section 4, we analyze the dispersion relation and present the interesting instability regimes, namely the fluid or hydrodynamic regime (strong beam or weak beam limits) and the kinetic regime (neutrino Landau damping). The significance of the neutrino two-stream instability during supernova explosions is considered. We also describe the instability scenario associated with strong neutrino and anti-neutrino fluxes of different flavours. Finally, in section 5 we discuss the generation of inhomogeneities and magnetic fields by incoherent neutrinos and apply our results to the early universe and type II supernova scenarios. Section 6 contains a brief summary of our investigation as well as pointing out future perspectives of neutrino plasma physics.

2. Neutrino dynamics in a dense plasma

The propagation of a single neutrino in a medium has been extensively studied within the particle physics community (Kuo and Pantaleone 1989). The interaction of the neutrinos with background matter occurs through the weak interaction force and thus corrections to the single neutrino dynamics are small. The interaction can be described as being equivalent to an effective potential that the neutrinos feel while propagating in a medium (Bethe 1986) and can also be interpreted as an index of refraction for the neutrinos (Bingham *et al* 1996). This is analogous to the index of refraction of photons propagating through a plasma. Due to the fact that different flavours of neutrinos (electron neutrinos, tau neutrinos, muon neutrinos) are subjected to different kinds of potentials (corresponding to a charge current and/or a neutral weak current), and also that different species of background matter give rise to different contributions to neutrino dispersion, new processes have been identified. Among those, the most notorious is the MSW effect (Wolfenstein 1978, Wolfenstein 1979, Mikheyev and Smirnov 1986), which predicts (Bethe 1986) a significant neutrino flavour conversion when neutrinos propagate through a medium. As shown by Bingham *et al* (1997), this is equivalent to the mode conversion of an electromagnetic wave in inhomogeneous fluids and plasmas, thus providing a bridge between the problems of the neutrino conversion in a matter and the extensive plasma physics literature on the mode conversion in plasmas.

Our focus here will be on the single particle dynamics, neglecting mode conversion or the MSW mechanism. The Hamiltonian describing the neutrino propagation can be put in the form (Bethe 1986)

$$H_{\text{eff}} = \sqrt{\boldsymbol{p}_\nu^2 c^2 + m_\nu^2 c^4} + V_{\text{eff}} \tag{1}$$

where V_{eff} is the effective potential due to weak interactions, $\boldsymbol{p}_\nu$ is the neutrino momentum, c is the speed of light and m_ν the neutrino mass (which is set to zero for massless neutrinos; our model does not require the neutrinos to be massless). The form of the effective Hamiltonian and the effective potential have been determined for different media with or without ambient magnetic fields (Nunokawa *et al* 1997, Kuo and Pantaleone 1989). For the particular case of electron neutrinos interacting with electrons, protons and neutrons, the effective potential in an unmagnetized medium is

$$V_{\text{eff}} = (1 + 4\sin^2\theta_{\text{W}})\frac{G_{\text{F}}}{\sqrt{2}}(n_{\text{e}}(\boldsymbol{r}, t) - n_{\bar{\text{e}}}(\boldsymbol{r}, t)) - \frac{G_{\text{F}}}{\sqrt{2}}n_{\text{n}}(\boldsymbol{r}, t) + (1 - 4\sin^2\theta_{\text{W}})\frac{G_{\text{F}}}{\sqrt{2}}n_{\text{p}}(\boldsymbol{r}, t) \tag{2}$$

where G_{F} is the Fermi constant of the weak interaction, θ_{W} the Weinberg mixing angle, $n_{\text{e}}(n_{\bar{\text{e}}})$ the electron (positron) number density, n_{p} the proton number density and n_{n} the neutron number density. We note that since $\sin^2\theta_{\text{W}} \approx 0.25$, the contribution of the protons to the effective potential can be discarded. The neutrino dynamics can be described by the quasiclassical equations of motion as long as the neutrino de Broglie wavelength $\lambda_\nu = 2\pi\hbar/|\boldsymbol{p}_\nu|$ is much smaller than the typical length scale of the changes in n_{e} or n_{p}. In this case, the quasiclassical equations of motion for the neutrinos reveal that the neutrinos are subjected to a force of the form $\boldsymbol{F} = -\nabla V_{\text{eff}}$, which dictates that the electrons contribute to a repulsive potential and the neutrons to an attractive potential: electron neutrinos (ν_{e}-s) will bunch in regions of lower electron density and in regions of higher neutron density. For typical conditions occurring in a supernova at a radius of 100–300 km ($n_{\text{e}} \approx 10^{29}$–$10^{32}$ cm^{-3}), the effective potential is roughly $V_{\text{eff}} \approx 10^{-8}$–$10^{-5}$ eV.

