Strong Langmuir turbulence as a source of radio emission

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Two mechanism for generation of electromagnetic radiation by strong Langmuir turbulence were investigated: radiation of the plasma frequency and at the second harmonic of the plasma frequency. Expressions were obtained for the electromagnetic-radiation power in these two cases. The presented theory is used for a quantitative explanation of type III solar radio bursts.

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The purpose of this paper is to investigate mechanisms for generation of electromagnetic radiation by strong Langmuir turbulence based on the theory of such turbulence that was formulated in Ref. 1.

Two mechanisms are possible for the generation of electromagnetic waves by Langmuir turbulence: a) radiation at frequencies close to the plasma frequency, which is based on the conversion of plasma waves by the density fluctuations produced by the turbulence; b) radiation at twice the plasma frequency because of production of an electromagnetic quantum as a result of a merging of two plasma waves.

For the first mechanism the production of electromagnetic waves is described by the equation

$$\frac{2i}{\omega_p}\frac{\partial E^{tr}}{\partial t} + \frac{c^2}{\omega_p^2}\,\mathrm{rot\,rot}\,E^{tr} + \frac{\delta n}{n_0}E^l = 0\,. \qquad (1)$$

Here, $\mathbf{E}^l(t,\mathbf{r})$ and $\mathbf{E}^{tr}(t,\mathbf{r})$ are complex amplitudes of the longitudinal (plasma) and transverse (electromagnetic) components of the electric field, respectively

$$\mathcal{E} = \frac{1}{2}\,\mathbf{E}(t,\mathbf{r})\,e^{-i\omega_p t} + \text{c.c.}\,.$$

According to Ref. 1, the main energy-containing region of Langmuir turbulence is the long-wave region of the source with characteristic wave numbers $k \sim \frac{1}{r_D}(\sqrt{W^l/n_0T})$, W^l is the energy density of Langmuir oscillations, and r_D is the Debye radius. The long-wave plasmons "mix" their phase during scattering by the density fluctuations with a characteristic time ν_{cor}^{-1}, where $\nu_{cor} \approx \omega_p W^l/n_0T$; the phase jumps correspond to the correlation function of the Fourier harmonics of the longitudinal electric field:

$$\langle \mathbf{E}_{\mathbf{k}}(t)\mathbf{E}_{\mathbf{k}'}(t')\rangle = |\mathbf{E}_{\mathbf{k}}|^2\delta_{\mathbf{k}\mathbf{k}'}\exp[-\nu_{cor}(t-t')]\,. \qquad (2)$$

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We use the following Fourier expansions of the electric field:

$$\mathbf{E}(t, \mathbf{r}) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} \mathbf{E}_{\mathbf{k}}(t) e^{-i\mathbf{k}\mathbf{r} - i\Phi_{\mathbf{k}}(t)},$$

V is the volume occupied by the turbulence and $\dfrac{d\Phi^l_{\mathbf{k}}}{dt} = \frac{3}{2}\omega_p k^2 \lambda_D^2$, $\dfrac{d\Phi^{tr}}{dt} = \dfrac{k^2c^2}{2\omega_p}$.

We have from Eq. (1) the following relation for the Fourier harmonic of the transverse electric field:

$$\mathbf{E}^{tr}_{\mathbf{k}} = \frac{\omega_p}{2n_0} \frac{1}{\sqrt{V}} \sum_{\vec{\kappa}} \delta n_{\mathbf{k}-\vec{\kappa}} \sin\psi_{\mathbf{k},\vec{\kappa}} \int_{-\infty}^{t} \mathbf{E}^l_{\vec{\kappa}}(t') \exp[i(\Phi^{tr}_{\mathbf{k}}(t') - \Phi^l_{\vec{\kappa}}(t')]dt' \quad (3)$$

ψ is the angle between the wave vectors of a plasmon ($\boldsymbol{\kappa}$) and an electromagnetic quantum ($\mathbf{k}$).

