Influence of the photon - neutrino processes on magnetar cooling

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Outline

Introduction

Magnetars are highly interesting objects in the Universe.

Recent observations give ground to believe that some astrophysical objects (SGR and AXP) are magnetars, a distinct class of isolated neutron stars with magnetic field strength of $B \gg B_e$, where

$$B_e = m^2/e \simeq 4.41 \times 10^{13} \text{ G}.$$

The magnetic field in magnetars for the different models may reach the values up to $B \sim 10^{14} - 10^{16}$ G.

However, the upper bound on the magnetic field strength in magnetars is undefined.

Introduction

We will consider the outer crust of young NS. Typically conditions in the outer crust are

$$T \lesssim 2 \text{ MeV}, \rho \lesssim 10^{11} \text{ g/cm}^3.$$

- Such medium is transparent for neutrino.
- Neutrinos play the main role in the NS cooling.

The estimation of the upper bound of magnetar magnetic field via neutrino cooling is the main goal of present talk.

Introduction

Strongly magnetized plasma limit $eB \gg \mu, T$ – the electrons and positrons in plasma occupy the ground Landau level. The more accurate relation for magnetic field and plasma parameters in this case can be written in the following form

$$\frac{B^2}{8\pi} \gg \frac{\pi^2 (n_{e^-} - n_{e^+})^2}{eB} + \frac{eBT^2}{12}.$$

The plasma in the crust of magnetars is degenerate.
$T \ll \mu$.

Introduction

The number of electron density in a strongly magnetized, degenerate plasma can be estimated as

$$n_{e^-} \simeq \frac{m^3}{2\pi^2}\,\frac{\rho_6\, Z}{A}, \quad \rho_6 = \frac{\rho}{10^6 \mathrm{g/cm}^3}\,.$$

The typically parameters in the outer crust of NS are $Z = 26$, $A = 56$ and $T < m$ (D. Yakovlev et al. 2001).
Therefore, the condition

$$\frac{B^2}{8\pi} \gg \frac{\pi^2 n_{e^-}^2}{eB}$$

can be performed up to the density $\rho \sim 10^{10}$ g/cm^3 for the magnetic field strength $B \gtrsim 10^{15}$ G.

Introduction

The main neutrino processes in a magnetar crust are

- Pair annihilation, $e^+e^- \to \nu\bar{\nu}$ and synchrotron mechanism, $e \to e\nu\bar{\nu}$ are negligible in strongly magnetized, degenerate plasma (D. Yakovlev et al. 2001).
- Photoneutrino process, $e\gamma \to e\nu\bar{\nu}$ (N. Itoh et al. 1992 – in the plasma without magnetic field).
- Photon conversion, $\gamma \to \nu\bar{\nu}$ (D. Melrose et al. 1998 – in weak magnetic field, N. Mikheev et al. 1997 – in strong magnetic field without plasma).
- Two photon annihilation, $\gamma\gamma \to \nu\bar{\nu}$ (M. Chistyakov et al. 2005 – in strongly magnetized, degenerate plasma $\mathcal{M} \sim eB$).

Introduction

We will investigate the magnetar cooling via neutrino emissivity (energy carried out by neutrinos from unit volume per unit time) with taking into account of the photon dispersion in strong magnetic field and plasma.

Introduction

Some notations.

The four-vectors with indices $\perp$ and $\|$ belong to the Euclidean $\{1, 2\}$-subspace and the Minkowski $\{0, 3\}$-subspace correspondingly in the frame were the magnetic field is directed along third axis; $(ab)_\perp = (a\Lambda b) = a_\alpha \Lambda_{\alpha\beta} b_\beta$, $(ab)_\| = (a\tilde{\Lambda} b) = a_\alpha \tilde{\Lambda}_{\alpha\beta} b_\beta$. The tensors $\Lambda_{\alpha\beta} = (\varphi\varphi)_{\alpha\beta}$, $\widetilde{\Lambda}_{\alpha\beta} = (\tilde{\varphi}\tilde{\varphi})_{\alpha\beta}$, with equation $\widetilde{\Lambda}_{\alpha\beta} - \Lambda_{\alpha\beta} = g_{\alpha\beta} = diag(1, -1, -1, -1)$ are introduced. $\varphi_{\alpha\beta} = F_{\alpha\beta}/B$ and $\tilde{\varphi}_{\alpha\beta} = \frac{1}{2}\varepsilon_{\alpha\beta\mu\nu}\varphi_{\mu\nu}$ are the dimensionless field tensor and dual field tensor correspondingly.

