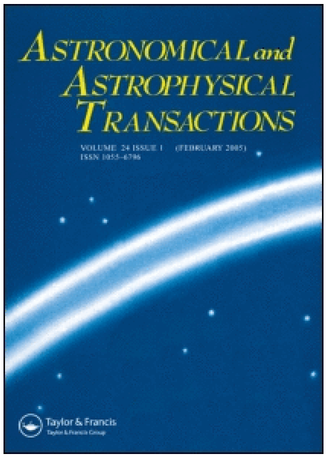

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QUANTUM CYCLOTRON EMISSION OF MOVING PLASMAS

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The effect of plasma motion along a magnetic field on the quantum cyclotron emission is investigated. The thresholds $\omega_c(\nu, n)$ do not depend on the plasma γ-factor. The motion of the thermal plasma affects only the amplitudes of quantum fine structure peaks. For the emissivity of a plasma with a strong "transverse" temperature anisotropy, the fine structure components are centered at frequencies $\omega_e(\nu, n)$ shifted by the motion. Quantum relativistic oscillations can be observed under the angles ϑ (with respect to $\vec{B}$) if they are pronounced under the corresponding angles ϑ' in the plasma rest-frame. For the relativistic motion, the strongest oscillations for $\vartheta' = \pi/2$ can be observed at $\vartheta \simeq 1/\gamma \ll 1$, and the emissivity spectra can sharply vary in a narrow range $0 < \vartheta < 1/\gamma$.

KEY WORDS Cyclotron radiation, neutron stars.

1. INTRODUCTION

In the emission regions of neutron stars, plasma can move along magnetic field either toward the stellar surface (due to accretion) or outward (e.g., under the action of radiative pressure—see Mitrofanov and Pavlov, 1981). Relativistic plasma motion affects strongly the cyclotron radiation. For investigating this effect, one can calculate the absorption coefficients $\mu_{1,2}$ and emissivities $j_{1,2}$ from Eqs. (1) and (2) of Bezchastnov and Pavlov (this volume, hereafter Paper I) for suitable particle distribution in the observer's rest-frame. However, it is easier to deal with the distribution function $f_n(p_z)$ in the plasma rest frame and perform appropriate Lorentz transformations of equations of Paper I.

2. BASIC EQUATIONS

Let the plasma rest-frame K' move with respect to the lab frame K at velocity $\vec{v}$ along the magnetic field $\vec{B}$. Then the relationships between frequencies ω and ω' and angles ϑ and ϑ' in these frames are (e.g., Landau and Lifshitz, 1971)

$$\omega' = \gamma(1 - \beta \cos\vartheta)\omega, \qquad \cos\vartheta' = \frac{\cos\vartheta - \beta}{1 - \beta\cos\vartheta}, \qquad \sin\vartheta' = \frac{\sin\vartheta}{\gamma(1 - \beta\cos\vartheta)}, \quad (1)$$

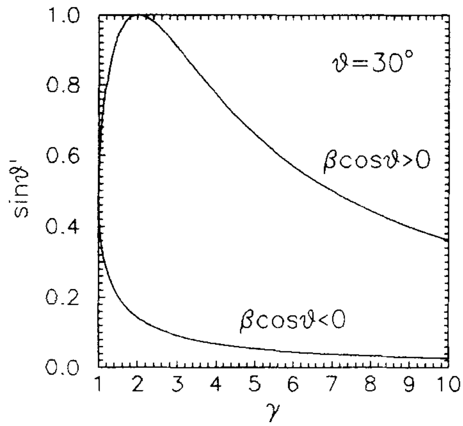

Figure 1 The dependence of $\sin\vartheta'$ on the γ-factor for two directions of the plasma motion along the magnetic field.

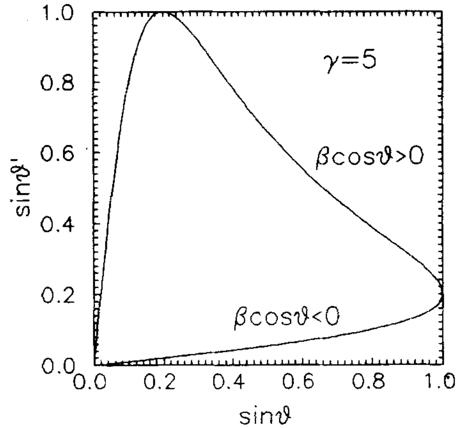

Figure 2 The dependence of $\sin\vartheta'$ on $\sin\vartheta$ for a given γ-factor for two directions of the plasma motion along magnetic field.