Below we shall assume that the generation of electromagnetic waves occurs primarily in the long-wave region of the Langmuir turbulence source. The phase jumps of the long-wave plasmons produce a continuous flow of energy into the electromagnetic radiation, which, as follows from Eqs. (1) and (3), is

$$\frac{dW^{tr}}{dt}(\omega = \omega_p) = \frac{\omega_p^2}{2V^2} \sum_{\mathbf{k},\vec{\kappa}} \frac{|\delta n_{\mathbf{k}-\vec{\kappa}}|^2}{n_0^2} |\mathbf{E}^l_{\vec{\kappa}}|^2 \frac{\nu_{cor} \sin^2\psi_{\mathbf{k},\vec{\kappa}}}{(\dot{\Phi}^{tr}_{\mathbf{k}} - \dot{\Phi}^l_{\vec{\kappa}})^2 + \nu^2_{cor}}$$

$$\approx \frac{\omega_p}{4} \frac{W^{l\,2}}{n_0 T} \left(\frac{3T}{mc^2}\right)^{3/2}. \quad (4)$$

Here, $W^{tr} = \dfrac{1}{V}\Sigma_k \dfrac{\partial}{\partial\omega}(\epsilon\omega)\dfrac{|\mathbf{E}_{\mathbf{k}}|^2 + |\mathbf{H}_{\mathbf{k}}|^2}{16\pi}$ is the energy density of the electromagnetic waves; the factor $(3T/mc^2)^{3/2}$ in Eq. (4) reflects the smallness of the phase volume of electromagnetic oscillations ($k \leqslant \omega_p/c$) as compared with the volume occupied by plasma oscillations ($\kappa < 1/r_D$).

The electromagnetic radiation produced by short-wave plasmons localized in the collapsing caverns was investigated.[2] As shown by estimates based on the coherent theory of Langmuir turbulence, such radiation is negligible for two reasons. First, most of the energy of plasma oscillations is in the long-wave region of the source and, second, the turbulence is almost isotropic in the short-wave region and the average electromagnetic field $E^{tr} \wedge |\langle \delta n E^l \rangle|$ is close to zero (this argument does not apply to the case when an external magnetic field ensures turbulence anisotropy, see Ref. 3). The incorrect calculation of electromagnetic radiation in Ref. 2 is due to the lack of an accurate picture of the turbulence in the cited paper.

The equation for determining the electromagnetic field at twice the plasma fre-

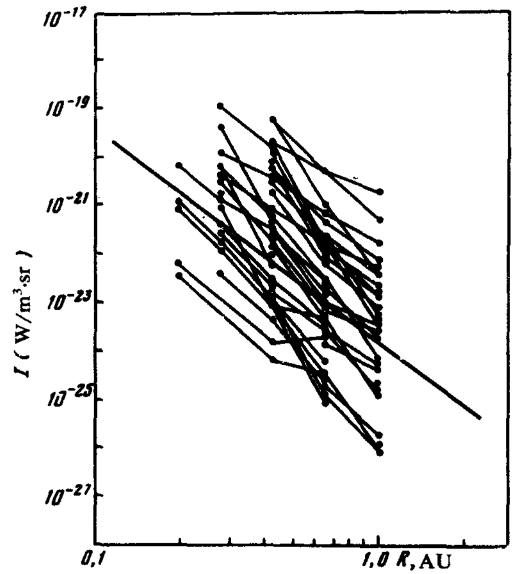

FIG. 1.

quency is

$$\frac{1}{\omega_p^2}\frac{\partial^2 \vec{\mathcal{E}}^{tr}}{\partial t^2} + \frac{c^2}{\omega_p^2}\,\mathrm{rot}\,\mathrm{rot}\,\vec{\mathcal{E}}^{tr} + \vec{\mathcal{E}}^{tr} = \frac{e}{4m\omega_p^2}\{[(\vec{\mathcal{E}}^{l}\nabla)\vec{\mathcal{E}}^{l} + 2\vec{\mathcal{E}}^{l}\,\mathrm{div}\,\vec{\mathcal{E}}^{l}] \times e^{-2i\omega_p t} + \mathrm{c.c.}\}. \quad (5)$$

Using the concept of random jumps of the plasmon phases with a frequency ν_{cor}, in complete analogy to the foregoing discussion, we obtain the following formula for the electromagnetic radiation power at a frequency $2\omega_p$:

$$\frac{dW^{tr}}{dt}(\omega = 2\omega_p) = \frac{3e^2}{64\pi m^2 c^2}\frac{1}{V^2}\sum_{\mathbf{k},\vec{\kappa}} |\mathbf{E}^{l}_{\mathbf{k}-\vec{\kappa}}|^2 |\mathbf{E}^{l}_{\kappa}|^2 \frac{\nu_{cor}\sin^2\psi_{\mathbf{k},\vec{\kappa}}}{(\dot{\Phi}^{tr}_{\mathbf{k}} - \dot{\Phi}^{l}_{\mathbf{k}-\vec{\kappa}} - \dot{\Phi}^{l}_{\vec{\kappa}})^2 + \nu_{cor}^2}$$

$$\approx \frac{3}{32}\,\omega_p\,W^{l}\left(\frac{3T}{mc^2}\right)^{5/2}. \quad (6)$$

The additional factor $T/mc^2 \sim k^2/\kappa^2$ in this formula in contrast to Eq. (4), is due to the absence of dipole radiation at twice the plasma frequency—this was first mentioned in Ref. 3.