Photon dispersion in the magnetized medium

The propagation of the electromagnetic radiation in any active medium is convenient to describe in terms of normal modes (eigenmodes). In turn, the polarization and dispersion properties of normal modes are connected with eigenvectors $\varepsilon_\alpha^{(\lambda)}(q)$ and eigenvalues of polarization operator $\mathcal{P}^{(\lambda)}(q)$ correspondingly.

Photon dispersion in the magnetized medium

The dispersion properties of the normal modes are defined from the dispersion equations

$$q^2 - \mathcal{P}^{(\lambda)}(q) = 0 \qquad (\lambda = 1, 2, 3).$$

Their analysis shows that processes with the $\lambda = 2$ – mode and with polarization vector

$$\varepsilon_\alpha^{(2)}(q) = \frac{(q\tilde{\varphi})_\alpha}{\sqrt{q_\parallel^2}}$$

Photon dispersion in the magnetized medium

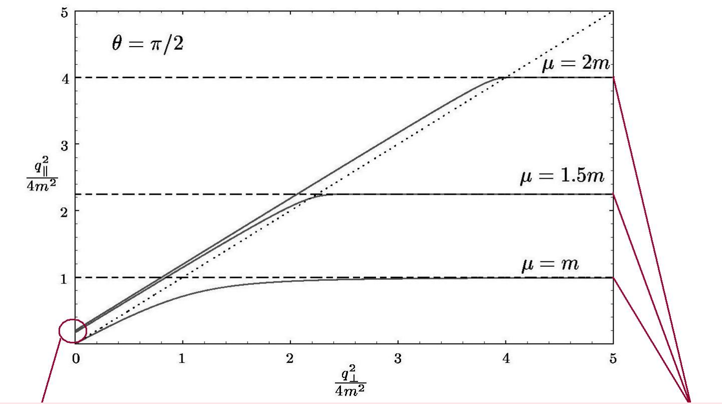
and eigenvalues of polarization operator

$$\mathcal{P}^{(2)}(q) \simeq -\frac{2eB\alpha}{\pi}\left[H\left(\frac{q_{\|}^2}{4m^2}\right) + \mathcal{J}(q_{\|})\right]$$

are provided the leading contribution in the neutrino emissivity. The functions H and $\mathcal{J}$ correspond to magnetized vacuum and magnetized plasma contributions accordingly.

Photon dispersion in the magnetized medium

The dispersion laws of the mode-2 photon for $B = 200 B_e$.



ω_{pl}^2

Pair-creation thresholds

Photon dispersion in the magnetized medium

As can be seen from the Figure, in the degenerate plasma the pair-creation threshold is moved

$$4m^2 \to 4\mu^2$$

under the condition $q_z = 0$ $(\theta = \pi/2)$. In general case the shift of the pair-creation threshold is

$$4m^2 \to 2\left(\mu^2 - p_F q_z + \mu\sqrt{(p_F - q_z)^2 + m^2}\right)$$

under the condition $|q_z| < 2p_F$.

Photon dispersion in the magnetized medium

As can be seen from dispersion law, the situation where mode-2 photon can have a positive value of q^2 in the kinematic region $q_{\parallel}^2 < 4\mu^2$ is possible. It is connected with the appearance of the plasma frequency

$$\omega_{pl}^2 = \frac{2\alpha eB}{\pi}\, v_F.$$

In this region, a channel $\gamma \to \nu\bar{\nu}$ becomes possible. The analysis shows, that the integral over phase space gains its value in the vicinity of the plasma frequency. In this region of the dispersion law for a mode-2 photon can be written as

$$\omega^2 = q_{\perp}^2 + q_z^2 + \omega_{pl}^2.$$

Neutrino emissivity

A general expression for neutrino emissivity can be defined in the following way:

$$Q = \frac{1}{V} \int \prod_i \mathrm{d}\Gamma_i f_i \prod_f \mathrm{d}\Gamma_f (1 \pm f_f)\, q_0 \,\frac{|S_{if}|^2}{\tau},$$

where $\mathrm{d}\Gamma_i$ ($\mathrm{d}\Gamma_f$) are the number of states of initial (final) particles; f_i (f_f) are the corresponding of distribution functions, the sign $+$ $(-)$ corresponds to final bosons (fermions); q_0 is the neutrino pair energy; V is the plasma volume, τ is the interaction time, S_{if} is S - matrix element.

