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Double Langmuir frequency radiation due to transformation processes in turbulent plasma

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We investigate the transformation process of longitudinal Langmuir wave into the transverse electromagnetic wave in turbulent plasma subjected to an upper hybrid pump. The case, when upper hybrid pump wave decays into daughter and ion – sound waves is considered. The transformation of the Langmuir wave into electromagnetic one is considered as the possible mechanism of energy radiation from the plasma. It is shown that the frequency of such radiation is chosen to be near double electron Langmuir frequency $2\omega_{pe}$. These results give us the possibility to explain the nature of radiation from the laboratory and cosmic plasmas (particularly, from the solar crown).

1. Introduction

An important instrument for studying the properties of matter is the scattering and transformation of electromagnetic radiation. Completely homogeneous medium cannot scatter radiation because any scattering or transformation processes may occur due to turbulence or inhomogeneities in the medium. So, in plasma with certain fluctuation level the propagation of electromagnetic waves can lead to radiation of waves (with new frequencies and wavenumbers in comparison with incident wave) and new type of waves – transformed waves.

The theory of the waves scattering and transformation in plasma was developed in Akhiezer et al. (1978).

A lot of information concerning the plasma characteristics may be obtained from the spectral properties of the radiation from the plasma. This method of plasma diagnostics has proved to be powerful both in laboratory and space plasmas. In Golant (1968) and Sheffield (1975), the various possibilities for the use of scattered and transformed radiation in plasma diagnostics were described.

The kinetic theory of plasma instabilities in magnetized plasma has been developed in Liu and Tripathi (1986). The theory of plasma fluctuations in magnetized plasma and the effect of finite amplitude oscillating electric field were discussed by Klimontovich (1982). In Pavlenko (1990), Wilhelmsson (1991) and Pavlenko (2002) on the base of kinetic fluctuations theory, the scattering in nonequilibrium plasma with hybrid pump is studied. Notice must be taken that the fluctuations theory for magnetized plasma with the pump was developed in Pavlenko (1986) and (1992). The various transformation processes in magnetized turbulent plasma with lower hybrid pump were observed in Pavlenko (2010), (2011) and (2013).

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In the present paper, we investigate the transformation process of longitudinal Langmuir wave into the transverse electromagnetic wave in turbulent plasma subjected to an upper hybrid pump. The case, when upper hybrid pump wave decays into daughter and ion – sound waves is considered.

Note that the main contribution to the intensity of the electromagnetic radiation which has been calculated is given by the high-frequency turbulent fluctuations at upper hybrid frequency. The transformation of the Langmuir wave into electromagnetic one is considered as the possible mechanism of energy radiation from the plasma. It is shown that the frequency of such radiation is chosen to be near double electron Langmuir frequency $2\omega_{pe}$. These results give us the possibility to explain the nature of radiation from the solar crown.

Numerous experimental observations confirm that such solar radiation takes place (Zeleznyakov 1964). The different mechanisms for the interpretation of such radiation were presented in Tsytovich (1967) and Nambu (1986).

2. Results

Neglecting the interaction of the incident wave with the electron's velocity, electric and magnetic field fluctuations we can write the differential cross section $d\sum_{l\to t}$ for transformation into a space angle $d\mathrm{O}$ (Akhiezer et al. 1978; Pavlenko 2011):

$$d\sum\nolimits_{l\to t} = \frac{1}{2\pi}\left(\frac{e^2}{mc^2}\right)^2 \frac{\omega'^4}{\omega_{pe}^4} N < \delta n_e^2 >_{\vec{q},\Delta\omega} d\omega'' d\mathrm{O}, \tag{1}$$

where $\Delta\omega = \omega' - \omega'', \vec{q} = \vec{k}' - \vec{k}'', \omega', \vec{k}'$ and $\omega'', \vec{k}''$ are the frequencies and wave vectors of the incident and transformed waves respectively, O is the space angle, and $< \delta n_e^2 >_{\Delta\omega,\vec{q}}$ is the correlator of the electron density fluctuations at the combination frequency $\Delta\omega$.

The factor N in formula (1) is given by

$$N = \frac{\eta''^3 \left|\vec{e}''^*(\hat{\varepsilon}'' - 1)\vec{k}'\right|^2}{\eta'\xi'(\vec{e}''^*\hat{\varepsilon}''\vec{e}'')},$$

where $\vec{e}, \eta, \hat{\varepsilon}$ are the polarization vector, refraction index, the tensor of plasma permittivity for the incident ($'$) and transformed ($''$) waves, respectively.

