COMMENTS

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Comment on "Oscillating two-stream instability in ionospheric heating experiments" [Phys. Plasmas 9, 1456 (2002)]

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It is noted that the coupled mode equations of Kuo [Phys. Plasmas **9**, 1456 (2002)] can be extended for studying the oscillating two-stream instability of high-frequency electrostatic (HFES) waves in the Earth's ionosphere where Joule heating of electrons in the HFES wave fields play a significant role. Accordingly, a complete set of equations governing the nonlinear coupling between HFES waves and nonresonant density and temperature perturbations including the HFES ponderomotive force and thermal nonlinearity is presented. © *2002 American Institute of Physics.*
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In a recent Brief Communication, Kuo[1] examined the oscillating two-stream instability (OTSI) of high-frequency electrostatic (HFES) waves (modified Langmuir waves) that are excited by the O-mode heating wave in mid-latitude ionospheric heating experiments. For this, purpose, he derived the coupled mode equations (1) and (2), which are similar to Dysthe *et al.*[2] An examination of the right-hand side of Eq. (1) reveals that the so-called Langmuir sidebands of Ref. 1 contain electrostatic upper-hybrid (UH) waves whose dispersion relation for $k_z \ll |\mathbf{k}_\perp|$ is[3]

$$\omega^2 \approx \omega_{UH}^2 + \frac{3k_\perp^2 V_{Te}^2}{1-3\omega_{ce}^2/\omega_{pe}^2} - \frac{k_z^2}{k_\perp^2}\frac{\omega_{pe}^2\omega_{ce}^2}{\omega_{UH}^2}, \tag{1}$$

where ω is the wave frequency, $\mathbf{k}=\mathbf{k}_\perp + k_z\hat{\mathbf{z}}$ is the wave vector, the subscripts $\perp$ and z stand for the components perpendicular and parallel to $B_0\hat{\mathbf{z}}$, B_0 is the strength of the geomagnetic field, $\hat{\mathbf{z}}$ is the unit vector along the z axis, $\omega_{UH}=(\omega_{pe}^2+\omega_{ce}^2)^{1/2}$ is the UH resonance frequency, ω_{pe} and ω_{ce} are the electron plasma and electron gyrofrequencies, respectively, and V_{Te} is the electron thermal speed. In the Earth's ionosphere, we typically have $\omega_{pe}^2 \gg 3\omega_{ce}^2$; hence the UH waves have a positive group dispersion. Porkolab and Goldman[4] studied the OTSI of the UH waves and the UH envelope solitons. Kuo[1] and other authors[2,4] did not include the important thermal nonlinearity associated with the electron Joule heating in the HFES and UH wave fields. Hence, the results of Refs. 1 and 2 have to be extended when applied to understand phenomena during ionospheric heating experiments in the high-altitude Earth's ionosphere. The objective here is to improve the governing equations of Kuo[1] by incorporating the HFES ponderomotive force and thermal Joule heating nonlinearities on an equal footing.

For positive group dispersive HFES waves we can use the electron continuity and momentum equations, together with Poisson's equation, to derive the HFES wave equation in the presence of electron density perturbation (n_{es}) associated with non-resonant plasma slow motions. The result is[2]

$$\left(\frac{\partial^2}{\partial t^2} - 3V_{Te}^2\nabla^2 + \omega_p^2\right)\left(\nabla^2\frac{\partial^2\phi}{\partial t^2} + \omega_{ce}^2\frac{\partial^2\phi}{\partial z^2}\right) + \omega_{ce}^2\nabla_\perp^2\frac{\partial^2\phi}{\partial t^2} = -\nabla\left[\omega_p^2\frac{n_{es}}{n_0}\nabla\frac{\partial^2\phi}{\partial t^2}\right] - \frac{\partial}{\partial z}\left[\omega_p^2\frac{n_{es}}{n_0}\omega_{ce}^2\frac{\partial\phi}{\partial z}\right], \tag{2}$$

where $\omega_p=(4\pi n_0 e^2/m_e)^{1/2}$ is the unperturbed electron plasma frequency involving the equilibrium plasma number density n_0, the electron mass m_e and the magnitude of the electron charge e, $\omega_{ce}=eB_0/m_e c$ is the electron gyrofrequency, c is the speed of light in vacuum, and ϕ is the HFES wave potential. We have assumed that the HFES wave frequency is much larger than the electron collision frequency ν_e. We note that Eq. (1) of Ref. 1 is slightly different from Eq. (2) above.