Neutrino emissivity

We will consider the case of relatively low momentum transfers $|q^2| \ll m_W^2$. Under this condition, the weak interaction of neutrinos with electrons can be considered in the local limit by using the effective Lagrangian

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left[\bar{e}\gamma_\alpha (C_V + C_A \gamma_5) e\right] j_\alpha \, ,$$

where $C_V = \pm 1/2 + 2\sin^2\theta_W$, $C_A = \pm 1/2$, $j_\alpha = \bar{\nu}\gamma_\alpha(1+\gamma_5)\nu$ – is the neutrino current.

Photoneutrino process, $\gamma e \longrightarrow e\nu\bar{\nu}$

We consider two cases of nonrelativistic and relativistic plasma. The emissivity due to the photoneutrino process is

$$Q_{\gamma e \to e\nu\bar{\nu}} \simeq \; 1.3 \times 10^{19} \frac{\text{erg}}{\text{cm}^3\ \text{s}} \frac{B}{B_e} \left(\frac{T}{m}\right)^8 \frac{T}{p_F}, \quad \mu \sim m;$$

$$Q_{\gamma e \to e\nu\bar{\nu}} \simeq 5.4 \times 10^{17} \frac{\text{erg}}{\text{cm}^3\ \text{s}} \frac{B}{B_e} \left(\frac{\mu}{m}\right)^5 \left(\frac{T}{\omega_{pl}}\right)^{3/2} \left(\frac{\omega_{pl}}{2\mu} + 1\right) \times$$
$$\times \int\limits_0^1 dx\,(1-x) \frac{(\omega_{pl}/2\mu)^2 - x^2}{1 - \exp\left[-\frac{\mu}{T}(\omega_{pl}/2\mu - x)\right]}, \quad \mu \gg m.$$

Photon conversion, $\gamma \to \nu\bar{\nu}$

The emissivity due to the photon conversion process is

$$Q_{\gamma\to\nu\bar{\nu}} \simeq 10^{21}\,\frac{\text{erg}}{\text{cm}^3\,\text{s}}\left(\frac{T}{m}\right)^9\left(\frac{\omega_{pl}}{T}\right)^4\left[18.7 + 3.3\left(\frac{\omega_{pl}}{T}\right)^2\right], \quad \mu \sim m;$$

$$Q_{\gamma\to\nu\bar{\nu}} \simeq 10^{20}\,\frac{\text{erg}}{\text{cm}^3\,\text{s}}\left(\frac{T}{m}\right)^9\left(\frac{\omega_{pl}}{T}\right)^{15/2}\left[5.5 + 9.0\,\frac{T}{\omega_{pl}}\right]\exp\left(-\frac{\omega_{pl}}{T}\right), \quad \mu \gg m.$$

Two photon annihilation, $\gamma\gamma \to \nu\bar{\nu}$

The emissivity due to the two photon annihilation process is

$$Q_{\gamma\gamma\to\nu\bar{\nu}} \simeq 5.3 \times 10^{19}\, \frac{\text{erg}}{\text{cm}^3\ \text{s}} \left(\frac{\omega_{pl}}{T}\right)^4 \left(\frac{T}{m}\right)^{11}, \quad \mu \sim m\,,$$

$$\begin{aligned} Q_{\gamma\gamma\to\nu\bar{\nu}} \;\simeq\; & 10^{16}\, \frac{\text{erg}}{\text{cm}^3\ \text{s}} \left(\frac{B}{B_e}\right)^2 \left(\frac{T}{m}\right)^7 \left(\frac{\omega_{pl}}{T}\right)^3 \left(\frac{m}{\mu}\right)^6 \times \\ & \times \left[2.5 + 2.0\left(\frac{T}{\omega_{pl}}\right)\right] \exp\left(-\frac{2\omega_{pl}}{T}\right), \quad \mu \gg m\,. \end{aligned}$$