where $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$. According to (1), $\omega'\sin\vartheta' = \omega\sin\vartheta$. This reflects the Lorentz invariance of the transverse (to $\vec{B}$) wave vector component $q_\perp = \omega\sin\vartheta$ and yields the invariance of kinematic spectral and angular thresholds $\omega_{c,p}(\nu, n) = (\varepsilon_{n'0} \mp \varepsilon_{n0})/\sin\vartheta$ and $s_{c,p}(\nu, n) = (\varepsilon_{n'0} \mp \varepsilon_{n0})/\omega$, respectively. The transformation law for $j/N = \mathrm{d}\mathscr{E}/\mathrm{d}t/\mathrm{d}\Omega/\mathrm{d}o$ [erg/s/KeV/sr] is

$$\frac{j'}{N'} = \frac{\mathrm{d}\mathscr{E}'}{\mathrm{d}\Omega'}\frac{1}{\mathrm{d}t'}\frac{1}{\mathrm{d}o'} = \frac{\mathrm{d}\mathscr{E}}{\mathrm{d}\Omega}\frac{\gamma}{\mathrm{d}t}\frac{\gamma^2(1-\beta\cos\vartheta)^2}{\mathrm{d}o} = \gamma^3(1-\beta\cos\vartheta)^2\frac{j}{N}. \tag{2}$$

Thus, one can transform the spectral emissivity (2) of Paper I as

$$j_{1,2} = \frac{amc^2 b\omega}{2\gamma\sin^2\vartheta}\sum_{\nu=\nu_{\min}}^{\infty}\sum_{n=0}^{n_{\max}}\frac{D_{1,2}}{\sqrt{(\omega_c^2-\omega^2)(\omega_p^2-\omega^2)}}\sum_{\lambda=1,2} f_{n+\nu}(p_{z\lambda}^*), \tag{3}$$

where $p_{z\lambda}^* = (h_\nu + q_\perp)\cot\vartheta' - (-1)^\lambda\sqrt{h_\nu^2 - \varepsilon_{n0}^2}\operatorname{cosec}\vartheta'$, while h_ν, D_1, D_2, $\nu_{\min}$ and $n_{\max}$ are still given by equations of Paper I due to the invariance of $q_\perp$. To explain the spectra obtained from (3), Figures 1 and 2 show the dependences of $\sin\vartheta'$ on γ and $\sin\vartheta$, respectively, as determined from (1).

3. THERMAL PLASMAS

At given ϑ, the positions of fine structure components associated with kinematic singularities are independent of γ (Figure 3). However, the motion affects the quantum peak amplitudes (restricted by the natural widths obtained from Eq. (45) of Bezchastnov and Pavlov, 1991, by the replacement of ϑ by ϑ') and the spectral shapes. When the plasma moves "from the observer" ($\beta\cos\vartheta < 0$), $\sin\vartheta'$ rapidly decreases with increasing γ (Figure 1). For instance, at $\gamma = 1.5$ the observation angle $\vartheta = 30°$ corresponds to $\vartheta' = 11.5°$ ($\sin\vartheta' \simeq 0.2$) when the threshold peaks at energies $\omega_c(\nu, n)$ are strongly suppressed by a poor temperature population of corresponding resonant electron states with $p_{z\lambda}^* = \varepsilon_{n'0}\cot\vartheta'$.

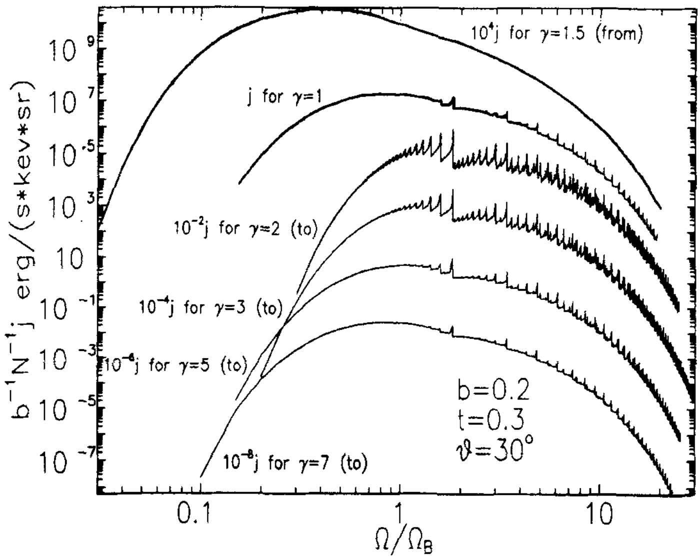

Figure 3 The emissivity spectra of a thermal plasma, moving along the magnetic field, for different γ-factors and directions of motion.

