TRANSITION RADIATION OF THE ELECTRON ROTATING IN THE DIFFUSE PLASMA BOUNDARY

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The diffuse boundary model is suggested to describe the transition radiation of relativistic electrons drifting through the interplanetary shock. The detailed description of the solution for electrons moving along the circular orbit is presented. Maximum of the transition radiation spectrum calculated for one electron rotating in the diffuse plasma boundary lies in the same frequency range as the electromagnetic emission detected by satellites' devices. This result justifies the assumption of the possible contribution of relativistic electrons transition radiation to the observed radiation.

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1. INTRODUCTION AND MODEL

CLUSTER and WIND satellites performed in situ measurements of strong electromagnetic emission at the frequency $\sim(1.4\ldots1.6)f_{pe}$ [1] in the vicinity of interplanetary quasi-perpendicular shock crossing on 22 January, 2004. The increased density of relativistic electrons ($E \sim 300$keV) was detected simultaneously in the same region. The authors of [1] suggested the transition radiation to be a possible mechanism of the electromagnetic waves' generation. The interplanetary shock of January 22, 2004 event [2] was quasi-perpendicular and supercritical with Mach number $M_A \sim 5.6$; the shock ramp width could be resolved down to 150 km; ratios of downstream to upstream magnetic field and density values were about 3.8.

Relativistic electrons' trajectories in the vicinity of the shock front are driven by constant component of the magnetic field, i.e. cyclotron rotation (Fig.1.), gradient drift with the velocity $\sim(2\ldots3)\times10^4$ km/s and $E\times B$-drift with solar wind velocity. These drift velocities are significantly smaller than full electron velocity $\sim(0.5\ldots0.8)c$, where c is the velocity of light.

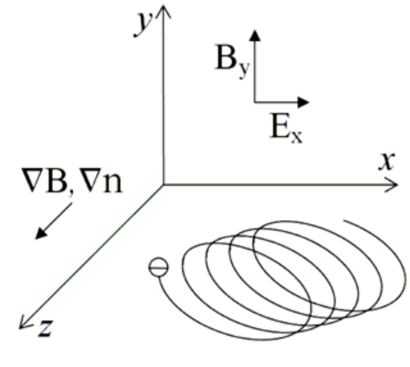

Fig.1. Electron drifting inside the interplanetary shock region (schematic plot)

In the measurements [1] electron Larmor radius R_L was about hundreds of kilometres and the length of the formation zone of the transition radiation [3] was about few tens of kilometres. The cyclotron frequency of the electron rotation ω_c was several orders smaller than the local electron plasma frequency ω_p, which in turn was few times smaller than the electromagnetic emission frequency ω. In this case the magnetic field influence on the dielectric permittivity can be neglected and the role of the magnetic field consists only in the formation of the curvilinear trajectories of electrons. Thus, we come to the model of electron having quite complicated trajectory in the weakly inhomogeneous isotropic plasma. The velocity of the guiding centre is much smaller than the velocity of electron cyclotron rotation. Therefore we considered the model of relativistic electron rotating around motionless centre inside inhomogeneity region neglecting the magnetic field influence on dielectric permittivity (Fig.2) [3].

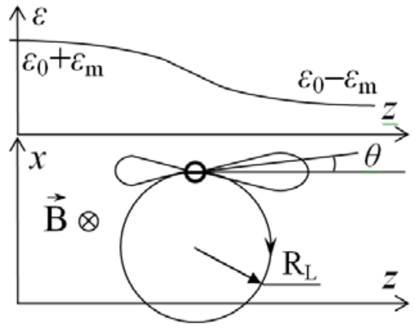

Fig.2. Model of the electron rotating in diffuse plasma boundary (schematic plot)

The most intense electromagnetic radiation was observed in close vicinity of the shock ramp, where plasma density changed abruptly from about 10 cm^{-3} to 22 cm^{-3}. It corresponds to variation of dielectric permittivity from 0.64 to 0.84 for the frequency of the detected waves. The relative difference between dielectric permittivities before and after the shock is quite small, therefore the dielectric permittivity dependence along 0z axis can be considered as a sum of the constant part and small variable part $\varepsilon(z) = \varepsilon_0 - (\varepsilon_m/2)\tanh(z/L)$, where L is the inhomogeneity region spatial scale [3] (see Fig.2). The amplitude ε_m is much smaller then ε_0 and wave equation can be solved using successive approximations method over the small parameter $\varepsilon_m/\varepsilon_0$.