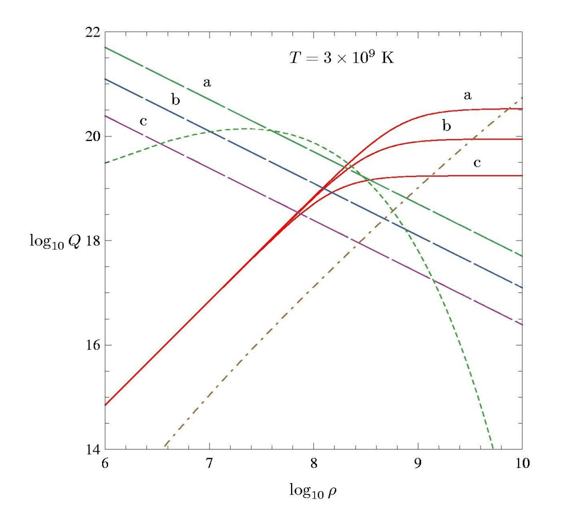
Two photon annihilation, $\gamma\gamma \to \nu\bar{\nu}$

We analyse the $\gamma\gamma \to \nu\bar{\nu}$ process contribution in the neutrino emissivity in the regions of the temperature ($10^8 \lesssim T \lesssim 3 \times 10^9$ K), the density ($10^6 \lesssim \rho \lesssim 10^{10}$ g/cm^3) and the magnetic field strength ($B \lesssim 10^{16}$ G.). The obtaining results show, that the influence of this process on the emissivity is suppressed as compared with the contributions of photoneutrino and photon conversion processes under these conditions. Therefore, the possible influence of process $\gamma\gamma \to \nu\bar{\nu}$ on the magnetar cooling is negligible.

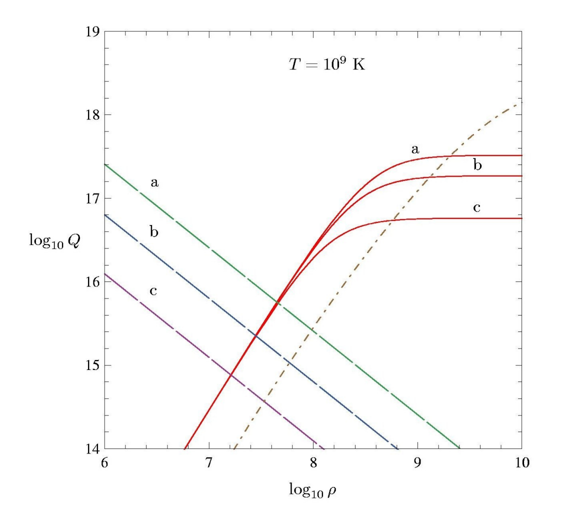
Application to magnetar cooling

We have made the numerical calculation of the neutrino emissivity dependence on the density caused by processes $\gamma e \to e \nu \bar{\nu}$ (dashed line) and $\gamma \to \nu \bar{\nu}$ (solid line). The results are represented in Figures (see below) for different temperatures $T = 3 \times 10^9, 10^9, 3 \times 10^8, 10^8$ K and magnetic field strength a – 10^{16} G., b – 5×10^{15} G., c – 2.2×10^{15} G. The dotted line corresponds to the $e^+ e^-$ pair annihilation process. The chain line corresponds to the plasmon decay process.