The spectrum is generally red-shifted as compared to that for $\gamma = 1$. When the plasma moves "to the observer" ($\beta \cos\vartheta > 0$), $\sin\vartheta'$ passes through the maximum $\sin\vartheta' = 1$ which corresponds to $\gamma = 1/\sin\vartheta$. Therefore, at $\gamma = 2$, the cyclotron emission spectrum for $\vartheta = 30°$ corresponds to the case of transverse propagation in the plasma rest-frame, when the threshold peaks are the strongest. With further increase of the γ-factor, $\sin\vartheta'$ decreases ($\gamma = 3$, 5 and 7 at $\vartheta = 30°$ correspond to $\vartheta' \simeq 66.5°$, $\simeq 41.3°$ and $= 30°$, respectively) and the quantum peaks become less pronounced. Besides, the emission is suppressed at high frequencies and amplified at low ones (suffering the total suppression by a factor of $1/\gamma$). Notice that all frequency and angle dependent quantities in Eq. (2) of Paper I, except for the resonant particle momenta, are invariant with respect to the Lorentz transformations (1). Since $p_{z\lambda}$ is determined by both angles, ϑ and ϑ', the shapes of the cyclotron emission spectra in the frames K and K' are different. However, at $\beta\cos\vartheta > 0$ one has $\gamma = \gamma_* = (1+\cos^2\vartheta)/\sin^2\vartheta$, for which $\vartheta + \vartheta' = \pi$. For $\vartheta = 30°$, we get $\gamma_* = 7$, and since $f_n(p_z) = f_n(-p_z)$, the spectral shape for $\gamma = \gamma_*$ coincides with that for $\gamma = 1$ (see Figure 3).

4. PLASMA WITH ANISOTROPIC TEMPERATURE

Consider a plasma with the distribution function

$$f_n(p_z) = \frac{N\tanh(b/2t_\perp)}{\pi b\sqrt{2\pi t_\parallel}} \exp\left(-\frac{nb}{t_\perp} - \frac{p_z^2}{2t_\parallel}\right),$$

where $t_\perp = T_\perp/mc^2$ and $t_\parallel = T_\parallel/mc^2$ are the dimensionless transverse and longitudinal temperatures, respectively. If

$$\max(2\sqrt{2t_\parallel}\,|\cos\vartheta'|,\, t_\parallel) \lesssim b \lesssim t_\perp, \tag{4}$$

then quantum spectral features arise due to the radiative transitions from the states with $p_z = 0$ in the plasma rest frame (Bezchastnov and Pavlov, 1991). The peaks corresponding to the transitions $n' = n + \nu \rightarrow n$ are centered at the frequencies

$$\omega_e'(\nu, n) = \frac{2\nu b}{\sqrt{\varepsilon_{n0}^2 + 2\nu b} + \sqrt{\varepsilon_{n0}^2 + 2\nu b \cos^2 \vartheta'}}, \tag{5}$$

while the line widths (at $2\nu b \ll 1$) are estimated as

$$\gamma_e'(\nu, n) \simeq \nu b \max(\sqrt{2t_\parallel}\varepsilon_{n0}^{-2} |\cos \vartheta'|, 0.5 t_\parallel \varepsilon_{n0}^{-3}). \tag{6}$$

The inequality (4) describes the situation when many Landau levels are populated in a narrow range of p_z. Then many transitions are involved in the spectra, while the distances between adjacent peaks exceed their widths.

For a plasma motion along $\vec{B}$, one can see that the transformation $\omega_e(\nu, n) = (\cos \vartheta'/\sin \vartheta)\omega_e'(\nu, n)$ does not reduce to the replacement of ϑ by ϑ' in (5). Contrary to the thresholds $\omega_c(\nu, n)$, the frequencies $\omega_e(\nu, n)$ are not invariant. Since the transformation of line widths is the same, $\gamma_e(\nu, n) = (\sin \vartheta'/\sin \vartheta)\gamma_e'(\nu, n)$, the condition at which the lines are pronounced in the emission spectra does not depend on $\sin \vartheta'/\sin \vartheta$. Therefore, quantum relativistic oscillations can be observed in the cyclotron emission spectra of a moving plasma under angle ϑ if only they appear in the rest frame under the corresponding angle ϑ', i.e., if condition (4) is fulfilled.