2. TRANSITION RADIATION CALCULATION

In the considered model the relativistic electron is rotating. It is advisable to expand this electron current into plane waves, solve Maxwell equations for one plane wave, and then summing the contribution of every plane wave gives the required transition radiation [3-4]. Assuming that the electron orbit is situated in the $x0z$ plane and expanding the current into Fourier series by time and then Fourier integral by coordinates, the full current density can be expressed as follows:

$$j_x\left(\vec{k},t\right)=iC\sum_{n=-\infty}^{n=\infty}e^{in\omega_c t}B_{nx}(k_x,\kappa),$$
$$j_z\left(\vec{k},t\right)=C\sum_{n=-\infty}^{n=\infty}e^{in\omega_c t}B_{nz}(k_x,\kappa), \quad (1)$$

where coefficients C and $B_{\mathrm{nx,nz}}$ are given by expressions:

$$C=v_e e/(2(2\pi)^3);$$
$$B_{nx,nz}=J_{n-1}\left(R_L\sqrt{k_x^2+\kappa^2}\right)\exp(i(n-1)\arctan(k_x/\kappa))\mp$$
$$\mp J_{n+1}\left(R_L\sqrt{k_x^2+\kappa^2}\right)\exp(i(n+1)\arctan(k_x/\kappa)),$$

and $\boldsymbol{\kappa}$ and $\boldsymbol{k}$ are wave-vectors of current and electromagnetic radiation respectively. Then for one plane wave of current $j\sim\exp(i(\omega t-\boldsymbol{\kappa r}))$ wave equation for vector-potential can be written as

$$rotrot\vec{A}=\frac{4\pi}{c}\vec{j}+\varepsilon k_0^2\vec{A}, \quad (2)$$

where it was taken into account that $A\sim\exp(i(\omega t-\boldsymbol{kr}))$. Since the density gradient imposes the chosen direction along $0z$ axis, it is convenient to consider wave-vectors and vector-potentials as a sum of components parallel and perpendicular to the density gradient.

$$\vec{A}=\vec{e}_z A_{\|}+\vec{A}_{\perp};\ \vec{k}=\vec{e}_z k_{\|}+\vec{k}_{\perp};\ \vec{\kappa}=\vec{e}_z\kappa_{\|}+\vec{\kappa}_{\perp}.$$

Diffuse boundary model permits us to solve the equation (2) using successive approximation method. Therefore we will seek for the solution of (2) in a form $\boldsymbol{A}=\boldsymbol{A}_0+\boldsymbol{A}_1$, taking into account that $\varepsilon(z)=\varepsilon_0+\varepsilon_1(z)$, and $\varepsilon_0 \gg \varepsilon_1$; $\boldsymbol{A}_0 \gg \boldsymbol{A}_1$. Then leaving only the zero order terms the following equation is obtained:

$$\vec{A}_0=\frac{4\pi\left(k_0^2\varepsilon_0\vec{j}-\vec{\kappa}\left(\vec{\kappa}\cdot\vec{j}\right)\right)}{ck_0^2\varepsilon_0\left(\kappa^2-k_0^2\varepsilon_0\right)},$$

where it was taken into account that $\boldsymbol{A}_0\sim\exp(i(\omega t-\boldsymbol{\kappa r}))$. Zero order solution $\boldsymbol{A}_0$ describes the proper field of electron current wave and also cyclotron radiation induced by electron cyclotron rotation. The first order vector-potential $\boldsymbol{A}_1$ contains the transitions radiation we are interested in.