3. Ponderomotive force of neutrinos

The question to answer now is how the presence of a strong neutrino flux disturbs the plasma. We have seen that even though the interaction is weak, the neutrinos are affected by the presence of the background plasma. In the same way, we should expect the background plasma to be affected by the presence of the neutrinos. An analogy with electromagnetic waves can be easily established (Mendonça *et al* 1995); a localized distribution of electromagnetic waves exerts a ponderomotive force on the background medium, corresponding to the gradient of the radiation pressure. Thus, we should also expect that a similar force (Bingham *et al* 1996) should arise whenever a localized distribution of neutrinos is present in the plasma. In fact, the force exerted in a background medium due to a non-uniform field (neutrinos or photons) can also be seen as a pressure gradient arising due to some inhomogeneity in the particle or quasiparticle spatial distribution (Silva *et al* 1998a).

We have introduced a formalism based on the distribution of non-interacting dressed particles (neutrinos) or quasiparticles (photons) in a plasma, which provides a unified picture of the ponderomotive force (Silva *et al* 1998a). Starting from the effective Hamiltonian, for neutrinos, or the dispersion relation for electromagnetic waves, we are able to derive the force exerted by an arbitrary distribution of photons and neutrinos, recovering the usual results found in the literature for the ponderomotive force of electromagnetic waves.

For neutrinos, the driving force assumes a different functional dependence than the ponderomotive force of photons. The driving force, which is caused by the pressure of an intense electron neutrino flux, acting on *a single electron* is given by

$$\boldsymbol{F}_{\nu-\mathrm{e}} = -\frac{\sqrt{2}}{2}(1+4\sin^2\theta_{\mathrm{W}})G_{\mathrm{F}}\boldsymbol{\nabla} n_{\nu\mathrm{e}}(\boldsymbol{r},t) \tag{3}$$

where $n_{\nu\mathrm{e}}$ represents the number density of neutrinos. In the same way, the force exerted by a distribution of ν_{e} and anti-ν_{e} over a single electron (positron) is

$$\boldsymbol{F}_{\nu\,\bar{\nu}-\mathrm{e}^+(\mathrm{e}^-)} = \mp\frac{\sqrt{2}}{2}(1+4\sin^2\theta_{\mathrm{W}})G_{\mathrm{F}}\boldsymbol{\nabla}(n_{\nu\mathrm{e}}(\boldsymbol{r},t) - n_{\bar{\nu}\mathrm{e}}(\boldsymbol{r},t)) \tag{4}$$

where the minus (plus) sign refers to the electrons (positrons), and $n_{\bar{\nu}\mathrm{e}}(\boldsymbol{r},t)$ is the anti-ν_{e} number density. Furthermore, for *a single neutron*, the ponderomotive force is written as

$$\boldsymbol{F}_{\nu\bar{\nu}-\mathrm{n}} = \frac{\sqrt{2}}{2}G_{\mathrm{F}}\boldsymbol{\nabla}(n_{\nu\mathrm{e}}(\boldsymbol{r},t) - n_{\bar{\nu}\mathrm{e}}(\boldsymbol{r},t)). \tag{5}$$

For typical parameters in a supernova, the ratio between the ponderomotive force $|\boldsymbol{F}_{\mathrm{p}}|$ (as given by (3)) and the single neutrino-electron collisional force is roughly $|\boldsymbol{F}_{\mathrm{p}}|/|F_{\mathrm{coll}}| \approx 10^{10}$ (Bingham *et al* 1996).

An examination of equations (3)–(5) reveals that the neutrinos push electrons to regions of lower neutrino density and positrons and neutrons to regions of higher neutrino density, by the ponderomotive force. On the other hand, as we have seen in the previous section, neutrinos are pushed to regions of lower electron density and to regions of higher positron or higher neutron number density. For a background plasma of electrons and ions, charge separation leads to a restoring electrostatic force leading to an instability which shall be described in the next two sections.