Figure 4 shows the cyclotron emission spectra for $\vartheta = 30°$ and different motion directions at different γ. At $\gamma = 1$ the longitudinal Doppler widths are somewhat smaller than the distances between the lines only for some transitions involving low Landau levels in the first and second cyclotron harmonics. In this case

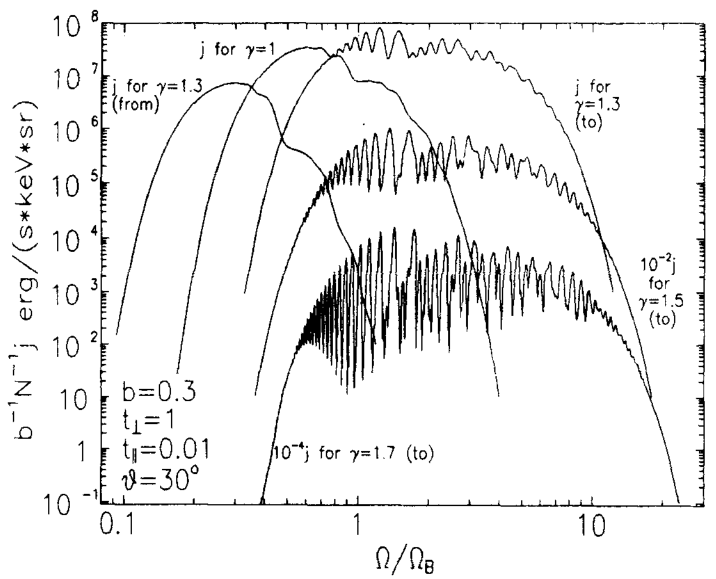

Figure 4 Same as in Figure 3, for a plasma with anisotropic temperature.

quantum relativistic oscillations of the emission spectrum are not very pronounced. For a motion "from the observer" with $\gamma = 1.3$ at $\vartheta = 30°$, all the emission lines are strongly red-shifted ($\omega_e/\omega_e' \simeq 0.5$), so that the whole spectrum is shifted. Besides, the left inequality (4) becomes less strict ($\vartheta' < \vartheta$) than at $\gamma = 1$, and the oscillations almost disappear. For a motion "to the observer", the increase of γ (as long as $\gamma < 1/\sin\vartheta$) leads to the increase of $\sin\vartheta'$ and produces a blueshift of the lines ($\omega_e/\omega_e' \simeq 1.72$, 1.88 and 1.96 for $\gamma = 1.3$, 1.5 and 1.7, respectively), making the oscillations more pronounced. The maximum blueshift is realized at $\gamma = 1/\sin\vartheta$, when the frequencies $\omega_e(\nu, n)$ approach the kinematic thresholds $\omega_c(\nu, n)$ and the line broadening is determined by the transverse Doppler effect only (the corresponding spectrum for $\gamma = 2$ at $\vartheta = 30°$ is not presented because of too many quantum oscillations). Note that smaller ϑ

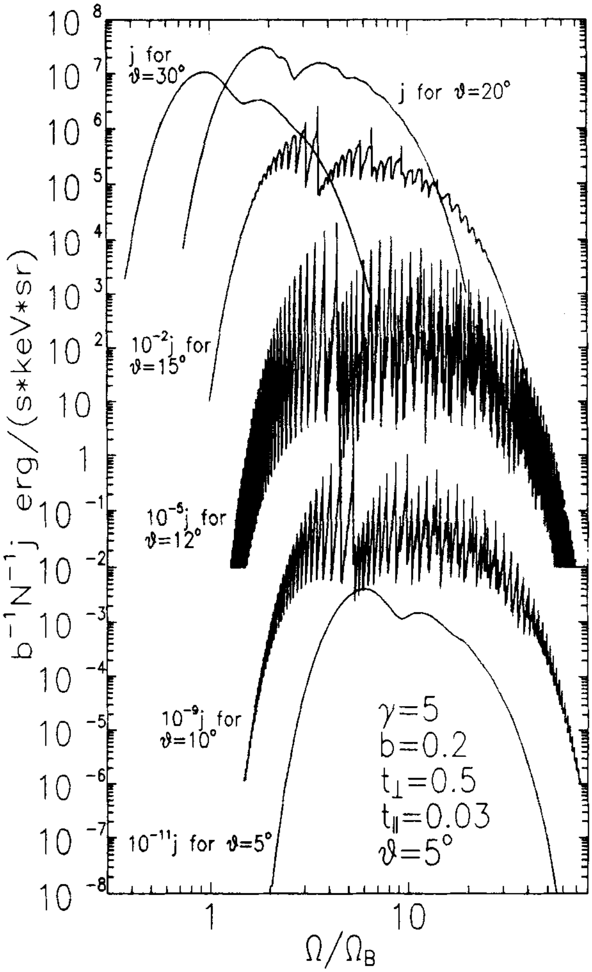

Figure 5 The cyclotron emission spectra of the plasma with anisotropic temperature moving at relativistic velocity along magnetic field lines "to the observer" for different angles ϑ.

correspond to larger line blueshift which can be reached due to relativistic plasma motion. However, if $\vartheta = \pi/2$, the lines can be red-shifted only, independently of the motion direction. Further increase of γ will lead to decreasing $\sin\vartheta'$ (Figure 1), red-shifting the lines (at $\gamma = \gamma_*$ their profiles are not changed by motion) and smoothing the oscillations.

