Electromagnetic Processes In Strongly Magnetized Plasma

Michael Chistyakov

Yaroslavl State University, Division of Theoretical Physics

May 28, 2008

International Seminar *"Quarks-2008"*, Sergiev Posad, Moscow Region, May 23-29, 2008

In collaboration with Dmitry Rumyantsev

D. A. Rumyantsev, M. V. Chistyakov, JETP 101 (2005) 635
D. A. Rumyantsev, M. V. Chistyakov, hep-ph/0609192

Outline

Introduction

Critical value of magnetic field

$$B_e = \frac{m_e^2}{e} \simeq 4.41 \cdot 10^{13}\ \text{G}.$$

Magnetars: SGR, AXP.

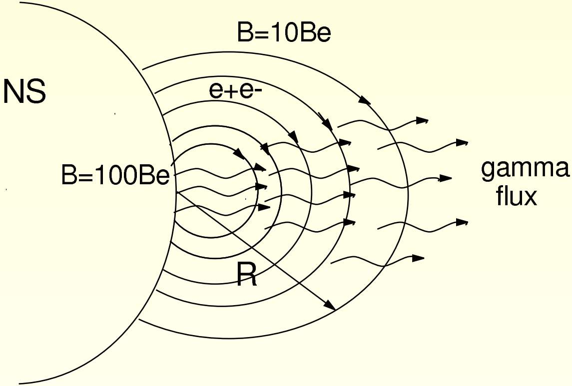
$B \sim 10^{14} \div 10^{15}$ G.

Strongly magnetized plasma

$$\sqrt{eB} \gg m_e, T, \mu$$

$c = \hbar = k = 1$

Introduction



C.Tompson, R.C. Duncan, MNRAS, 1995

Intoduction

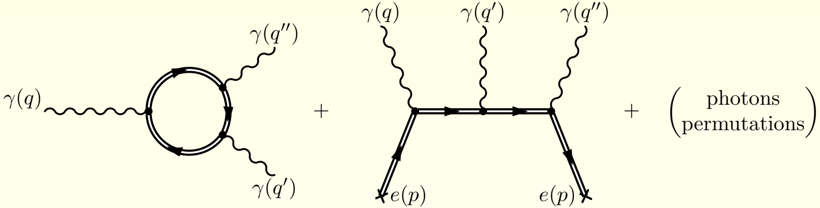
The main processes

- Compton scattering

Intodution

The main processes

- Compton scattering
- Photon splitting and merging



Intodaction

The main goal

To demonstrate that the self-consistent accounting of strong magnetic field and dense plasma influence is nessesary for the correct description of radiation transfer.

Photon dispersion properties...

Are defined by the eigenvectors and eigenvalues of the polarisation operator

$$\mathcal{P}_{\mu\nu}(q)\varepsilon_\nu^{(\lambda)}(q) = \mathcal{P}^{(\lambda)}(q)\varepsilon_\mu^{(\lambda)}(q).$$

Dispersion equations

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

Renormalization

$$\varepsilon_\mu^{(\lambda)} \to \varepsilon_\mu^{(\lambda)}\sqrt{Z_2}, \quad Z_\lambda^{-1} = 1 - \frac{\partial \mathcal{P}^{(\lambda)}(q)}{\partial \omega^2}.$$

Photon dispersion properties...

Polarisation vectors in the case $\mu = 0$

$$\varepsilon_\mu^{(1)} = \frac{(\varphi q)_\mu}{\sqrt{q_\perp^2}}, \quad \varepsilon_\mu^{(2)} = \frac{(\widetilde{\varphi} q)_\mu}{\sqrt{q_\parallel^2}}, \quad \varepsilon_\mu^{(3)} = \frac{q_\parallel^2 (\Lambda q)_\mu - q_\perp^2 (\widetilde{\Lambda} q)_\mu}{\sqrt{-q^2 q_\parallel^2 q_\perp^2}}$$

$\varepsilon_\mu^{(3)}$ - unphysical mode!