The first order equation has a form:

$$\left(\frac{d^2}{dz^2}-\left(k_\perp^2-k_0^2\varepsilon_0\right)\right)\left(\vec{k}_\perp\vec{A}_{1\perp}(z)\right)=$$
$$=\left(k_\perp^2-k_0^2\varepsilon_0\right)\frac{\varepsilon_1(z)}{\varepsilon_0}\left(\vec{k}_\perp\vec{A}_{0\perp}\right)+\frac{ik_\perp^2}{\varepsilon_0}\frac{d}{dz}\left(\varepsilon_1(z)A_{\|0}\right). \quad (3)$$

Similarly to solution described in [3], one can find the transition radiation for one plane wave of current:

$$\left(\vec{k}_\perp\vec{A}_{1\perp}(z)\right)=-\frac{\varepsilon_m L}{2}\frac{k_\perp^2}{\varepsilon_0}\frac{\left(B_m\pm A_{\|0m}|k_z|\right)\exp\left[\mp i|k_z|z\right]}{k_z\sinh\left(\left(|k_z|\mp\kappa_{\|}\right)L\pi/2\right)}, \quad (4)$$

where upper and lower signs correspond to forward and backward wave respectively.

The full transition radiation of the current created by rotating electron can be found by performing the inverse Fourier transform with respect to wave-numbers k_{x}, k_{y} and $\kappa_{\|}$. Integrals by k_{x} and k_{y} can be taken using stationary phase method in far zone. The integral by $\kappa_{\|}$ has to be taken numerically.

$$\left(\vec{k}_\perp\vec{A}_{1\perp}(z)\right)=\int_{-\infty}^{\infty}d\kappa_{\|}\sin 2\Theta_r\frac{\varepsilon_m}{\varepsilon_0}\frac{v_e e}{4\pi}k\times$$
$$\times\frac{\exp\left(-ikr+i\left(\delta_{\varphi 0}+\delta_{\theta 0}\right)\pi/4\right)}{r\sinh\left(\left(k\cos\Theta_r-\kappa_{\|}\right)L\pi/2\right)\left(\left(k\cos\Theta_r\right)^2-\kappa_{\|}^2\right)}\frac{L}{c}\times$$
$$\times\left(i\left(\cos^2\Theta_r\left(k\cos\Theta_r-\kappa_{\|}\right)+\kappa_{\|}\right)k\cos\Phi_r B_{nx}-\right.$$
$$\left.-\sin\Theta_r\left(k_0^2\varepsilon_0+\kappa_{\|}\left(k\cos\Theta_r-\kappa_{\|}\right)\right)B_{nz}\right),$$

where Θ_{r} and Φ_{r} indicate the direction to the measurement point in spherical coordinates.

The Pointing flux radial component can be obtained as follows:

$$\Pi_R=\frac{c\sqrt{\varepsilon}}{4\pi}E_\theta^2=\frac{c}{\pi}\frac{1}{\sqrt{\varepsilon}}\left(\frac{1}{\sin 2\theta}\right)^2\left(\vec{k}_\perp\vec{A}_\perp\right)^2.$$

3. RESULTS

The typical transition radiation pattern for Fourier harmonic of Pointing flux radial component in far zone is shown on Fig.3.

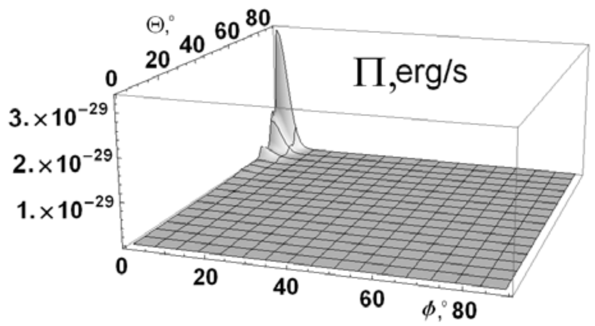

Fig.3. Transition radiation spectrum for n = 265 harmonics of Pointing flux radial component

One can see that maximum of the radiation lies in the electron rotation plane and directed perpendicularly to the density gradient. The propagation in this direction is a phenomenon analogous to the presence of reflection point on the density profile, where the efficiency of the transition radiation is usually increased.