We now obtain the relevant equations for n_{es}, by assuming that the frequency of the plasma slow motion is much smaller than $\nu_e \ll \omega_{ce}$. When the parallel (to $\hat{\mathbf{z}}$) wavelength of the plasma slow motion is much smaller than V_{Te}/ν_e, we have from the parallel component of the electron equation of motion

$$\frac{n_{es}}{n_0} = \frac{T_1}{T_e} + \frac{e\varphi}{T_e} - \frac{1}{4}\frac{e^2|\nabla_\perp\phi|^2}{m_e T_e(\omega_0^2-\omega_{ce}^2)}, \tag{3}$$

where T_e is the unperturbed electron temperature, T_1 is a small temperature perturbation produced by the differential electron Joule heating, and $\omega_0 \sim \omega_{UH}$. The electron motion

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is coupled with the slow ion motion through the ambipolar potential φ. The third term in the right-hand side of (3) represents the HFES ponderomotive potential.[4]

The electron temperature perturbation T_1 is determined from[5]

$$\left(\frac{\partial}{\partial t}+\frac{1}{\tau_e}-\nabla\cdot\mathbf{H}_e\cdot\nabla\right)T_1=\frac{2}{3n_0}T_e\frac{\partial n_{es}}{\partial t}+\frac{4}{3}\frac{e^2\omega_0^2\nu_e}{m_e(\omega_0^2-\omega_{ce}^2)^2}|\nabla_\perp\phi|^2, \tag{4}$$

where τ_e is the electron energy relaxation time and $\mathbf{H}_e$ is the electron heat-diffusion tensor. Here the components H_{ez} and $H_{e\perp}$ are of order V_{Te}^2/ν_e and $\nu V_{Te}^2/\omega_{ce}^2$, respectively. The second term in the right-hand side of (4) represents the electron Joule heating in the HFES wave electric field.

The ponderomotive force of the HFES waves does not act directly on the ions involved in plasma slow motions. Hence, the ion density perturbation n_{is} is obtained by combining the ion continuity and momentum equations. We have for $\rho_i^2|\nabla^2|\ll 1$

$$\left[D_t^2\left(\frac{\partial}{\partial t}+\nu_i\right)\frac{\partial}{\partial t}-3\left(\frac{\partial}{\partial t}+\nu_i\right)^2V_{Ti}^2\nabla^2-3\omega_{ci}^2V_{Ti}^2\frac{\partial^2}{\partial z^2}\right]n_{is}=\frac{n_0e}{m_i}\left[\left(\frac{\partial}{\partial t}+\nu_i\right)^2\nabla^2+\omega_{ci}^2\frac{\partial^2}{\partial z^2}\right]\varphi, \tag{5}$$

where $D_t^2=(\partial/\partial t+\nu_i)^2+\omega_{ci}^2$, ν_i is the ion collision frequency, $\omega_{ci}=eB_0/m_ic$ is the ion gyrofrequency, m_i is the ion mass, V_{Ti} is the ion thermal speed, and $\rho_i=V_{Ti}/\omega_{ci}$ is the thermal ion gyroradius.

By invoking the quasi-neutrality approximation, viz. $n_{is}\approx n_{es}$, we readily obtain from (2), (3), and (5)

$$\left[D_t^2\left(\frac{\partial}{\partial t}+\nu_i\right)\frac{\partial}{\partial t}-\left(\frac{\partial}{\partial t}+\nu_i\right)^2V_s^2\nabla^2+\omega_{ci}^2V_s^2\frac{\partial^2}{\partial z^2}\right]\frac{n_{es}}{n_0}+C_s^2\left[\left(\frac{\partial}{\partial t}+\nu_i\right)^2\nabla^2+\omega_{ci}^2\frac{\partial^2}{\partial z^2}\right]\frac{T_1}{T_e}=\frac{C_s^2}{16\pi n_0T_e}\frac{\omega_p^2}{\omega_0^2-\omega_{ce}^2}\times\left[\left(\frac{\partial}{\partial t}+\nu_i\right)^2\nabla^2+\omega_{ci}^2\frac{\partial^2}{\partial z^2}\right]|\nabla_\perp\phi|^2, \tag{6}$$

where $V_s^2=C_s^2+3V_{Ti}^2$ and $C_s=(T_e/m_i)^{1/2}$. In the absence of the electron temperature fluctuation and ion collisions Eq. (6) exactly reduces to Eq. (2b) of Ref. 2.

Equations (1), (4), and (6) are significantly improved version of Eqs. (1) and (2) in Ref. 1. They describe the nonlinear coupling between the HFES waves and nonresonant density and temperature fluctuations that are created by the HFES wave ponderomotive force and by the electron Joule heating in a magnetized plasma. The newly presented coupled equations should then be used for investigating OTSI and collapse of HFES waves in the Earth's ionosphere during artificial heating experiments.

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