We note that the anti-neutrinos will push the electrons in the opposite direction to the neutrinos but, due to the opposite effective potential affecting the neutrinos and anti-neutrinos, the neutrinos will bunch in the regions of lower electron density while the anti-neutrinos bunch in the regions of higher electron density. Thus, the ponderomotive force due to neutrinos and anti-neutrinos act together to reinforce the density modulations and will still be a fundamental ingredient for this instability scenario (Silva *et al* 1999).

4. Two-stream instability of neutrinos in a plasma

Having determined the forces acting on the single plasma electron and the single neutron, as well as on the single neutrino, all the information necessary to develop a kinetic theory for dressed neutrinos and electrons is available. We note that while constructing our kinetic equations from the ponderomotive force and the neutrino effective Hamiltonian, an average over the fast time scale (the neutrino frequency ω_ν) is assumed (Silva *et al* 1998b). The relativistic collisionless kinetic equations for the neutrinos and electrons have also been derived from a relativistic statistical quantum field theory, revealing an equivalent set of kinetic equations (Semikoz 1987). This is not surprising since the limits of validity for a semiclassical approximation are clearly verified: we consider the interaction of the neutrinos with the electrons governed by quantum processes (included in V_{eff}) and we take into account the Fermi statistics of the phase space density of the particle numbers, but the neutrino dynamics is determined by the quasi-classical effective Hamiltonian, and we neglect the spins.

A straightforward analysis (assuming an isotropic plasma, and neglecting the ion motion) leads to the dispersion relation for electrostatic plasma waves (Langmuir waves) in the presence of neutrinos (Silva *et al* 1998b)

$$1 + \chi_{\text{e}}(\omega_{\text{L}}, \boldsymbol{k}_{\text{L}}) + \chi_{\nu}(\omega_{\text{L}}, \boldsymbol{k}_{\text{L}}) = 0 \tag{6}$$

where $\chi_{\text{e}}(\omega_{\text{L}}, \boldsymbol{k}_{\text{L}})$ ($\chi_{\nu}(\omega_{\text{L}}, \boldsymbol{k}_{\text{L}})$) is the relativistic electron (neutrino) susceptibility expressed as a function of the frequency ω_{L} and the wavevector $\boldsymbol{k}_{\text{L}}$ of the driven Langmuir waves. The neutrino susceptibility takes the form

$$\chi_{\nu}(\omega_{\text{L}}, \boldsymbol{k}_{\text{L}}) = -2G_{\text{F}}^2 \frac{k_{\text{L}}^3 n_{\text{e}0} n_{\nu 0}}{m_{\text{e}} \omega_{\text{pe}0}^2} \chi_{\text{e}}(\omega_{\text{L}}, \boldsymbol{k}_{\text{L}}) \int \mathrm{d}\boldsymbol{p}_{\nu} \frac{\boldsymbol{k}_{\text{L}} \cdot (\partial \hat{f}_{\nu 0}/\partial \boldsymbol{p}_{\nu})}{\omega_{\text{L}} - \boldsymbol{k}_{\text{L}} \cdot \boldsymbol{v}_{\nu}} \tag{7}$$

where $\hat{f}_{\nu 0}$ is the normalized neutrino distribution function, $n_{\text{e}0}$ ($n_{\nu 0}$) is the electron (neutrino) number density, $\boldsymbol{v}_{\nu}$ is the neutrino group velocity, $\omega_{\text{pe}0} = (4\pi n_{\text{e}0} e^2/m_{\text{e}})^{1/2}$ is the electron plasma frequency, e the magnitude of the electron charge and m_{e} the electron mass. For a monoenergetic neutrino beam propagating in a cold plasma, the dispersion relation can be determined analytically (Silva *et al* 1998b)

$$\omega_{\text{L}}^2 = \omega_{\text{pe}0}^2 + \left(\frac{m_{\nu}^2 c^4 \cos^2\theta}{E_{\nu 0}^2} + \sin^2\theta \right) \frac{\Delta_{\nu} k_{\text{L}}^4 c^4}{(\omega_{\text{L}} - k_{\text{L}} c \cos\theta\, p_{\nu 0} c/E_{\nu 0})^2} \tag{8}$$

