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Neutrino Emissions in Stellar Evolution through Electro-Weak Interaction

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The neutrino emissions take place, particularly, in the later stages of the stellar evolution. There are a number of processes that may contribute for the energy loss from star via neutrino emissions. In this paper we have discussed a brief outline of plasma neutrino process, photo-coulomb neutrino process and neutrino-synchrotron radiation process in the framework of the electro-weak theory. It has been observed that each process has significant effect in some particular region of densities and temperatures; in other region it may not have any remarkable effect. Those three processes, considered here, have important contributions, at least some phases of the late stages of evolution of stars.

1. Introduction

The neutrino emission process plays an important role during the final stages of the stellar evolution at high densities and temperatures, in both degenerate and non-degenerate region. This is because of the extremely large mean free path of the neutrino. Under some circumstances in the late stages of the star the neutrino radiation may be the principal means of the energy loss. In 1941 Gamow and Schoenberg [1] pointed out that the β -decay process might be responsible to carry out the energy from the stellar core. After that a number of processes that produce neutrinos have been studied in context with the stellar evolution by a number of researchers. In 1972 Dicus [2] and in 1996 Itoh [3] reviewed a number of neutrino emission processes in electro-weak theory with their possible implications. The photo-neutrino process significantly contributes for the energy-loss mechanism in the late stages of the stellar evolution, though there are some other processes may have some important role in this stage. Previously those processes were studied either by Fermi's current current coupling theory or by photon-neutrino weak coupling theory. The later one successfully explained the application of the phenomena like neutrino synchrotron radiation process, specially to white dwarf [4], whereas the former one could explain most of the neutrino emission processes. After the development of the Standard Model some of those processes were studied in the frame-work of the electro-weak theory. The concept of neutrino mass coming from 'solar neutrino problem' and 'atmospheric neutrino anomaly' [5] was also to introduce in this study, although a new theory is yet to be developed by considering the neutrino mass in the Standard Model. In this paper we restrict ourselves on the review of three important neutrino emission mechanisms - plasma neutrino process, photo-coulomb neutrino process and neutrino synchrotron process to give a brief outline of their effects in the high temperature and density.

2. Plasma neutrino process:

The plasma neutrino process is important since it does not occur in the vacuum and still dominates the stellar emission rates for a wide range of densities and temperatures. It occurs mainly in the white dwarves and the degenerate core of low mass red giants. The plasma, present in the core of very hot and dense stars, contains the mobile charged particles - electrons and positrons. An electromagnetic wave propagating through plasma behaves differently from the electromagnetic wave in vacuum. In the plasma the vibrations of both electromagnetic waves and charged particles generate transverse as well as longitudinal waves. When the dielectric constant of the electron gas becomes less than unity the photon behaves as if it has a rest mass equal to the plasma frequency ω_p. If this plasma frequency is not negligible relative to the temperature of the stellar core, the collective behavior of the plasma is more significant than effect from a single photon or electron. This collective modes of plasma can be represented by the polarization tensor $\Pi^{\mu\nu}(K)$ introduced by Adams et al. [6] in their pioneer work on plasma neutrino process, though they used a simple dispersion relation which would be accurate only in the range of temperatures and densities where the electrons are non-relativistic. A generalized expression for the dispersion relation was deduced by Braaten and Segel [7]. They have defined the residue functions Z_t and Z_l of the transverse and longitudinal modes as follows:

$$Z_t = [1 - \frac{\partial \Pi_t}{\partial \omega^2}]^{-1} \tag{2.1}$$

$$Z_l = \frac{|\overrightarrow{k}|^2}{\omega_l^2}[-\frac{\partial \Pi_l}{\partial \omega^2}]^{-1} \tag{2.2}$$

Where the polarization functions Π_t and Π_l are defined by [7]

$$\Pi_t = \frac{1}{2}(\delta^{ij} - \hat{k}^i \hat{k}^j)\Pi^{ij}(\omega, |\overrightarrow{k}|) \tag{2.3}$$

$$\Pi_l = \Pi^{00}(\omega, |\overrightarrow{k}|) \tag{2.4}$$

The frequency of the electromagnetic wave can be separated into transverse ω_t and longitudinal ω_l frequencies. The decay rates for the longitudinal and transverse plasma take the form

$$\Gamma_t = 1 \cdot 5 \times Z_t \times (\frac{\hbar^2\omega_t^2 - |\overrightarrow{k}|^2 c^2}{m_e^2 c^4})^3 (\frac{m_e c^2}{\hbar \omega_t}) \quad sec^{-1} \tag{2.5}$$

$$\Gamma_l = 1 \cdot 5 \times Z_l \times (\frac{\hbar^2\omega_l^2 - |\overrightarrow{k}|^2 c^2}{m_e^2 c^4})^2 (\frac{\hbar \omega_l}{m_e c^2}) \quad sec^{-1} \tag{2.6}$$

To evaluate the energy-loss rate for the decay of plasma into neutrino anti-neutrino pair it is important to note that the plasma frequency depends on temperature and density. For the plasma frequency being less than κT the energy-loss rate can be obtained as follows:

$$\mathcal{E}_t = 1 \cdot 47 \times 10^{14} \times (\frac{\hbar \omega_p}{m_e c^2})^6 T_8^3 \rho^{-1} \quad erg/gm - sec \tag{2.3}$$

and also

$$\mathcal{E}_l = 5 \cdot 31 \times 10^{18} \times (\frac{\hbar \omega_p}{m_e c^2})^9 T_8 \rho^{-1} \quad erg/gm - sec \tag{2.4}$$

where

$$T_8 = 10^{-8} \times T$$

The process has significant effect in the degenerate core rather than in non-degenerate region.

