Plasma Neutrino Process in Strong Magnetic Field

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Abstract

The decay of magneto-plasma into neutrino anti-neutrino pair has been studied in the framework of the electro-weak interaction theory. The decay rate is calculated and the expression for the energy-loss rate is obtained in the extreme relativistic case. The neutrino luminosity has also been computed for a neutron star. A comparative study between the decay of magneto-plasma and the ordinary plasma neutrino process has been outlined in view of the cooling of highly magnetized star. The effect of this process in the different regions during the late stages of stellar evolution is discussed briefly.

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1 Introduction:

The ordinary plasmon decay into neutrino anti-neutrino pair is widely discussed topic and it is believed to be one of the important mechanisms that is responsible for carrying away the energy from the stellar core. The neutrino emission from isotropic stellar plasma was considered earlier by Adams et al. [1]. After that it was studied by Braaten and Segel [2] to do some modifications in the calculations. It has been shown earlier that the neutrino bremsstrahlung process is affected in presence of super strong magnetic field [3]. In the same way the decay of plasma can occur in presence of magnetized environment. In 1969 Camuto et al. [4, 5] considered the plasma neutrino process in a strong magnetic field. A consistent study of the magnetized plasma neutrino process with the inclusion of axial vector current was carried out by Kennett and Melrose [6]. Here we have performed a brief study
of the plasmon decay with the influence of magnetic field and its possible implications in the stars having high core temperature, density and magnetic field. In this context we have also indicated the possible region where this process might have some effect.

2 Calculation of the decay rate and energy loss rate

The presence of magnetic field produces the anisotropy of plasma for which it is not possible to divide the electromagnetic waves into longitudinal and transverse parts unlike the case of isotropic plasma. In the cold magneto-plasma thermal motion of the particles are neglected since the phase velocity of such wave is much larger than the mean thermal velocity. The refractive index of the cold magneto-plasma is different\[7\] from that of the isotropic plasma.

If we ignore the effect of the magnetic field the refractive index will depend only on the plasma frequency.

The matrix element for this process can be constructed as follows:

\[ M_{fi} = -ie \frac{G_F}{\sqrt{2}} \xi_{\mu} [C_V \Pi^{\mu \rho}(k) + C_A \Pi_A^{\mu \rho}(k)] \pi_{\nu}(q_1) \gamma_\rho(1 - \gamma_5) v_\nu(q_2) \]  

(1)

The term \( \Pi^{\mu \rho}(k) \) present in the matrix element represents the response tensor \[6\] whereas \( \Pi_A^{\mu \rho}(k) \) stands for the same, but associated with axial vector part. The response tensor depends on the magnetic field as well as four momentum of the plasmon. Imposing the gauge invariance restriction one can think that the response tensor takes the form as

\[ \Pi^{\mu \rho}(k) = A(k^\mu k^\rho - g^{\mu \rho} k^2) \]  

(2)

where, \( A = A(H) \).

Similarly we can find the expression for the axial vector part. Now the decay rate is obtained from the following expression.

\[ \tau = \frac{4\pi S}{2\omega} \int \sum |M_{fi}|^2 \frac{N_{q_1} d^3 q_1 N_{q_2} d^3 q_2}{2q_1^3(2\pi)^3 2q_2^3(2\pi)^3} \delta^4(k - q_1 - q_2) \]

\[ = G_F^2 \alpha \frac{k^2}{\omega} |(g_V A + g_A A_5)k^2|^2 \]  

(3)

The term \( |(g_V A + g_A A_5)k^2|^2 \) can be obtained in different approximations. To calculate this term we have used the result of Kennett and Melrose \[6\]. If we consider the relativistic and degenerate plasma the term can be approximated as

\[ |(g_V A + g_A A_5)k^2| \approx \frac{\alpha}{3\pi^4} \left(\frac{H}{H_c}\right)m_e^4 [\ln(\frac{\mu}{m_e})] \]  

