Non-Fermi liquid correction to the kick velocity of pulsar

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Introduction

Exploration of the bizarre phenomenon of pulsar kicks i.e. the observed large escape velocities of neutron stars (NS) out of supernova remnants has drawn significant attention in recent years. For the past few years, it has been argued by several authors [1, 2] that assymmetric neutrino emission is responsible for the pulsar kicks during the evolution of the NS. Neutrinos are one of the foremost candidates responsible for the cooling of the NS composed of a normal (non-color superconducting) degenerate quark matter core. The cooling is carried out through the quark direct URCA process,

$$d \to u + e^- + \bar{\nu_e} \quad (1)$$

$$u + e^- \to d + \nu_e \quad (2)$$

For the case of degenerate quark matter core, it has been shown recently [3, 4] that specific heat contains the anomalous leading $T\ln\mathrm{T}^{-1}$ term giving rise to the non-Fermi liquid (NFL) behaviour. It will not be out of context to recall that quantities like emissivity, mean free path of neutrinos too receive such NFL correction in addition to the usual Fermi liquid (FL) behaviour [5, 6].
Motivated with these results, in this paper, we study the NFL behaviour to the kick velocity and compare it with the usual FL case.

Formalism

Anomalous specific heat

The expression of hard dense loop resummed quark self energy upto leading order (LO) has been calculated recently[7, 8] and is given as,

$$\Sigma_+ \simeq -g^2 C_f m\Big\{\frac{\varepsilon}{12\pi^2 m}\Big[\log\Big(\frac{4\sqrt{2}\mathrm{m}}{\pi|\varepsilon|}\Big) +1\Big] + \frac{i|\varepsilon|}{24\pi m}\Big\} \quad (3)$$

where $\varepsilon = \omega - \mu_q$. Thus the analytical expression for the one-loop quark self energy exhibits a logarithmic singularity close to the Fermi surface. Thus the long ranged character of the magnetic interactions spoils the normal Fermi-liquid behavior. Equipped with the above result, it has been calculated in the works of [3, 4] the low-temperature specific heat capacity of the degenerate quark matter. The Fermi liquid contribution (free part) and the LO correction are given as respectively,

$$C_v\Big|_{FL} = \frac{N_c N_f}{3}\mu_q^2 T \quad (4)$$

$$C_v\Big|_{LO} = \frac{N_c N_f}{9\pi}\mu_q^2 C_F \alpha_s T\log\Big(\frac{0.28\mathrm{m}}{\mathrm{T}}\Big) \quad (5)$$

Pulsar acceleration

The amount of pulsar acceleration depends on the polarisation of the electron spin and the momenta. The kick velocity can be written as [2],

$$dv = \frac{\chi}{M_{NS}}\frac{4}{3}\pi R^3 \epsilon dt \quad (6)$$

where ϵ is the neutrino emissivity, R is the radius (emitting quark phase) and M_{NS} is the mass of the neutron star respectively. The fraction of spin polarised electrons is denoted by χ. For the case of vanishing temperature (cold neutron stars) and weak external magnetic field the electron spin polarisation is given as [2],

$$\chi \simeq \frac{3}{2}\frac{m_e^2}{\mu_e^2 - m_e^2}\Big(\frac{B}{B_{cr}}\Big) \quad (7)$$

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where the critical value of magnetic field for electrons is given by $B_{cr} \simeq 4.4 \times 10^{13} Gauss$. Using the cooling equation,

$$C_v dT = -\epsilon dt \tag{8}$$

we obtain the Fermi liquid contribution to the pulsar kick velocity as [2],

$$v\Big|_{FL} \simeq \frac{8.3 N_C N_f}{3}\Big(\frac{\mu_q}{400MeV}\frac{T}{1MeV}\Big)^2 \times\Big(\frac{R}{10km}\Big)^3 \frac{1.4M_\odot}{M_{NS}}\chi\frac{km}{s} \tag{9}$$

Thus using the resummed one loop quark self energy, we obtain the NFL LO contribution to the kick velocity as,

$$v\Big|_{LO} \simeq \frac{16.6 N_C N_f}{3}(C_F\alpha_s)\Big(\frac{\mu_q}{400MeV}\frac{T}{1MeV}\Big)^2 \times\Big(\frac{R}{10km}\Big)^3 \frac{1.4M_\odot}{M_{NS}}\chi\Big[c_1 + c_2 \ln\Big(\frac{g\mu_q\sqrt{N_f}}{T}\Big)\Big]\frac{km}{s} \tag{10}$$

where $C_F = (N_C^2 - 1)/(2N_C)$ and the constants are $c_1 = -0.13807$ and $c_2 = 0.0530516$ respectively.

Now for the case of high magnetic field strengths, we choose the magnetic field strength to be much larger than the temperature, the chemical potential as well as the electron mass ($\mu_e, m_e, T \ll \sqrt{2eB}$). The electron polarisation is given as [2],

$$\chi \sim 1 - \frac{4}{\ln(2)}\sqrt{\frac{\pi T}{2\sqrt{2eB}}}e^{-\sqrt{2eB}/T}. \tag{11}$$

Thus, the pulsar kick velocity is obtained as,

$$v\Big|_{FL} = \frac{2N_C N_f \pi}{9}\Big(\frac{\mu_q^2 R^3}{M_{NS}}\Big)\Big[T^2 - \frac{2^{9/4}}{\ln(2)}\sqrt{\frac{\pi}{\sqrt{eB}}}\int T^{3/2} e^{-\sqrt{2eB}/T} dT\Big] \tag{12}$$

The LO contribution to the pulsar kick velocity is obtained as,

$$v\Big|_{LO} = \frac{4N_C N_f}{27}\Big(\frac{\mu_q^2 R^3}{M_{NS}}\Big)(C_F\alpha_s)\Big[\int T \times \ln\Big(\frac{0.04 g\mu_q\sqrt{N_f}}{T}\Big)dT - \frac{2^{5/4}}{\ln(2)}\sqrt{\frac{\pi}{\sqrt{eB}}} \times \int T^{\frac{3}{2}} \ln\Big(\frac{0.04 g\mu_q\sqrt{N_f}}{T}\Big)e^{-\sqrt{\frac{2eB}{T}}}dT\Big] \tag{13}$$

The above equations can be solved numerically. The net contribution to the pulsar kick velocity is obtained by the sum of the Fermi liquid result and including the non-Fermi liquid correction upto the LO.

Conclusion

We have shown that the pulsar kick velocity receives significant contribution from the logarithmic corrections. We have incorporated results upto logarithmic order to include plasma or quasiparticle effects which are anomalous (NFL) effects. The contribution from electron polarisation for different cases has been taken into account to calculate the velocities. The presence of the logarithmic term considerably enhance the kick velocity of the neutron star.

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