Note that the frequencies and wave vectors of the incident and transformed waves are connected by the conservation laws:

$$\omega'' = \omega' + \Delta\omega,\ \vec{k}'' = \vec{k}' + \vec{q}. \tag{2}$$

We suppose that plasma is subjected to a magnetic field $\vec{B}_0 = B_o\vec{z}$ and a pump wave electric field $E(t) = E_0\vec{y}\cos\omega_0 t$. Consider the case when the pump wave frequency is close to the upper hybrid frequency:

$$\omega_{\mathrm{UH}} \approx (\omega_{pe}^2 + \Omega_e^2)^{1/2},$$

where ω_{pe} is the electron Langmuir frequency and Ω_e is the electron gyrofrequency. Here $\omega_{pe} > \Omega_e$, i.e. we have the case of weakly magnetized plasma.

Such waves which we traditionally call 'pump wave' can be produced in turbulent solar plasma by beams of charged particles or by power electromagnetic radiation directed from inner solar layers to solar crown.

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We consider the decay of the pump wave into daughter upper hybrid and ion – sound wave:

$$\omega_0 = \omega_{\mathrm{UH}} + \omega_s, \tag{3}$$

where $\omega_s = \left|\vec{k}\right| v_s$ and $v_s = (T_e/m_i)^{1/2}$ is the ion – sound velocity. Assume that the damping rate of the upper hybrid wave $\gamma_{\mathrm{UH}} \approx \nu_{ei} + \eta_e k^2$, where ν_{ei} is the collision frequency between electrons and ions and η_e is the viscosity coefficient for electrons. We also suppose that the pump wave frequency ω_0 must be slightly above ω_{UH} because $\omega_s << \omega_0, \omega_{\mathrm{UH}}$.

The threshold value of such parametric instability is governed by

$$E_{th}^2 \approx 16 \frac{\omega_o^2 B_0^2}{k^2 c^2} \left(\frac{m_i}{m_e}\right)^{1/2} \frac{\omega_{pi} \gamma_s \gamma_{\mathrm{UH}}}{\omega_s^3}. \tag{4}$$

Note that the important role of parametric instabilities in the region of upper hybrid resonance was pointed out in Pavlenko et al. (1999).

For studying the electromagnetic waves transformation in a turbulent plasma, the expression (1) after integrating over ω'' may be written in the following form (Pavlenko 2011):

$$\frac{d\sum_{\pm}}{d\theta} \approx \frac{3}{16\pi^2} \left(\frac{e^2}{mc^2}\right)^2 \frac{\omega'^4}{\omega_{pe}^4} R_{tr} \frac{\pi}{\mathrm{Im}\varepsilon_E \times \partial \mathrm{Re}\varepsilon_E/\partial\Delta\omega} \left[\left| 1 + \chi_i^0 + \frac{\mu^2}{4} \chi_e^0 \chi_i^0 \frac{1}{\varepsilon_{-1}} \right|^2 \right.$$
$$\left. < \delta n_e^2 >_{\Delta\omega,\vec{q}}^0 + \left|\chi_e^0\right|^2 < \delta n_i^2 >_{\Delta\omega,\vec{q}}^0 + \frac{\mu^2}{4} \left|\chi_e^0\right|^2 \left|\chi_i^0\right|^2 \frac{< \delta \vec{E}^2 >_{\Delta\omega\mp\omega_0,\vec{q}}^0}{\left|\varepsilon_{\mp 1}\right|^2} \right] \tag{5}$$

where $\Delta\omega = \omega_{\mathrm{UH}}, \omega_s$ for the upper hybrid and ion – sound waves respectively, $\chi_\alpha^0 (\alpha = e, i)$ is the linear plasma susceptibility, and the expression for the nonlinear dielectric permittivity $\varepsilon_E(\omega, \vec{k})$ is given in Wilhelmsson et al. (1991) and Pavlenko et al. (1986). We note that $\mu = \frac{k_\perp E_0 c}{\omega_0 B_0} \ll 1$. Meanwhile, a limit for μ from below also exists because we consider the plasma turbulence region above the instability threshold where $E_0 > E_{th}$. Consequently, we may write $\mu > \mu_{th} = \frac{k_\perp E_{th} c}{\omega_0 B_0}$.

In formula (5), $< \delta n_e^2 >_{(i)} >_{\Delta\omega,\vec{q}}^0$, $< \delta \vec{E}^2 >_{\Delta\omega,\vec{q}}^0$ are the standard correlation spectral functions of electron (ion) density and electric field for non-interacting particles in magnetized plasma in the absence of the pump field (Pavlenko 1990; 2002).

As it follows from the conservation laws, high-frequency transformed wave may be excited by high-frequency or low-frequency incident wave. In our case, when high-frequency ($\omega' \sim \omega_{pe}$) incident wave takes place, the combination fluctuation frequency $\Delta\omega$ may be situated as in high-frequency as well as in low-frequency region.