Now consider the spectra for different ϑ. When the plasma moves "from the observer" and $\sin\vartheta$ changes from 0 to 1, $\sin\vartheta'$ varies smoothly from 0 to $1/\gamma$ (Figure 2). Then, even at not very small γ, all possible ϑ correspond to small ϑ', where condition (4) is most stringent. If the plasma moves "to the observer" and ϑ varies from 0 to $\pi/2$, then $\sin\vartheta'$ passes through the maximum, $\sin\vartheta' = 1$, which corresponds to $\sin\vartheta = 1/\gamma$ ($\cos\vartheta = \beta$), and, afterwards, approaches the value $1/\gamma$ at $\sin\vartheta = 1$. If $\gamma \gg 1$, the range of ϑ, for which ϑ' changes from 0 to $\pi/2$, becomes very narrow, $0 < \vartheta < 1/\gamma$. In this case small changes of ϑ can lead to sharp changes of the emission spectra. For illustration, we have calculated the emissivity for $b = 0.2$, $t_\perp = 0.2$, $t_\parallel = 0.03$, $\gamma = 5$ and six angles of observation (Figure 5). For $\vartheta = 5°$, the spectrum is smooth (the longitudinal Doppler width exceeds the distances between neighboring peaks in the plasma rest frame). However, for $\vartheta = 10°$, a great number of quantum cyclotron lines appear. When $\vartheta = 12°$, we have $\vartheta' \simeq \pi/2$. Then the oscillations are most pronounced and the line maxima coincide with the kinematic thresholds $\omega_c(\nu, n)$. Further increase of ϑ leads to decreasing $\sin\vartheta'$, to red-shifting the line centers $\omega_e(\nu, n)$ and the thresholds $\omega_c(\nu, n)$ (the thresholds are shifted stronger) and to smoothing the oscillations. For $\vartheta = 15°$, the temperature anisotropy still causes pronounced spectral oscillations. Then quantum singularities (restricted by the natural widths) associated with transitions on the ground and the first exited Landau levels in the harmonics $\nu = 1$, 2, 3 and 4 are visible in the emission lines. The oscillations become very weak for $\vartheta = 20°$ and completely disappear for $\vartheta = 30°$. Besides, the radiation of particles moving along $\vec{B}$ concentrates within a cone for which $\vartheta \lesssim 1/\gamma$. Thus, the frequency-integrated emissivity is suppressed at $\vartheta \gtrsim 1/\gamma$. Our consideration shows that cyclotron emission spectra for the plasma with approperiate anisotropy of the distribution function can sharply vary in a narrow range of ϑ, $0 < \vartheta < 1/\gamma$. In principle, this effect can be responsible for rapid spectral variations of gamma-ray sources (see, e.g., Mazets *et al.*, 1981, Mitrofanov *et al.*, 1989), if their spectra are associated with radiation of relativistic plasma clouds in the magnetic fields of a rotating neutron star.

5. CONCLUSIONS

We have analyzed quantum relativistic features of cyclotron radiation from a moving plasma for the particle distribution functions of two types. Although the thermal particle distribution is rather traditional and is widely used in the literature, it is hardly likely that the emitting particles are in thermal equilibrium under realistic conditions. For instance, the radiation of gamma-ray bursters seems to be essentially non-thermal. Plasma with anisotropic temperature gives a simple example of non-equilibrium distribution, which can lead to the fine spectral structure and to strong spectral variability in the case of relativistic plasma motion. A strong "transverse" anisotropy required for these effects may arise due to the plasma accretion onto magnetic poles of a neutron star (Gnedin *et al.*, 1981) or due to one-photon creation of e^-e^+-pairs in superstrong magnetic fields (Beskin, 1982). It would be desirable to study quantum relativistic effects in cyclotron radiation for other, more realistic distributions. One can expect to find a spectral fine structure and angular oscillations for a wide class of distributions if the magnetic field is sufficiently close to B_c and the non-equidistance of the Landau levels is significant. Direct observations of the fine quantum features in the cyclotron radiation of neutron stars would give important information about the strength, direction and inhomogeneity of the magnetic field, the size of the radiating region, and the distribution function of radiating particles.

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