Polarisation vectors in the case $\mu \neq 0$

$$\varepsilon_\mu^{(1)}(q) \simeq d_1 \varepsilon_\mu^{(1)} + i d_2 \varepsilon_\mu^{(3)}, \qquad \varepsilon_\mu^{(3)}(q) \simeq d_3 \varepsilon_\mu^{(1)} + i d_4 \varepsilon_\mu^{(3)},$$

$$\varepsilon_\mu^{(2)}(q) \simeq \frac{(\tilde{\varphi} q)_\mu}{\sqrt{q_\parallel^2}}.$$

$\varphi_{\alpha\beta} = F_{\alpha\beta}/B$, $\tilde{\varphi}_{\alpha\beta} = \frac{1}{2}\varepsilon_{\alpha\beta\mu\nu}\varphi_{\mu\nu}$, $(a\varphi b) = a_\alpha \varphi_{\alpha\beta} b_\beta$, $(ab)_\parallel = (a\tilde{\Lambda} b) = (a\tilde{\varphi}\tilde{\varphi} b)$,
$(ab)_\perp = (a\Lambda b) = (a\varphi\varphi b)$.

Photon dispersion properties...

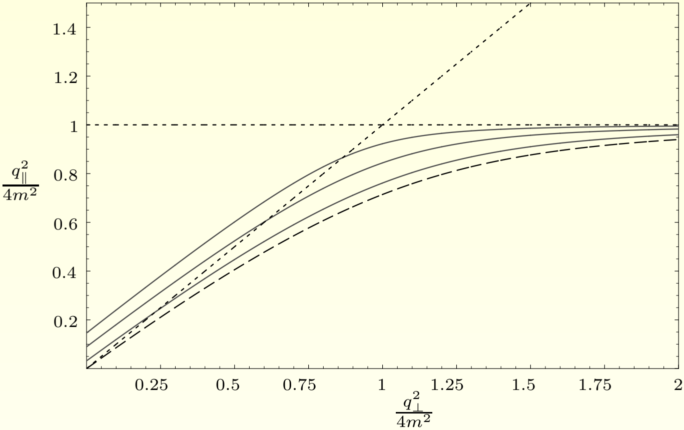


Figure: $B = 200B_e$, $T = 0.25; 0.5; 1MeV$, $\theta = \pi/2$

Photon dispersion properties...

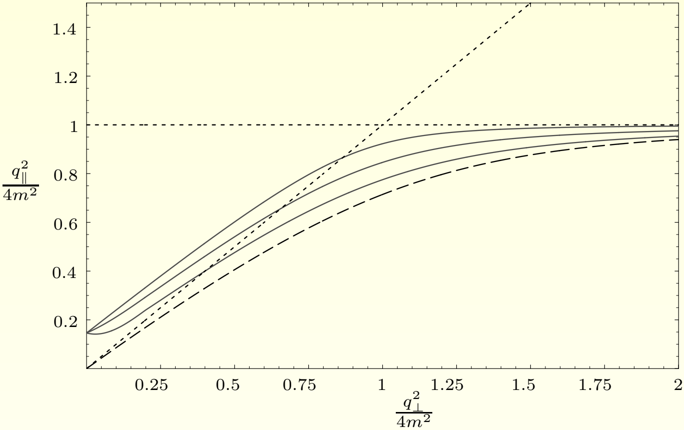


Figure: $B = 200B_e$, $T = 1MeV$, $\theta = \pi/12;\ \pi/6;\ \pi/2$

Photon dispersion properties...

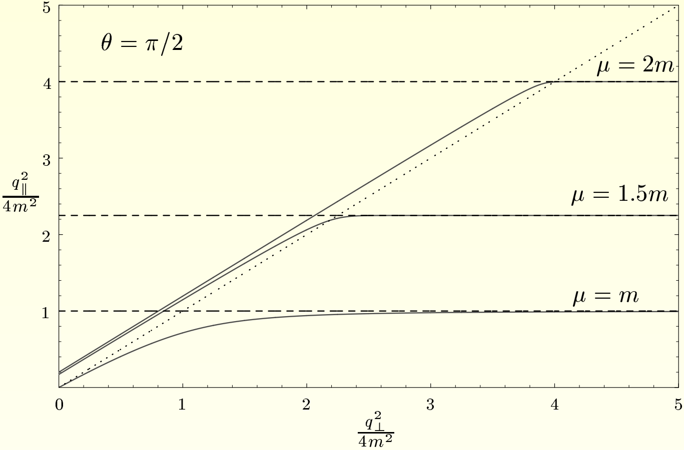


Figure: $B = 200 B_e$

Photon dispersion properties...