In previous works (Pavlenko 2010; 2011; 2013), the transformation processes have been investigated for the case when the pump wave frequency was chosen to be near the lower hybrid resonance frequency. So the main contribution to the correlator of the electron density was given by the low-frequency (ion – sound, drift, ion – cyclotron) oscillations, because the damping rate of the lower hybrid wave is exponentially small. Now we are interesting in the contribution of high-frequency (upper hybrid) component to the transformation coefficient. So, in formula (5), we put $\Delta\omega = \omega_{\mathrm{UH}}$ and $|\Delta\omega - \omega_0| = \omega_s$ according to (3).

In order to obtain the expression for the transformation coefficient in the stationary turbulent state of plasma (above the instability threshold), we introduce the redefined threshold value $\tilde{E}_{th}^2 = E_{th}^2 \frac{\nu_{ef}^2}{\gamma_{\mathrm{UH}}\gamma_s}$ when $\nu_{ef} = \frac{E_0^2}{E_{th}^2}(\gamma_{\mathrm{UH}}\gamma_s)^{1/2}$ is the effective collision

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frequency, which defines the additional wave damping. Such mechanism due to the scattering of charged particles by turbulent plasma fluctuations has been used for the saturation of various parametric instabilities and was presented in details in Pavlenko (1986), (1989) and (2002).

Note that we consider the regime above threshold where the effective collision frequency exceeds the Landau damping rates of the ion – sound and of the upper hybrid waves:

$$\gamma_{ef}(E_0) > \gamma_s, \gamma_{\mathrm{UH}}. \tag{6}$$

It must be borne in mind, however, that nonlinear stabilization mechanism for parametric instability is valid only if

$$\gamma_{ef} < \omega_s, \omega_{\mathrm{UH}}. \tag{7}$$

For the case $\theta \leqslant \frac{\pi}{2}$ and $\omega_{\mathrm{UH}} \sim \omega_{pe} > \Omega_e$ we have the following:

$$\chi_i^0 = \chi_i^{\mathrm{UH}} = -\frac{\omega_{pi}^2}{\omega^2 - \Omega_i^2}\sin^2\theta - \frac{\omega_{pi}^2}{\omega^2}\cos^2\theta \approx -\frac{\omega_{pi}^2}{\omega_{\mathrm{UH}}^2}, \tag{8a}$$

$$\chi_e^0 = \chi_e^{\mathrm{UH}} = -\frac{\omega_{pe}^2}{\omega^2 - \Omega_e^2}\sin^2\theta - \frac{\omega_{pe}^2}{\omega^2}\cos^2\theta \approx \frac{\omega_{pe}^2}{\omega_{\mathrm{UH}}^2}, \tag{8b}$$

$$\mathrm{Im}\varepsilon_E \approx \frac{2\gamma_{\mathrm{UH}}}{\omega_{pe}}\left(1 - \frac{E_0^2}{\tilde{E}_{th}^2}\right), \ \frac{\partial \mathrm{Re}\varepsilon_E}{\partial \Delta\omega}\,|_{\Delta\omega=\omega_{\mathrm{UH}}} \approx \frac{\partial \mathrm{Re}\varepsilon_0^{\mathrm{UH}}}{\partial \omega_{\mathrm{UH}}} \approx \frac{2\omega_{\mathrm{UH}}}{\omega_{pe}^2}, \tag{9a}$$

$$|\varepsilon_{-1}|^2 = |\varepsilon_{\omega_s}|^2 = |\mathrm{Re}\varepsilon_{\omega_s}|^2 + |\mathrm{Im}\varepsilon_{\omega}|^2 = |\mathrm{Im}\varepsilon_{\omega_s}|^2 = \left|\gamma_s \frac{\partial \mathrm{Re}\varepsilon_{\omega_s}}{\partial \omega_s}\right|^2, \tag{9b}$$

where $\frac{\partial \mathrm{Re}\varepsilon_{\omega_s}}{\partial \omega_s} = \frac{2\omega_{pi}^2}{\omega_s^2}$. Note that $\mathrm{Re}\varepsilon_{\omega_s} = 0$ for the eigen ion – sound plasma modes.

Using the fluctuation-dissipative theorem for calculating the correlators of the non-interacting particles, leaving the resonant terms in (5) we can write the following expression for the transformation coefficient:

$$\frac{d\sum_{\pm}}{d\mathrm{O}} \approx \frac{1}{8\pi}\left(\frac{e^2}{mc^2}\right)^2 \frac{\omega'^4}{\omega_{pe}^4} N \frac{q^2 T_e}{e^2}\left(1 + \frac{\mu^2}{16}\frac{\omega_s^2}{\gamma_{\mathrm{UH}}\gamma_s} + \frac{\mu^4}{16}\left(\frac{m_e}{m_i}\right)^2 \frac{\omega_s^6}{4\gamma_s^2\omega_{pi}^4}\right). \tag{10}$$

It is easy to check that ‘ the pump wave’ terms (proportional to μ) in the right-hand side of (10) play the dominant role in comparison with unity. Really this means that the interaction between the Langmuir wave and thermal oscillations is much smaller effect than wave’s interaction with turbulent fluctuations.