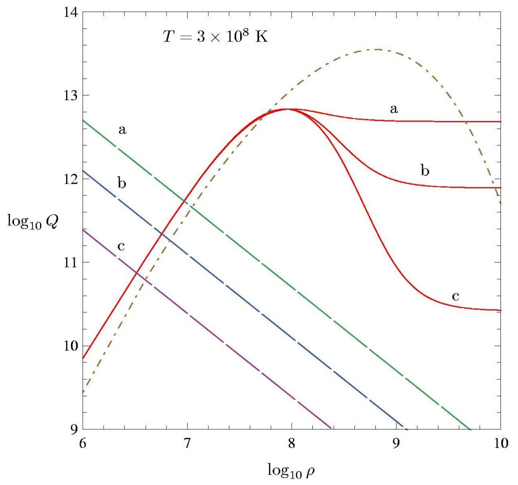
Application to magnetar cooling



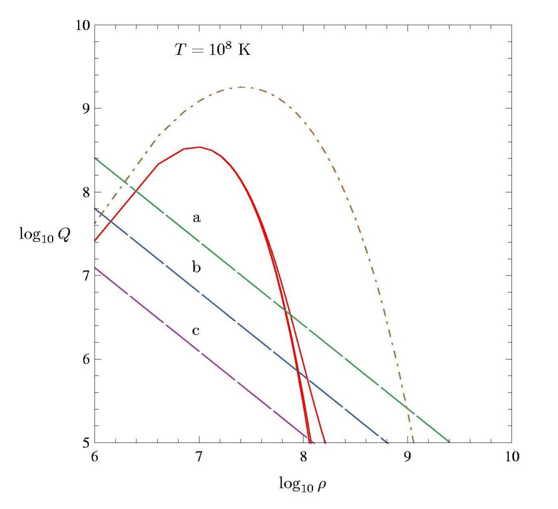
Application to magnetar cooling



Application to magnetar cooling



Application to magnetar cooling



Application to magnetar cooling

As can be seen from fig. the photoneutrino process is provided the leading contribution in the neutrino emissivity in the density region $10^6 \lesssim \rho \lesssim 10^8$ g/cm^3. The photon conversion process are suppressed by plasma frequency in this region.On the other hand, it is provided the main contribution in the neutrino emissivity in the density region $10^8 \lesssim \rho \lesssim 10^{10}$ g/cm^3.

Our results are unsuitable for the density $\rho \gtrsim 10^{10}$ g/cm^3.

Application to magnetar cooling

We will consider the NS cooling model (D. Yakovlev et al. 2001)
The neutrino processes in the NS crust are provided of the neutrino cooling during $10^{-2} \lesssim t \lesssim 100$ years in this model.
The plasmon decay in a weakly magnetized plasma is dominant in this period.
However, in a strongly magnetized plasma both processes $\gamma e \to e \nu \bar{\nu}$ and $\gamma \to \nu \bar{\nu}$ are leading at the temperature $10^9 \lesssim T \lesssim 3 \times 10^9$ K.

Application to magnetar cooling

Let us discuss the possible consequences of our results.

- Assumig, that the temperature profile in the outer crust weakly depends on magnetic field strength.
- Let us assume also that the magnetar cooling regime at the time $t \gtrsim 10^3$ years is the some one as for the ordinary NS.

When we can obtain the upper limit for magnetic field value 5×10^{15} G.

It is rough estimation of magnetic field.

Conclusions

- The influence of a strongly magnetized plasma on the photon-neutrino processes $\gamma e^{\pm} \to e^{\pm}\nu\bar{\nu}$, $\gamma \to \nu\bar{\nu}$ and $\gamma\gamma \to \nu\bar{\nu}$ is considered.

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- The influence of a strongly magnetized plasma on the photon-neutrino processes $\gamma e^{\pm} \to e^{\pm}\nu\bar{\nu}$, $\gamma \to \nu\bar{\nu}$ and $\gamma\gamma \to \nu\bar{\nu}$ is considered.
- The changes of the photon dispersion properties in a magnetized medium are investigated. We have found, that the pair-creation threshold is shifted $4m^2 \to 2\left(\mu^2 - p_F q_z + \mu\sqrt{(p_F - q_z)^2 + m^2}\right)$ in degenerate plasma under the condition $|q_z| < 2p_F$.

Conclusions

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- The changes of the photon dispersion properties in a magnetized medium are investigated. We have found, that the pair-creation threshold is shifted $4m^2 \to 2\left(\mu^2 - p_F q_z + \mu\sqrt{(p_F - q_z)^2 + m^2}\right)$ in degenerate plasma under the condition $|q_z| < 2p_F$.
- We have obtained the simple expressions for neutrino emissivity in the cold plasma limit. These results can be used for the simulation of the magnetar cooling.

Conclusions

- It is shown, that the possible influence of process $\gamma\gamma \to \nu\bar{\nu}$ on the magnetar cooling is negligible in the regions of temperature ($10^8 \lesssim T \lesssim 3 \times 10^9$ K), density ($10^6 \lesssim \rho \lesssim 10^{10}$ g/cm^3) and magnetic field strength ($B \lesssim 10^{16}$ G.).

Conclusions

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- From the possible modification of the magnetar cooling scenario we have obtained the upper bound on the magnetic field strength $B \lesssim 5 \times 10^{15}$ G.