Cooling of Neutron Star Including Magnetic Interaction

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In this work we calculate the neutrino mean free path (MFP) and neutrino emissivity with non-Fermi liquid (NFL) corrections of degenerate quark matter. Subsequently the role of these NFL corrections on the cooling of neutron star has been demonstrated. The cooling curve shows moderate enhancement due to this NFL corrections.

Key Words : Quark Matter; Neutron Star; Non-Fermi Liquid; Magnetic Interaction.

Introduction

Understanding the properties of the hot and dense ultrarelativistic plasma has been at the forefront of contemporary research for the past few decades. Such studies are important for the understanding of the properties of the astrophysical objects like neutron stars and pulsars. At the core of neutron stars density may go up to $5 \sim 6$ times the normal nuclear matter density. It would be more appropriate to describe the core of such dense stars as degenerate quark matter which is our main interest in the present paper (Boyanovsky and De Vega, 2001a,b; Pal and Dutt-Mazumder, 2011).

In ideal Fermi liquid calculations, like in degenerate electron matter one considers only the charge-charge or electric interaction and the current-current or magnetic interaction is usually neglected while calculating various physical quantities. This is justified in a regime where the velocity of the fermions (electrons or quarks) are small, as in this kinematic regime the magnetic interaction is suppressed in powers of $(v/c)^2$. The scenario, however, changes for dense plasma where the constituents like electrons or quarks are moving with a velocity close to the velocity of light. In such cases, the magnetic interaction becomes important. Hence, in dealing with dense plasma, one has to retain both electric and magnetic interactions mediated by the exchange of longitudinal and transverse gauge bosons respectively. In fact, the transverse

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interactions, due to its infrared sensitivity, may become more important than its longitudinal counterpart in this kinematic regime. This characteristic behavior has a a non-trivial origin residing in the analytical structure of the Fermion-self energy close to the Fermi surface (Boyanovsky and De Vega, 2001a,b; Pal and Dutt-mazumder, 2011; Schäfer and Schwenzer, 2004; Manuel, 2000; Gerhold *et al.*, 2004; Gerhold and Rebhan, 2005).

In the next section we see the effect of such non-Fermi liquid (NFL) corrections in quantities like neutrino emissivity (ϵ), neutrino mean free path (MFP) and specific heat (C_v). Equipped with these results, we have studied the cooling behavior of the neutron star.

Mean Free Path, Emissivity and Cooling Behavior

The neutrino mean free path is determined by the quark-neutrino interaction via weak processes, which are given by (Schäfer and Schwenzer, 2004)

$$d \to u + e^- + \overline{\nu}_e; \quad u + e^- \to d + \nu_e. \tag{1}$$

Now, the neutrino mean free path is related to the total interaction rate due to neutrino emission averaged over the initial quark spins and summed over the final state phase space and spins. It is given by (Pal and Dutt-Mazumder, 2011; Sarkar *et al.*, 2013)

$$
\begin{aligned}
\frac{1}{l_{mean}(E_\nu, T)} &= \frac{g}{2E_\nu} \int \frac{d^3 p_d}{(2\pi)^3} \frac{1}{2E_d} \int \frac{d^3 p_u}{(2\pi)^3} \frac{1}{2E_u} \int \frac{d^3 p_e}{(2\pi)^3} \frac{1}{2E_e} \\
&\times (2\pi)^4 \delta^4(P_d + P_\nu - P_u - P_e)|M|^2 \\
&\times \{n(p_d)[1 - n(p_u)][1 - n(p_e)] - n(p_u)n(p_e)[1 - n(p_d)]\}.
\end{aligned} \tag{2}
$$

Here, $|M|^2$, the squared invariant amplitude averaged over initial d quark spin and summed over final spins of u quark and electron, is given by (Pal and Dutt-mazumder, 2011; Sarkar *et al.*, 2013)

$$|M|^2 = \frac{1}{2} \sum_{\sigma_u, \sigma_d, \sigma_e} |M_{fi}|^2 = 64 G^2 \cos^2 \theta_c (P_d \cdot P_\nu)(P_u \cdot P_e) \tag{3}$$

The mean free path at leading order in T/μ is reduced to (Pal and Dutt-Mazumder, 2011; Sarkar *et al.*, 2013)

$$\frac{1}{l_{mean}} = \frac{3 C_F \alpha_s}{\pi^4} G^2 \cos^2 \theta_c \, \mu_d \, \mu_u \, \mu_e \, \frac{(E_\nu^2 + \pi^2 T^2)}{(1 + e^{-\beta E_\nu})} \left[1 + \frac{C_F \alpha_s}{3\pi} \ln\left(\frac{m_D}{T}\right)\right]^2. \tag{4}$$

To derive the above Eq. (4) we use the modified dispersion relation (Pal and Dutt-Mazumder, 2011; Sarkar *et al.*, 2013)

$$\frac{dp(\omega)}{d\omega} \simeq \left(1 - \frac{\partial}{\partial \omega} \mathrm{Re}\Sigma(\omega)\right) \frac{E_p(\omega)}{p(\omega)} = \left[1 + \frac{C_F \alpha_s}{3\pi} \ln\left(\frac{m_D}{T}\right)\right] \frac{E_p(\omega)}{p(\omega)} \tag{5}$$

where we denote the single particle energy $E_{u(d)}$ as ω. The one-loop quark self-energy Σ is (Manuel, 2000; Gerhold *et al.*, 2004)

$$\Sigma = \frac{g^2 C_F}{12\pi^2}(\omega - \mu)\ln\left(\frac{m_D}{\omega - \mu}\right) + i\frac{g^2 C_F}{12\pi}|\omega - \mu|. \tag{6}$$

Here m_D represents the Debye mass.