Add that from nonequalities (6) and (7), it is easy to obtain the constraints on the pump wave amplitudes:

$$\left(\frac{\gamma_s}{\gamma_{\mathrm{UH}}}\right)^{1/2} < \frac{E_0^2}{E_{th}^2} < \frac{\omega_s}{(\gamma_{\mathrm{UH}}\gamma_s)^{1/2}}. \tag{11}$$

Note that the transformation of the Langmuir wave into electromagnetic one is considered as the possible mechanism of energy radiation from the plasma. The intensity of such radiation is connected with the transformation coefficient by the relation (Pavlenko 2011; 2013)

$$I \sim V \iint d\sum_{l\to t} \times S' \frac{d^3k d\omega'}{(2\pi)^4}. \tag{12}$$

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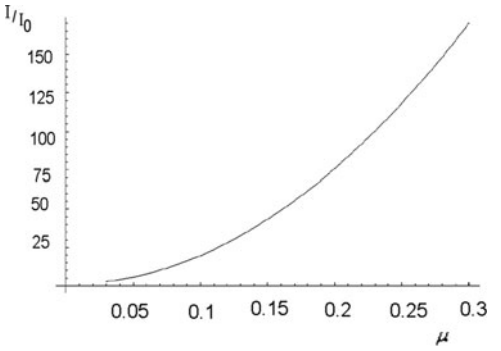


FIGURE 1. The dependence of the ratio I/I_0 on the parameter $\mu(E_0)$. Here I is the 'pump wave' contribution to the intensity of radiation, and I_0 is the corresponding contribution due to the thermal fluctuation, when the external electric field is absent.

For the energy density of Langmuir fluctuations S', we can write the expression (Pavlenko 2013):

$$S' = \frac{v_{gr}}{16}\frac{\partial}{\partial\omega'}(\varepsilon^l\omega') < \delta\vec{E}^2 >^0_{\omega',\vec{k}'}, \tag{13}$$

where, $v_{gr} = 3\omega_{pe}r_{De}^2k'$ and $\frac{\partial}{\partial\omega'}(\varepsilon^l\omega') = 3$ for $\omega' \sim \omega_{pe}$.

According to the fluctuation-dissipative theorem, we assume $\int < \delta\vec{E}^2 >^0_{\omega',\vec{k}'} d\omega' \sim T_e$. Then inserting in (12) the expression (10), taking into account (13), finally after integration over k' we obtain the following:

$$I \sim V\left(\frac{e^2}{mc^2}\right)^2 N\frac{\omega_{pe}T_e^2k'^2}{e^2}(k'r_{De}^2)^2\left[1+\mu^2\frac{\omega_s^2}{\gamma_{\mathrm{UH}}\gamma_s}+\mu^4\left(\frac{m_e}{m_i}\right)^2\frac{\omega_s^6}{4\gamma_s^2\omega_{pi}^4}\right]. \tag{14}$$

Calculations show that for typical parameters of solar crown plasma (Zeleznyakov 1964; NRL Plasma Formulary 1978) $n_e = 10^7 - 10^9 sm^{-3}, T_e, T_i \sim 10^6, H \approx 1 - 300G, (v_{Te}/c) \approx 10^{-2}, \nu_{ei} \sim 10^{-1} - 7\times 10s^{-1}$, the value of radiation intensity Ican exceed the analogous one I_0 for the case of stable plasma ($\mu = 0$) by two orders of magnitude (Fig. 1).

3. Conclusion

Notice must be taken that the scattering of Langmuir waves by coherent fluctuations on plasma electron frequency is impossible due to the conservation laws (2). When the transformation process takes place, the frequencies of transformed electromagnetic waves according to (2) are closed to the double plasma electron frequency $2\omega_{pe}$. This allows to propose one of the probable mechanism for the explanation of the anomalous radiation from the solar crown.

It is necessary to mark that the interpretation of the anomalous electromagnetic radiation from turbulent plasma is basic problem in plasma astrophysics. For example, mechanism of radiation on double plasma frequency based on L+L nonlinear wave interaction (L is the Langmuir plasma mode) was presented in Tsytovich (1967). Effects of turbulence on solar plasma radiation through the plasma-maser process were considered in Nambu (1986).

Accordingly, the results of this paper have the potential importance to interpret anomalous electromagnetic radiation in laboratory and cosmic plasmas (solar crown, superstars, ionospheric plasma etc.).

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