Possible channels

- mode 1 (extraordinary photon)
  $\gamma_1 e^\pm \to \gamma_1 e^\pm$, $\gamma_1 e^\pm \to \gamma_2 e^\pm$, $\gamma_1 \to \gamma_1 \gamma_2$,
  $\gamma_1 \to \gamma_2 \gamma_2$, $\gamma_1 \gamma_2 \to \gamma_1$, $\gamma_1 \gamma_1 \to \gamma_2$;
- mode 2 (ordinary photon)
  $\gamma_2 e^\pm \to \gamma_2 e^\pm$, $\gamma_2 e^\pm \to \gamma_1 e^\pm$, $\gamma_2 \to \gamma_1 \gamma_1$,
  $\gamma_2 \gamma_2 \to \gamma_1$, $\gamma_2 \gamma_1 \to \gamma_1$.

Photon dispersion properties...

$$\sigma_{1\to 1} = \frac{3}{4}\,\sigma_T \left(\frac{B_e}{B}\right)^2 \frac{\omega^2}{m^2},$$

$$\sigma_{1\to 2} = \frac{1}{4}\,\sigma_T \left(\frac{B_e}{B}\right)^2 \frac{\omega^2}{m^2},$$

$$\sigma_{2\to 1} = \frac{3}{4}\,\sigma_T \left(\frac{B_e}{B}\right)^2 \frac{(\omega-\omega_{pl})^2}{m^2} u^2\,\Theta(\omega-\omega_{pl}),$$

$$\sigma_{2\to 2} = \sigma_T \left\{(1-u^2) + \left(\frac{B_e}{B}\right)^2 \frac{(\omega-\omega_{pl})^2}{m^2} u^2\right\}\Theta(\omega-\omega_{pl}),$$

Transfer Equation...

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 D_1 \frac{dn_1}{dr}\right) + K_1(\bar{n} - n_1) + S_{12}(n_2 - n_1) = 0,$$

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 D_2 \frac{dn_2}{dr}\right) + K_2(\bar{n} - n_2) + S_{21}(n_1 - n_2) = 0,$$

$$\bar{n} = \frac{\omega^3}{2\pi^2} f_\omega, \qquad f_\omega = [\exp(\omega/T) - 1]^{-1}$$

.

Transfer Equation...

Difusion, absorption and scattering coefficients

$$D_\lambda = \int \frac{d\Omega}{4\pi} \ell_\lambda(\theta, r) \cos^2\theta,$$

$$K_\lambda = \int \frac{d\Omega}{4\pi} \left[W_{\lambda\to\lambda'\lambda''}(\theta, r) + W_{\lambda\lambda'\to\lambda''}(\theta, r)\right],$$

$$S_{\lambda\lambda'} = \int \frac{d\Omega}{4\pi} W_{\lambda\to\lambda'}(\theta, r),$$

$$\ell_\lambda = \left[\sum_{\lambda'=1}^{2} W_{\lambda\to\lambda'} + \sum_{\lambda',\lambda''=1}^{2} \left(W_{\lambda\to\lambda'\lambda''} + W_{\lambda\lambda'\to\lambda''}\right)\right]^{-1}$$

Transfer Equation...

- photon scattering

$$W_{\lambda\to\lambda'} = \frac{eB}{16(2\pi)^4\omega_\lambda}\int \mid \mathcal{M}_{\lambda\to\lambda'} \mid^2 Z_\lambda Z_{\lambda'} \times$$

$$\times f_E\left(1 - f_{E'}\right)\left(1 + f_{\omega'}\right)\delta(\omega_\lambda(\mathbf{k}) + E - \omega_{\lambda'}(\mathbf{k}') - E')\frac{dp_z\, d^3k^{'}}{EE'\omega_{\lambda'}};$$

Transfer Equation...

- photon scattering

$$W_{\lambda\to\lambda'} = \frac{eB}{16(2\pi)^4\omega_\lambda}\int |\mathcal{M}_{\lambda\to\lambda'}|^2 Z_\lambda Z_{\lambda'} \times$$

$$\times f_E\left(1-f_{E'}\right)\left(1+f_{\omega'}\right)\delta(\omega_\lambda(\mathbf{k})+E-\omega_{\lambda'}(\mathbf{k}')-E')\frac{dp_z\, d^3k'}{EE'\omega_{\lambda'}};$$

- photon splitting

$$W_{\lambda\to\lambda'\lambda''} = \frac{1-(1/2)\delta_{\lambda'\lambda''}}{32\pi^2\omega}\int |\mathcal{M}_{\lambda\lambda'\lambda''}|^2 Z_\lambda Z_{\lambda'} Z_{\lambda''} \times$$

$$\times(1+f_{\omega'})(1+f_{\omega''})\delta(\omega_\lambda(\mathbf{k})-\omega_{\lambda'}(\mathbf{k}-\mathbf{k}'')-\omega_{\lambda''}(\mathbf{k}''))\frac{d^3k''}{\omega_{\lambda'}\omega_{\lambda''}},$$

Transfer Equation...