with $\Delta_{\nu} = 2G_{\text{F}}^2 n_{\nu 0} n_{\text{e}0}/(m_{\text{e}} c^2 E_{\nu 0})$. A similar analysis as for the two-stream instability gives the maximum growth for the mode $k_{\text{L}} c \cos\theta \approx \omega_{\text{pe}0}$, with the growth rate γ, for the weak beam case ($\gamma/\omega_{\text{pe}0} \ll 1$)

$$\gamma = \frac{\sqrt{3}}{2} \omega_{\text{pe}0} \left(\frac{\Delta_{\nu}}{\cos^2\theta} \right)^{1/3} \tag{9}$$

which means that the growth rate is proportional to $G_{\text{F}}^{2/3}$. For the strong neutrino beam scenario, viz $\gamma/\omega_{\text{pe}0} \gg 1$, the growth rate scales as $\gamma \propto G_{\text{F}}^{1/2}$. As expected, the present collective plasma process is much stronger than the single particle process, such as single neutrino–electron scattering, which is proportional to G_{F}^2. It is then obvious that a complete description of the phenomena involving intense fluxes of neutrinos must account for the collective processes, as described here. For supernova conditions, we predict roughly 100 e-foldings during a ν_{e} neutrino burst period of $\tau \approx 5$ ms (Silva *et al* 1998b).

The general dispersion relation (equation (6)) describes not only the fluid or hydrodynamic (also known as reactive) regime of the neutrino driven instabilities discussed earlier, but also the neutrino kinetic regime of the streaming instability (Silva *et al* 1998c), i.e. an instability arising due to the specific features of the neutrino distribution function. From a purely mathematical point of view, the kinetic regime is related to the contribution from the pole in the neutrino susceptibility in equation (7). Using Landau's prescription in the evaluation of χ_{ν} leads us to a physical understanding equivalent to electron Landau damping or photon Landau damping, but now for neutrinos. In the hydrodynamic regime, the neutrinos transfer part of their free energy to the plasma as electron plasma oscillations. When the hydrodynamic instability saturates, the kinetic regime can become important: the neutrinos which move slower than the phase velocity of the electron plasma waves (EPWs) drain energy from the wave (i.e. are accelerated by the wave, i.e. the wave is neutrino Landau damped), while the neutrinos which move faster than the EPWs give energy to the wave (i.e. inverse neutrino Landau damping where the plasma waves absorb energy from the neutrino bursts). The qualitative differences between the two regimes in the framework of neutrino driven instabilities have been recently clarified by Silva *et al* (1998d).

For a Fermi–Dirac neutrino distribution, the kinetic growth rate γ_{Landau} is proportional to $-G_{\mathrm{F}}^2 n_{\mathrm{e}0}^{3/2}$, corresponding to a damping of EPWs by energy transfer to the neutrinos (Silva *et al* 1998c). This process could decrease the energy deposited by the neutrinos in the EPWs, for instance in a supernova explosion. However, for astrophysical conditions where strong neutrino fluxes are present, other EPW damping mechanisms are more effective (collisional damping, electron Landau damping). Therefore, the energy deposited by the neutrinos into the EPWs via the hydrodynamic instability is not transferred back to the neutrinos and significant plasma heating is predicted. This physical model can provide a definite answer to the long-standing problem of supernova explosions.

5. Neutrinos generating inhomogeneities and magnetic fields

In this section, we discuss the generation of inhomogeneities and magnetic fields by the ponderomotive force of intense neutrino bursts.

First, we consider the generation of neutron-acoustic oscillations (NAOs) when the neutron number density is much larger than the electron number density. Accordingly, we employ the continuity, modified (by the neutrino pressure) momentum and energy equations for the neutron fluid and couple them with the wave kinetic transport equation for incoherent neutrinos. The nonlinear dispersion relation for the driven NAOs is (Shukla *et al* 1998)

$$\Omega^2 - q^2 c_{\mathrm{n}}^2 \approx -\frac{G_{\mathrm{F}}^2 n_{\mathrm{n}0} q^2}{2 m_{\mathrm{n}} \hbar} \int \mathrm{d}\boldsymbol{k}_\nu \frac{\boldsymbol{q}\cdot(\partial f_\nu^0/\partial \boldsymbol{k}_\nu)}{\Omega - \boldsymbol{q}\cdot\boldsymbol{v}_\nu} \tag{10}$$

where Ω and $\boldsymbol{q}$ are the frequency and the wavevector of the NAOs, c_{n} the neutron-acoustic velocity, $n_{\mathrm{n}0}$ the unperturbed neutron number density, m_{n} the mass of the neutrons and $\int \mathrm{d}\boldsymbol{k}_\nu f_\nu^0$ is equivalent to the unperturbed neutrino number density.

