Strong Langmuir turbulence in the earth's magnetosphere as a source of kilometer radio emission

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The source of the earth's radio emission is taken in this paper to be the strong Langmuir turbulence excited by a beam of electrons that spill out of the tail of the earth's magnetosphere, followed by a reradiation of their energy at double the plasma frequency. The obtained efficiency of this conversion is capable of ensuring an observable effectiveness of the radiation.

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The discovery that the earth is a powerful source of radio emission (see, e.g., the review of Gurnett[1]) has added the earth to the list of cosmic objects having a clearly pronounced magnetosphere and emitting electromagnetic waves when the plasma surrounding the object interacts with the magnetosphere of the object. Therefore a verification of various radiation mechanisms with the feasible direct sounding of the earth's magnetosphere as an example will permit a correct estimate of the relative role of these mechanisms for such remote cosmic objects as, say, pulsars. It is now clear that the source of nonthermal electromagnetic radiation are powerful streams of spilled electrons and electric currents which are responsible for the application of the voltages that are produced at the interface between the magnetosphere and the plasma flowing around the object to the conducting ionosphere of the planet. The conversion of the electron-stream energy into electromagnetic-wave energy is direct, but includes as an intermediate step excitations of various types of plasma oscillations. Therefore the explanation of the high conversion efficiency (the radio-emisssion power $\sim 10^9$ W is approximately 1% of all the energy dissipated by the spilled particles in the auroral ionosphere[1]) is a complicated task. All the more undesirable are radio-emission mechanisms[2,3] that propose the presence of additional links in this chain. Thus, in Benson's mechanism[2] is postulated a sequential linear transformation of the wave excited in the magnetosphere with frequencies near the upper hybrid resonance at first into an extraordinary wave that remains in the plasma, and only then into the ordinary wave that leaves the plasma; this can yield in the best case a wave-into-wave conversion efficiency (without allowance for the efficiency of the wave particle system) on the order of 1%. Palmadesso *et al.*[3] have recently proposed a method for the excitation of the extraordinary electromagnetic wave by a beam of electrons in the presence of ion-density fluctuations, i.e., by conversion of the low-frequency oscillations into electromagnetic oscillations on the beam electrons. This mechanism, however, requires that there exists simultaneously a source of sufficiently large density fluctuations (for example, an electric current). In addition, it is obvious that the Langmuir oscillations excited in a linear manner will lead to the beam relaxation before the electromagnetic waves manage to grow substantially, owing to the small nonlinear increment.

We therefore start in this paper from two main premises.

1) The electron beam is formed in the external region of the magnetosphere, where the plasma frequency ω_p exceeds the electron cyclotron frequency ω_c, and loses an appreciable fraction of its energy (50%), to excitation, in this region, of Langmuir oscillations of frequency

$$\omega = \omega_p\left\{1 + \frac{3}{2} k_z^2 \lambda_D^2 + \frac{\omega_c^2}{2(\omega_p^2 - \omega_c^2)} \frac{k_\perp^2}{k_z^2}\right\} , \qquad (1)$$

where λ_D is the Debye radius, and k_z and $k_\perp$ are the wave-vector components along and across the magnetic field, which is directed along the z axis.

2) At typical plasma parameters in the radiation region ($n_0 = 2\times10^2$ cm^{-3}, $T_e = 100$ eV)[1,4] and under the assumption that the entire current present in that region with density $j_0 = 10$ mA/m^2 is transported with the beam of electrons with energy $mv_R^2/2 \sim 10$ keV, the level of the beam-excited turbulence, according to the estimates of[5], exceeds the critical value with respect to formation of plasma cavitons in which Langmuir oscillations are trapped and to their subsequent collapse.

Among the nonlinear processes whereby electromagnetic radiation is generated by Langmuir turbulence (see, e.g., [6]), we shall consider here only the generation at double the plasma frequency, since it is the only one capable of emerging from a plasma with not too small a magnetic field ($\omega_c \lesssim \omega_p$). In addition, owing to the modulation instability of the Langmuir waves, we can no longer use the results of[6], which were obtained earlier within the framework of the theory of weak turbulence.

The intensity of the coherent radiation of electrons in a collapsing caviton can be calculated from the known formulas of field theory[7]:

$$P_\omega = \frac{4\pi\omega k_0}{c^2}\int_0^\pi \sin^3\theta d\theta \left| \int d^3 r\, j_{z\omega}(\mathbf{r}) e^{-i\mathbf{k}_0\mathbf{r}}\right|^2 , \qquad (2)$$

where $j_{z\omega} = (ie/2\pi m\omega_p)\psi(\partial\psi/\partial z) + \text{c.c.}$ is the component of the electric current at double the plasma frequency, due to oscillations of the electron in the electric field of the Langmuir waves $E_z = \psi(\mathbf{r},t)e^{-\omega_p t} + \text{c.c.}$, $\mathbf{k}_0$ is the wave vector of the radiated oscillation, and θ is the angle between the direction of the radiation and the axis. The integration is carried out here over the volume of the caviton, which has the shape of a disk of thickness Δ_z and diameter $\Delta_\perp$:

$$\Delta_z = \lambda_D\left(\frac{n_0 T_e}{W}\right)^{1/2} , \qquad \Delta_\perp = \lambda_D \frac{n_0 T_e}{W} \frac{\omega_c}{\sqrt{3(\omega_p^2 - \omega_c^2)}} , \qquad (3)$$

where W is the wave energy density at the plasma parameters given above. The value of W, calculated under the assumption that the modulation instability limits its growth, is given by the relation[5]

$$\frac{W}{n_o T_e} \approx \frac{j_o}{n_o v_b e}\left(\frac{v_b}{\Delta v_b}\right)^2 \sim 10^{-2} . \qquad (4)$$

Therefore the thickness of the caviton turns out to be much smaller than the wavelength and expression (2) for the radiation intensity becomes greatly simplified

$$p_\omega = 16\omega_p^4 \int_{-1}^{+1} x^2(1 - x^2)dx \left| \int_0^\infty r_\perp dr_\perp \int_{-\infty}^{+\infty} dz\, \psi^2 J_o(k_o r_\perp \sqrt{1 - x^2}) \right|^2, \qquad (5)$$

where J_0 is a Bessel function.

A comparison of the radiation intensity and of the rate of absorption as a result of the modulation instability with increment $\sim \omega_p(mW/n_0T_eM)^{1/2}$ of the subsequent collapse of the caviton and the absorption of the Langmuir waves by the electrons make it possible to calculate the efficiency of the conversion of the Langmuir-wave energy into radiation energy; this efficiency reaches a maximum value

$$20\left(\frac{M}{m}\right)^{1/2}\left(\frac{T_e}{mc^2}\right)^{3/2} \qquad (6)$$

at a caviton diameter $\Delta_\perp \sim \lambda_0$. Since, as shown in[8], a caviton with dimensions $\Delta_\perp > \lambda_0$ (i.e., with small W) breaks up gradually into smaller cavitons, the maximum of the radiation takes place during the stage when $\Delta_\perp \sim \lambda_0$.

We see that the obtained effectiveness with which the electromagnetic radiation is produced by Langmuir turbulence turns out to be sufficient to explain the kilometer radio emission of the earth. It should be noted here, however, that the effectiveness of the radiation can increase if the solitons of Langmuir waves with dimensions $\Delta_\perp \sim \lambda_0$, which were obtained in[9], turn out to be stable. As to the processes of linear transformation, their analysis in the real case of strong fields ($E \sim 100$ mV/m) should be reviewed with allowance for the production of solitons or collapsing cavitons.

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