- photon merging

$$W_{\lambda\lambda' \to \lambda''} = \frac{1}{32\pi^2\omega} \int \mid \mathcal{M}_{\lambda\lambda'\lambda''} \mid^2 Z_\lambda Z_{\lambda'} Z_{\lambda''} \times$$

$$\times f_{\omega'}(1 + f_{\omega''})\delta(\omega_\lambda(\mathbf{k}) + \omega_{\lambda'}(\mathbf{k}') - \omega_{\lambda''}(\mathbf{k} + \mathbf{k}^{'}))\frac{d^3k^{'}}{\omega_{\lambda'}\omega_{\lambda''}}.$$

Difusion coefficient...

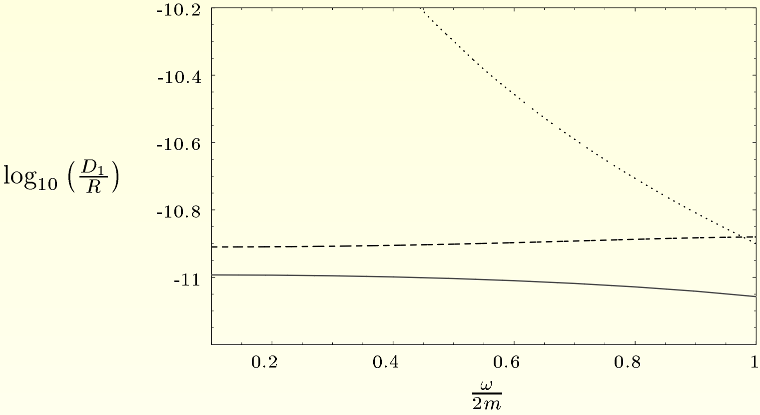


Figure:
$B = 100B_e; 60B_e, \quad T = 1MeV; 0.5MeV, \quad \ell_1^{-1} = n_e\sigma_T(B_e\omega/Bm)^2$

Difusion coefficient...

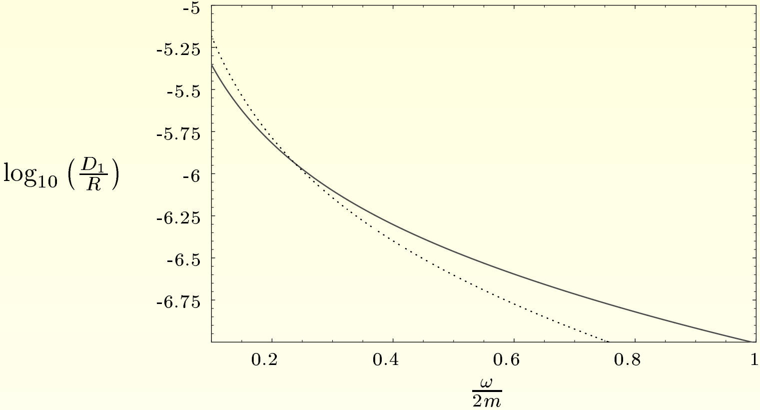


Figure: $B = 10B_e, \quad T = 0.05MeV$
$\ell_1^{-1} = n_e\sigma_T(B_e\omega/Bm)^2 + (\alpha^3 \sin^6\theta/2160\pi^2)(\omega/m)^5 m$

Difusion coefficient...

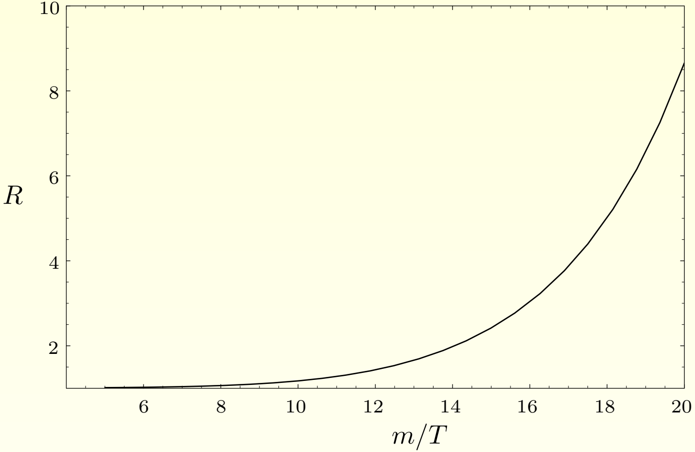


Figure: $B = 200 B_e, \qquad R = D_1^0 / D_1^{splitting}$

Scattering coefficient ...