Equation (10), which is structurally similar to (6) together with (7), admits both the two-stream and kinetic instabilities, in addition to an oscillatory reactive instability, the growth rate of which for $\Omega \gg \boldsymbol{q}\cdot\boldsymbol{v}_\nu$ is

$$\gamma_{\mathrm{n}} \approx \frac{\sqrt{3}}{2} \left| \frac{G_{\mathrm{F}}^2 n_{\mathrm{n}0} q^2}{2 m_{\mathrm{n}} \hbar} \int \mathrm{d}\boldsymbol{k}_\nu\, \boldsymbol{q}\cdot\frac{\partial f_\nu^0}{\partial \boldsymbol{k}_\nu} \right|^{1/3}. \tag{11}$$

Expression (11) exhibits a growth rate that is proportional to $G_{\mathrm{F}}^{2/3}$ and it depends on the details of the unperturbed neutrino distribution function.

The neutrino driven NAOs will attain large amplitudes. By including the nonlinear terms and a kinematic neutron fluid velocity, we are able to derive a Burger equation, which admits monotonic shock structures which sweep out regions of space forming voids surrounded by dense material. Thus, large scale inhomogeneities can be created by intense neutrino bursts.

Second, we focus our attention on the generation of magnetic fields by non-uniform neutrino beams. Taking the curl of the electron equation of motion (that also includes the neutrino driver) and eliminating the electromagnetic fields by means of Ampere and Faraday laws, we obtain (Shukla *et al* 1998) an evolution equation for the spontaneously generated magnetic field $\boldsymbol{B}$, i.e.

$$((1-\lambda_e^2\nabla^2)\partial_t - \eta\nabla^2)\boldsymbol{B} = \frac{c}{en_e}\nabla T_e \times \nabla n_e + \nabla\cdot(\boldsymbol{B}\boldsymbol{v}_i - \boldsymbol{v}_i\boldsymbol{B}) - \frac{4\pi}{c^2}\lambda_e^2\nabla \times(\nabla\cdot(\boldsymbol{J}\boldsymbol{v}_i + \boldsymbol{v}_i\boldsymbol{J})) - \frac{1}{c}\nabla\times\left(\frac{\boldsymbol{J}}{n_e}\times\boldsymbol{B}\right) + \frac{cG_F}{\sqrt{2}e}\nabla n_\nu \times \nabla\left(\frac{n_n}{n_e}\right) \tag{12}$$

where $\lambda_e = c/\omega_{pe}$ is the collisionless electron skin depth, $\eta = \nu_e\lambda_e^2$ is the plasma resistivity, $\boldsymbol{v}_i$ the ion fluid velocity and $\boldsymbol{J} = (c/4\pi)\nabla\times\boldsymbol{B}$ is the plasma current. The origin of various terms on the right-hand side of equation (12) is obvious. The first term represents the Biermann battery, the second is the standard dynamo, the third arises from the nonlinear electron inertial force and the fourth comes from the nonlinear Lorentz force; the latter two play an important role in the dynamical evolution of the magnetic fields. On the other hand, the last term on the right-hand side of equation (12) is our new contribution and this source is responsible for creating spontaneous magnetic fields when the gradient of the neutrino number density and the gradient of n_n/n_e are non-parallel.

In steady state, the magnetic fields are also directly produced by a non-uniform Gaussian neutrino beam. The electron gyrofrequency $\omega_{ce} = eB_\theta/m_e c$ (Shukla *et al* 1997, Shukla and Stenflo 1998a) can be written in the form

$$\omega_{ce} \sim \omega_{pe}\left(\frac{\omega_G W_0}{\omega_\nu E_p}\right)^{1/2} \tag{13}$$

where W_0 is the neutrino energy density on the beam axis, $E_p = n_0 m_e c^2$ is the plasma energy density and $\omega_G = G_F n_0/\hbar$. Taking some typical type II supernova parameters, namely, neutrino power density $P_\nu = 10^{29}$ W cm^{-2}, $n_0 = 10^{30}$ cm^{-3}, $\omega_G/\omega_\nu = 10^{-13}$ for 1 MeV neutrinos and $E_p = 10^{24}$ erg cm^{-3}, we obtain an azimuthal magnetic field of order 10–100 megagauss for $W_0/E_p \sim 100$. On the other hand, we find that a few microgauss magnetic fields are produced by intense neutrino beams in the early universe during the Lepton era that lasted between a period of a fraction of a second to a few seconds (3–10 s). We note that the propagation of neutrinos in magnetic fields is significantly altered (Shukla and Stenflo 1998b).