One of the most important applications of the theory discussed by us is the quantitative explanation of type III radio bursts. The current viewpoint on the physics of this phenomenon, which has been confirmed experimentally (see, for example, Ref. 4), reduces to the following fact. A flux of high-energy (tens of keV) electrons produced during solar bursts propagates in the solar-wind plasma along the magnetic lines of force and excites plasma oscillations, which in turn generate electromagnetic radiation at the local plasma frequency and its second harmonic. As the electron beam propagates from the sun, the local plasma frequency decreases, and this results in a monotonic decrease of the radiation frequency as a function of time.

According to the measurements performed in the Helios 1 and 2 satellites at a distance of 0.5 AU, the parameters of the electron beam are as follows: density $n_1 \approx (4\times10^{-5}-10^{-4})$ cm^{-3}, velocity $v_0 \approx 1.5\times10^{10}$ cm/sec, and velocity spread $\Delta v/v_0 \approx 0.3$; the parameters of the thermal plasma of solar wind at these distances are $n_0 \approx 40$ cm^{-3} and $T \approx 10^{5\circ}$. By using the results of Ref. 5 we can easily show that the parameters of the effect in question roughly correspond to the boundary between the weak and the strong turbulence of plasma oscillations that appear during the relaxation of the electron beam in a plasma. In this case the energy of the oscillations must correspond to the modulation-instability threshold, which in the so-called subsonic limit $W^l/n_0T < m/M$ is:[6] $W^l/n_0T \sim 3(\Delta k)^2 r_D^2$; for the beam-excited plasma oscillations $(k \approx \omega_p/v_0)$, this is equivalent to the following condition:

$$\frac{W^l}{n_0 T} = 3\frac{T}{m v_0^2}\,\frac{(\Delta v)^2}{v_0^2} \approx 1.2\cdot 10^{-5}. \tag{7}$$

The plasma density of the solar wind varies as $n_0 \sim R^{-2}$ and the temperature varies as $T \sim R^{-2/7}$ with distance from the sun (see Ref. 7), and Eq. (7) corresponds to the following radial dependence of the plasma field: $E^l \sim R^{-1.3}$. At a distance of 0.5 AU the experiment gives a value $W^l/n_0T \approx 5\times10^{-6}-10^{-5}$, and $E^l \sim R^{-1.4}$.

For the threshold intensity of the Langmuir oscillations, which is defined by the relation (7), Eqs. (4) and (6) correspond to the following electromagnetic radiation intensities:

$$I\,(\omega \approx \omega_p,\ R \approx 0.5\ \text{AU}) \approx 2\cdot 10^{-23}\ \frac{\text{W}}{\text{m}^3\cdot\text{sr}}\ , \tag{8}$$

$$I\,(\omega \approx 2\omega_p,\ R = 0.5\ \text{AU}) \approx 3\cdot 10^{-23}\ \frac{\text{W}}{\text{m}^3\cdot\text{sr}}\ ,\ I(\omega \approx 2\omega_p) \sim R^{-4.5}.$$

In estimating I we assumed that the radio emission source has an angular half-width of $\approx 45^\circ$.[8] In fact, the error in determining the angular dimensions results in an uncertainty of the order of 2–3 in the intensity estimate.

The results of a measurement of the radiation intensity at twice the plasma frequency, which were obtained in Ref. 4, are shown in Fig. 1. The solid line represents the theoretical results, in satisfactory agreement with experiment.

In conclusion, we note that the radio-emission models, which are based on the generation of electromagnetic waves in a weakly turbulent medium, give a $I \sim E^{14}$ dependence.[9,10] In this case the theoretical estimate of I coincides with the experiment only for the maximum E^l values; if, however, the average experimental value is used as E^l, then the theoretical value of the radiation intensity obtained in Refs. 9 and 10 will be much smaller than the measured value.

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