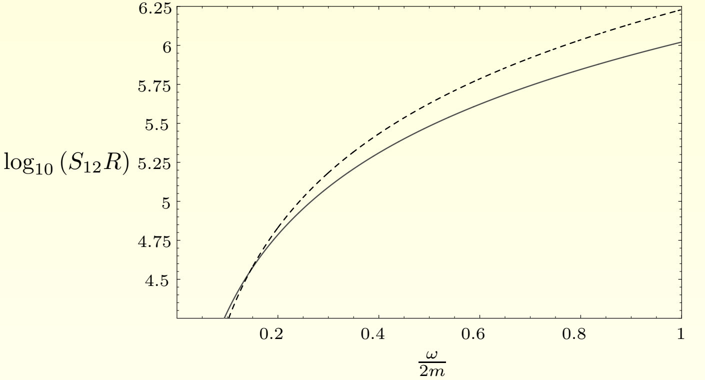


Figure: $B = 10B_e, \quad T = 0.05MeV, \quad \ell_1^{-1} = n_e\sigma_T(B_e\omega/Bm)^2$

Absorption coefficient ...

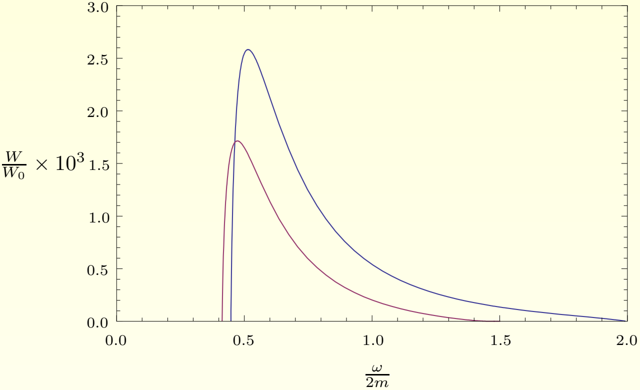


Figure: $\gamma_2 \to \gamma_1 \gamma_1$, $B = 200 B_e$, $\mu = 1.5m; 2m$, $W_0 = (\alpha/\pi)^3 \, m \simeq 3.25 \cdot 10^2 cm^{-1}$.

Absorption coefficient ...

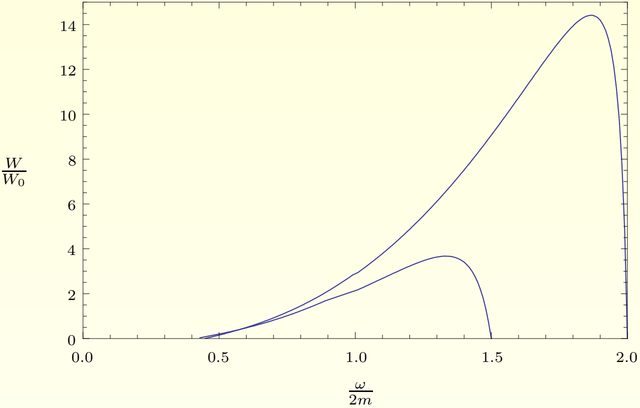


Figure: $\gamma_2 e^{\pm} \to \gamma_1 e^{\pm}$, $B = 200 B_e$, $\mu = 1.5m; 2m$, $W_0 = (\alpha/\pi)^3 \, m \simeq 3.25 \cdot 10^2 cm^{-1}$.

Conclusion

- Photon dispersion and radiative correction in strongly magnetized plasma could essentialy influence on the radiation trensfer process.

Conclusion

- Photon dispersion and radiative correction in strongly magnetized plasma could essentialy influence on the radiation trensfer process.
- In charge symmentric plasma ($\mu = 0$) it is nessesary to take into account the processes of photon splitting and photon merging.

Conclusion

- Photon dispersion and radiative correction in strongly magnetized plasma could essentialy influence on the radiation trensfer process.
- In charge symmentric plasma ($\mu = 0$) it is nessesary to take into account the processes of photon splitting and photon merging.
- In strongly degenerate plasma the influence of the photom splitting and photon merging processes on radiation transfer is negligibly small.