Due to the chosen model of the electron having circular orbit in diffuse plasma boundary, the forward and backward radiations have almost identical value and radiation patterns.

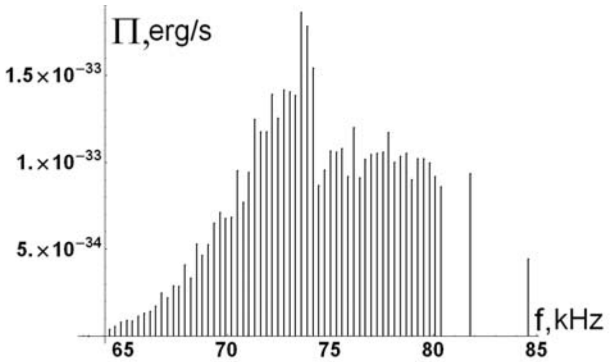

Fig.4. Transition radiation spectrum for electron having energy 300keV, Larmor raduis R_L = 132 km, inhomogeneity spatial scale L = 150 km, cyclotron frequency f_c = 282 Hz, plasma densities before and after shock ramp n_1 =10 cm^{-3} and n_2 = 22 cm^{-3}

The obtained transition radiation spectrum, (Fig.4) has the maximum in the same frequency range as the high intensity radiation detected in measurements [1]. Thus measured radiation can indeed be transition radiation of relativistic electrons.

4. CONCLUSIONS

In this article the model of the electron rotating in diffuse plasma boundary is suggested to explain CLUSTER and WIND measurements performed near interplanetary shock ramp on 22 January, 2004. The calculation of transition radiation of electron rotating in diffuse plasma boundary is described in detail.

Since in the considered model the boundary is diffuse and electron has rotational trajectory, the forward and backward radiations have almost identical values and radiation patterns. Spectrum, obtained using suggested model (Fig.4.) has the maximum in the same frequency region as the high intensity radiation detected in measurements [1], therefore observed electromagnetic radiation can be attributed to transition radiation of high energetic electrons crossing the interplanetary shock region. The results of the calculation using diffuse boundary model agree by the order of magnitude with the estimates made using WKB approximation and linear density profile [4].

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ПЕРЕХОДНОЕ ИЗЛУЧЕНИЕ ЭЛЕКТРОНА, ВРАЩАЮЩЕГОСЯ В РАЗМЫТОЙ ГРАНИЦЕ ПЛАЗМЫ

К.С. Мусатенко, И.А. Анисимов

Для описания переходного излучения релятивистского электрона, дрейфующего через межпланетную ударную волну, предложена модель размытой границы плазмы. Приводится детальное описание решения для электрона, имеющего круговую орбиту. Максимум спектра переходного излучения одного электрона, который вращается в размытой границе плазмы, находится в том же частотном диапазоне, что и наблюдаемое спутниковыми приборами электромагнитное излучение. Этот результат подтверждает предположение о возможном вкладе переходного излучения релятивистских электронов в наблюдаемое излучение.

ПЕРЕХІДНЕ ВИПРОМІНЮВАННЯ ЕЛЕКТРОНА, ЩО ОБЕРТАЄТЬСЯ В РОЗМИТІЙ ГРАНИЦІ ПЛАЗМИ

К.С. Мусатенко, І.О. Анісімов

Для опису перехідного випромінювання релятивістського електрону, що дрейфує через міжпланетну ударну хвилю, запропоновано модель розмитої границі плазми. Представлено детальний опис розв’язки для електрона, що має кругову орбіту. Максимум спектру перехідного випромінювання одного електрона, що обертається в розмитій границі плазми, знаходиться в тому ж частотному діапазоні, що і електромагнітне випромінювання, що спостерегається супутниковими приладами. Цей результат підтверджує припущення про можливий внесок перехідного випромінювання релятивістських електронів в спостережуване випромінювання.