Once the mean free path is known, we can easily calculate the neutrino emissivity (ϵ) by evaluating the integral

$$
\begin{aligned}
\epsilon &= \int \frac{d^3 p_\nu}{(2\pi)^3} \frac{E_\nu}{l_{mean}(-E_\nu, T)} \\
&\approx \frac{457}{630} G^2 \cos^2\theta_c \alpha_s \mu_u \mu_d \mu_e T^6 \left[1 + \frac{C_F \alpha_s}{3\pi}\log\left(\frac{m_D}{T}\right)\right]^2.
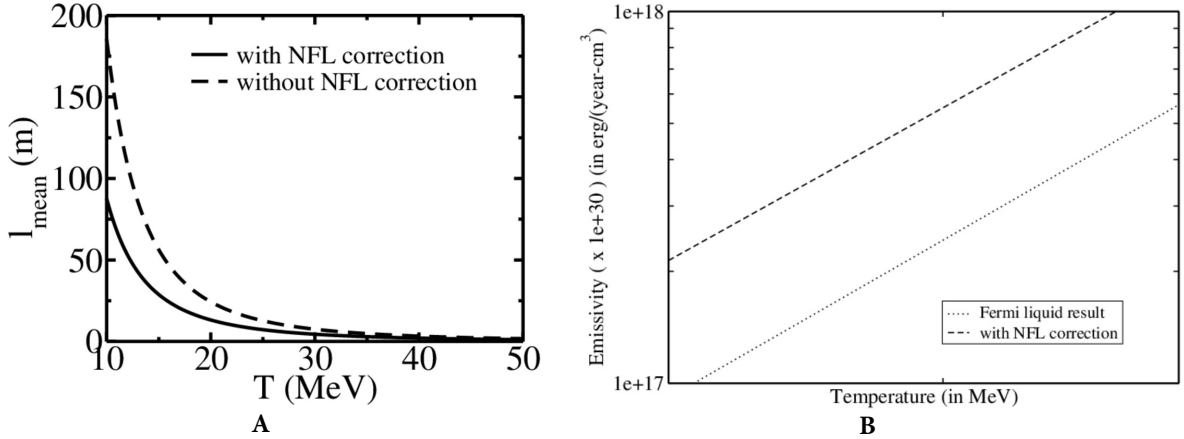\end{aligned} \tag{7}
$$

Fig. 1: Neutrino mean free path (A) and neutrino emissivity (B) of degenerate quark matter

In Fig. 1, we find that the anomalous logarithmic term reduces the value of the mean free path appreciably at low temperature while at higher temperature it tends to merge (Pal and Dutt-Mazumder, 2011). For the emissivity, the anomalous logarithmic terms dominate in the relevant temperature range and exceed the Fermi liquid result considerably (Schäfer and Schwenzer, 2014; Sarkar *et al.*, 2013). This reduced mean free path or enhanced emissivity is expected to influence the cooling of neutron star.

To analyze the cooling of the star the specific heat capacity of the quark matter core needs to be taken into consideration along with the emissivity via the cooling equation (Boyanovsky and De Vega, 2001a,b; Schäfer and Schwenzer, 2004)

$$C_v(T)\frac{dT}{dt} = -\epsilon(T), \tag{8}$$

where C_v is the specific heat at constant volume and baryon number, ϵ is the emissivity, t is time, T is the temperature.
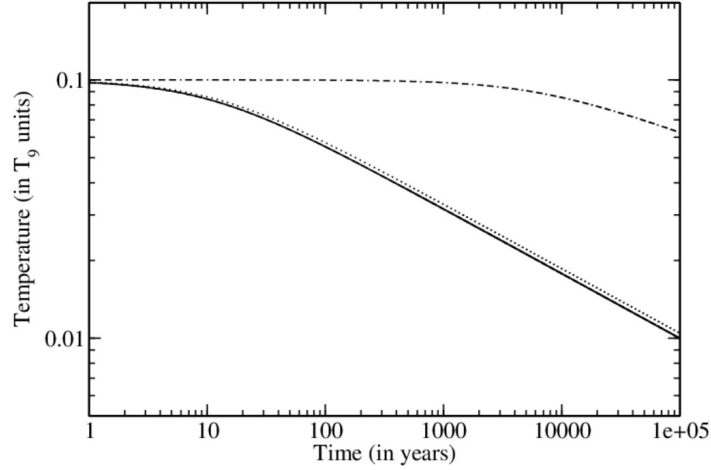

Fig. 2: The cooling behavior of neutron star with core as neutron matter and degenerate quark matter. The dotted line represents the Fermi liquid result, the solid line gives the result including non-Fermi liquid correction. The dash-dotted line represents for purely neutron matter

In Fig. 1A, we note that there is a considerable decrease in MFP of neutrinos due to NFL corrections over the Fermi liquid result. This difference in the MFP between NFL and Fermi liquid corrections also leads to modest increase in the emissivity of the neutrinos for the two cases as displayed in Fig. 1B. This in turn causes the cooling of neutron star to become significantly faster in case of NFL as compared to the Fermi liquid result as shown in Fig. 2 (Schäfer and Schwenzer, 2004; Sarkar *et al.*, 2013).

Summary and Conclusion

In this work, we have calculated the MFP and neutrino emissivity including NFL corrections of degenerate quark matter. It is seen, both the MFP and the emissivity receives logarithmic corrections. Equipped with these results we have examined the cooling behavior of a neutron star.

Acknowledgments

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