3. Photo-coulomb neutrino process:

The photo-coulomb neutrino process [8, 9] is another energy generation mechanism which is significantly important in the temperature range $10^8 \sim 10^9$ K. In this process photon breaks up in presence of coulomb field into the neutrino-antineutrino pair. The neutrino emission takes place through a fermionic loop that may consist of electrons as well as quarks. Apparently a divergent integral appears in the expression of the scattering matrix due to the presence of such loop, but such divergency is removed by imposing the gauge invariant criteria. It is to be mentioned that the nucleus involved in this process may not be in rest, but for the sake of the simplicity of calculation this rest frame is chosen, though it violets the generality of this process slightly. The process is considered in electro-weak theory and the energy of the incoming photon is assumed to be low compared to the rest energy of the electron. The scattering cross-section is obtained as [9]

$$\sigma = 2 \cdot 87 \times 10^{-55} \times Z^2 (\frac{E}{m_e c^2})^6 \quad cm^2 \tag{3.1}$$

Of course here we have considered all three type of neutrinos and also we cannot ignore the neutrino mass however small it may be. Note that the diagrams contributing $e^- - W - \nu_e$ effect [9] should be taken into account. The energy-loss rate for this process is calculated as follows:

$$\mathcal{E} = 0 \cdot 99 \times 10^{-9} T_8^{10} \quad erg/gm - sec \tag{3.2}$$

The neutrino luminosity expressed in the unit of solar luminosity becomes significant near the temperature 10^9 °K.

4. Neutrino synchrotron radiation:

So far in our discussion we have not considered the effect of the magnetic field which is inevitable during the contraction of stellar core. In the high magnetic field the relativistic degenerate electron emits neutrino anti-neutrino pair and the process is termed as neutrino synchrotron radiation, in analogy with the ordinary synchrotron radiation i.e. radiation of electromagnetic energy by a magnetically accelerated electron. Large electron energies are found in the degenerate stars having very high central temperatures and densities, such as white dwarves and neutron stars. Some degenerate stars may have very high magnetic fields. Landstreet [10] was the pioneer to study this process. He calculated the neutrino luminosity and discussed the effect of this process in white dwarf and neutron star. Raychaudhuri [4] considered the neutrino synchrotron process in the photon-neutrino weak coupling theory and obtained the neutrino luminosity much greater than that obtained by Landstreet for both white dwarf as well as neutron star. After that lot of works have been carried out on neutrino synchrotron radiation. We [11] developed a new technique to calculate the neutrino luminosity for this process and our study has shown that the neutrino synchrotron radiation has almost no effect in the non-degenerate region; even in the degenerate star, like white dwarf, it has very little effect. The process is important in the neutron star, where the density (10^{15} gm/cc) and the magnetic field (10^{13} G) is very high.

5. discussion

We have studied three important neutrino emission processes and their significance in the later phase of the stellar evolutions.It is clear that all processes may not be effective simultaneously, rather in a specific region a particular process may have a remarkable effect. It can be found from the calculation [6] for a stellar core density of 2×10^6 gm/cc and temperature of $T = 10^9$ K, the energy loss rate due to plasma neutrino process is greater than 3×10^6 ergs/gm-sec; it is almost same as that from pair annihilation process. The plasmon-pair emission rises as the density and plasma frequency increase. Another important process we have taken into account is photo-coulomb neutrino process, which becomes significant near about the temperature 10^9 K. In the non-degenerate core and for small radiation pressure the neutrino luminosity expressed in the unit of solar luminosity for the photo-coulomb neutrino process reaches to $2 \cdot 57$ [9] at the temperature 10^9 K. The energy loss rate for this process rises rapidly with increasing the temperature, but unlike the plasma neutrino process it does not depend on the density. Presence of high magnetic field in the stellar core causes neutrino synchrotron process. This process has significant effect when the density and the magnetic field is very high, in the region where the electrons are extremely relativistic and degenerate.Undoubtedly the process is very much effective in the neutron star [10, 11] i.e. when the temperature and density are extremely high. In the white dwarf star the process has very little effect. For any white dwarf having the temperature less than $5 \cdot 5 \times 10^7$ K and the magnetic field less than 10^{11} G, the luminosity for the neutrino synchrotron radiation is smaller than photon luminosity by a factor 10^3 or more. It is worth noting that we consider all those processes in the electro-weak theory, but the photon-neutrino weak coupling theory [4] showed the neutrino synchrotron process may cause a significant amount of energy loss, even in the white dwarf. It can be predicted that the collective effect of all such neutrino emission processes significantly contribute in the various ranges of temperatures and densities characterizing the later phases of the stellar evolution.

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