Finally, we have found that the neutrino ponderomotive force that generates space charge electric fields in a plasma also gives rises to an effective neutrino charge (Mendonça *et al* 1997)

$$Q_\nu = -\sqrt{2}\frac{G_F n_0 n_\nu}{e^2\lambda_e^2} \tag{14}$$

which agrees with that derived earlier by particle physicists using Feynman diagrams.

6. Discussion and future perspectives

In this paper, we have discussed the status of collective processes involving the nonlinear interaction between intense neutrino bursts and an unmagnetized plasma. It is shown that neutrinos interact with collective plasma modes and neutron-acoustic oscillations due to the neutrino driving force involving weak nuclear interactions between fermions and W- and Z-bosons. Thus, collective effects in plasmas produce a long-range interaction of short neutrino wave trains with the medium through which they propagate. The neutrino driving force far exceeds the collisional force produced by the neutrino–electron interactions. This significant enhancement is attributed to the interaction of a broad-band spectrum of neutrino oscillations with resonant as well as non-resonant electron plasma or neutron-acoustic disturbances. Accordingly, there are possibilities of generating plasma waves and neutral density irregularities by incoherent neutrino beams. Nonlinearly excited electron plasma waves are subjected to Landau damping, thereby producing anomalous absorption of the neutrino energy in the background plasma. Thus, we have a new possibility of heating plasma particles by neutrinos released from a collapsing star allowing shock waves to be revived which result in the supernova explosion. On the other hand, neutrino driven neutron-acoustic disturbances attain large amplitudes in the form of shocks. The latter can be associated with inhomogeneities and structures in the early universe and galaxies. Furthermore, we have shown that intense neutrino beams passing through a medium sweep charged and neutral particles from their paths, thereby producing space charge fields and currents which are responsible for the generation of magnetic fields. Numerical values suggest that magnetic fields of a few microgauss in the early universe as well as superstrong magnetic fields of hundreds of megagauss in the type II supernova (or on the surface of a neutron star) could be directly created by non-uniform intense neutrino beams. Thus, there is no need to rely on the production of a seed magnetic field by the Biermann battery and consequent amplification by the dynamo process, which is unable to account for the desired magnetic field strengths in astrophysical environments.

In conclusion, the nonlinear collective interactions between neutrinos and plasmas open a whole new subject and that the collective interactions between weak and electromagnetic forces will be able to solve many complex problems in the universe. The ideas set forth in this paper dictate that neutrinos should be considered as building blocks of the universe, as they are able to explain the phenomena of neutrino energy absorption as well as the generation of inhomogeneities and primordial magnetic fields which give rise to large scale structures of the universe. Furthermore, we anticipate that the knowledge of the nonlinear neutrino plasma coupling should provide clues to the 'anti-gravity force' necessary for inflation, missing hot dark matter (massive neutrinos with a mass of roughly 1 eV could provide 20% of the Universe while the other main constituent for the mass could be x-ray emitting plasma at 1–10 keV temperatures within clusters of galaxies) of cosmology, dominance of matter over anti-matter (a process intimately linked to our very existence), fusion in stellar plasmas, relativistic fireballs as well as γ-ray bursts and other types of radiation in active galactic nuclei. Neutrinos may also be the highest energy cosmic rays ($>10^{20}$ eV) (Bordes *et al* 1998) and they have been proposed as a possible solution of the chirality of the DNA molecule, the very substance of life. (Cline *et al* 1995). Clearly, significant progress can be made towards a better understanding of the neutrino propagation through a plasma provided that we combine our plasma physics knowledge with that of particle physics, thereby coupling the weak nuclear forces with electromagnetism and gravitational forces in a system containing both elementary, as well as charged and neutral particles.

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