(4)
Table 1: Neutrino luminosity for neutron star (ρ = 10^{15} \text{gm/cm}^3, and magnetic field H = 10^{12}, 10^{13}, 10^{14}, 10^{15} \text{G}) due to the decay of plasma in presence and absence of magnetic field respectively in the temperature range $10^{10} - 10^{11}$ K. The bold numbers indicate the former dominates over the later.

| $T_{10}$ | $\log \frac{L}{L_{\odot}}$ |
|----------|----------------------------|
|          | With magnetic field | Without magnetic field |
| $10^{12}$ | $10^{13}$ | $10^{14}$ | $10^{15}$ | $10^{12}$ | $10^{13}$ | $10^{14}$ | $10^{15}$ |
| 1        | 4.06 | 6.07 | 8.07 | 10.07 | 10.12 |
| 2        | 4.97 | 6.97 | 8.97 | 10.97 | 10.57 |
| 3        | 5.50 | 7.50 | 9.50 | 11.50 | 10.61 |
| 4        | 5.87 | 7.87 | 9.87 | 11.87 | 10.57 |
| 5        | 6.16 | 8.16 | 10.16 | 12.16 | 10.51 |
| 6        | 6.40 | 8.40 | 10.40 | 12.40 | 10.46 |
| 7        | 6.60 | 8.60 | 10.60 | 12.60 | 10.40 |
| 8        | 6.78 | 8.78 | 10.78 | 12.78 | 10.35 |
| 9        | 6.93 | 8.93 | 10.93 | 12.93 | 10.30 |
| 10       | 7.07 | 9.07 | 11.07 | 13.07 | 10.25 |

Now from the equations (3) and (4) the decay rate in the extreme relativistic and highly degenerate case is calculated as follows.

$$\tau \approx 2.198 \times 10^{-10} \left(\frac{H}{H_c}\right)^2 \frac{\hbar \omega}{m_e c^2} (1 - \eta^2) \frac{1}{\ln \left(\frac{\mu}{m_e c^2}\right)} \text{sec}^{-1} (5)$$

Here $\eta^*$ represents the refractive index of the plasma that is free from magnetic influence and so clearly it depends on the plasma frequency but not on the magnetic field. Finally we obtain an expression for the energy loss rate as follows:

$$\mathcal{E} \approx 5.74 \times 10^3 \times \left(\frac{H}{H_c}\right)^2 \times T^{3\frac{1}{3}} \left[\ln \rho - 6.672\right] \text{erg/gm - sec} (6)$$

We have computed the neutrino luminosity expressed in the unit of solar luminosity (Table-1) at the fixed density $\rho = 10^{15} \text{gm/cc}$ in the temperature range $10^{10} - 10^{11}$ K and magnetic field $10^{12} - 10^{15}$ G. We have computed the same for the decay of plasma in absence of magnetic field in the same table.

3 Discussion:

Adams et al. [1] pointed out that the energy loss rate due to the radiation of neutrino - anti neutrino pairs by unmagnetized plasmons is very high in the non-relativistic degenerate region, as much as pair annihilation process. Eventually our result would not give any significant contribution here as the magnetic field present here is very low compared to the critical value. The scenario changes drastically when we consider this process in the degenerate extreme relativistic region (e.g. stellar core of a newly born neutron star). From the Table-1
it is quite clear that in the temperature range $10^{10} - 10^{11}$ K the neutrino luminosity for the decay of magneto-plasma is very high. When we compare the effect of magneto-plasma decay with respect to that of unmagnetized plasma, we see in the low magnetic field of the neutron star the later process is much dominating the former, but the first one becomes significant with the increase of magnetic field strength, especially after exceeding the critical value. From Table-1 it is very much clear that the presence of magnetic field will have significant effect in the neutron star when the temperature $\geq 7 \times 10^{11}$ K and magnetic field $\geq 10^{14}$ G. It is worth noting that in case of newly born neutron star having the core temperature more than $10^{11}$ K the magneto-plasma neutrino process could be more effective than ordinary plasma neutrino process, even below the critical magnetic field. Thus the plasma neutrino process in presence of strong magnetic field plays a crucial role to carry away the energy from stars in the later stages of the stellar evolution. It might be one of the very important processes for the cooling of neutron stars and magnetars.

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