GENERATION OF NONLINEAR ELECTROSTATIC ION-CYCLOTRON-DRIFT WAVES ASSOCIATED WITH ION ACCELERATION IN AURORAL PLASMAS

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It is well known that magnetic field-aligned sheared plasma flows and currents affect the dynamic coupling between the Earth's ionosphere and magnetosphere. These flows and currents are also potential sources for nonthermal plasma waves, which could be responsible for the acceleration of charged particles in the auroral plasmas. In fact, recent satellite observations [1, 2] have conclusively shown signatures of large amplitude time domain electric field structures in the auroral acceleration region where also discrete auroras are produced.

The development of auroral arcs is often characterized by the formation and evolution of nonlinear coherent structures, such as auroral arcs, folds, spirals, and vortex streets. In order to understand the salient features of the latter in the auroral zone, Shukla *et al.* [3] presented a nonlinear model in which a magnetic field-aligned equilibrium sheared ion flow generates low-frequency (in comparison with the ion gyrofrequency) electrostatic drift-like fluctuations (EDLFs). The nonlinear interactions between such finite amplitude EDLFs give rise to coherent vortex street structures whose propagation speeds and sizes are in agreement with observations [4].

In this paper, we generalize the work of Ref. [3] by including wave frequencies which are close to, or larger than, the ion gyrofrequency, but smaller than the electron gyrofrequency $\omega_{ce} = eB_0/m_e c$, where e is the magnitude of the electron charge, B_0 is the strength of the external magnetic field, m_e is the electron mass, and c is the speed of light. Specifically, we focus on the instability of coupled electrostatic drift-ion-cyclotron waves in a nonuniform magnetoplasma containing equilibrium density gradients and magnetic field-aligned sheared plasma flows. The parallel ion-velocity (PIV) driven electrostatic fluctuations saturate by some nonlinear processes (viz., particle trapping, mode coupling, etc.) and attain then large amplitudes. The ponderomotive force of such intense electrostatic ion-cyclotron waves (EICWs) can create a space charge electric field by pushing the electrons and ions locally due to the ponderomotive force [5]. This electric field could be responsible for the acceleration of ions and electrons across and along the geomagnetic field lines.

Let us consider a nonuniform electron-ion plasma in an external magnetic field $B_0\hat{\mathbf{z}}$, where $\hat{\mathbf{z}}$ is the unit vector along the z axis. The equilibrium density gradient $\partial n_0/\partial x$ and the equilibrium magnetic field aligned sheared plasma flow gradients $\partial v_{j0}/\partial x$ are supposed to be along the x axis, where $n_0(x)$ and $v_{j0}(x)$ are the unperturbed number density and the equilibrium parallel (to $\hat{\mathbf{z}}$) velocity of particle species j (j equals e for the electrons and i for the ions). The equilibrium is maintained by continuous injection of particles in the auroral plasma from the magnetosphere.

In the presence of a low-frequency ($\omega << \omega_{ce}$) electrostatic electric field $\mathbf{E} = -\nabla\phi$, the electron velocity is given by $\mathbf{v} \approx \mathbf{v}_E + \mathbf{v}_{De} + \hat{\mathbf{z}}v_{ez}$, where $\mathbf{v}_E = c(\mathbf{E}\times\hat{\mathbf{z}})/B_0$, $\mathbf{v}_{De} = -(cT_e/eB_0n_e)\hat{\mathbf{z}}\times\nabla n_e$ is the electron diamagnetic drift, T_e is the electron temperature, and n_e the electron number density. Substituting for the electron drift in the electron continuity equation and eliminating the parallel electron velocity perturbation v_{ez} by means of the parallel component of the electron momentum equation, we obtain, for $\omega << k_z v_{te}, k_y V'_{e0}/\omega_{ce} << k_z$, and $\omega\omega_{e*} << k_z^2 v_{te}^2$, the electron number density

$$n_e \approx n_0 \exp(e\phi/T_e), \tag{1}$$

where k_z and k_y are the components of the wavevector $\mathbf{k}$ along the z and y axis, respectively, v_{te} is the electron thermal velocity, $V'_{e0} = \partial v_{e0}/\partial x$, $\omega_{e*} = -(cT_e/eB_0L_n)k_y$, and $L_n = n_0/\left(\partial n_0/\partial x\right)$.

The ion dynamics is governed by

$$\left(\partial_t + \mathbf{v}_i\cdot\nabla\right) ln\; n_i + \nabla\cdot\mathbf{v}_i = 0, \tag{2}$$

$$\left[\left(\partial_t + \mathbf{v}_i\cdot\nabla\right)^2 + \omega_{ci}^2\right]\mathbf{v}_{i\perp} = \frac{e}{m_i}\omega_{ci}\hat{\mathbf{z}}\times\nabla\varphi - \frac{e}{m_i}\left(\partial_t + \mathbf{v}_i\cdot\nabla\right)\nabla_\perp\varphi, \tag{3}$$

and

$$\left(\partial_t + \mathbf{v}_i\cdot\nabla\right) v_{iz} + \mathbf{v}_{i\perp}\cdot\nabla v_{i0}(x) = -\frac{e}{m_i}\partial_z\varphi, \tag{4}$$

where $\mathbf{v}_i = \hat{\mathbf{z}}(v_{i0} + v_{iz}) + \mathbf{v}_{i\perp}$ is the ion fluid velocity, $\omega_{ci} = eB_0/m_i c$ is the ion gyrofrequency, $\varphi = \phi + (T_i/e) ln\; n_i$, m_i is the ion mass, T_i the ion temperature, and n_i the ion number density.

Letting $n_j = n_0(x) + n_{1j}$, we combine Eqs. (1)–(4) by using the quasineutrality condition $n_{e1} = n_{i1}$, which is valid as long as the ion plasma frequency ω_{pi} is much larger than the ion gyrofrequency. Thus, (2)–(4) take the form

$$d_t\phi + \frac{T_e}{e}\left[\mathbf{v}_{i\perp}\cdot\nabla ln\; n_0(x) + \nabla\cdot\mathbf{v}_{i\perp}\right] + \frac{T_e}{e}\partial_z v_{iz} = 0, \tag{5}$$

$$\left(d_t^2 + \omega_{ci}^2\right)\mathbf{v}_{i\perp} = \frac{e}{m_i}(1+\sigma)\left(\omega_{ci}\hat{\mathbf{z}}\times\nabla\phi - d_t\nabla_\perp\phi\right), \tag{6}$$

and

$$d_t v_{iz} = -\frac{e}{m_i}(1+\sigma)\partial_z\phi - \mathbf{v}_{i\perp}\cdot\nabla v_{i0}(x), \tag{7}$$

where $d_t = \partial_t + \mathbf{v}_i\cdot\nabla$ and $\sigma = T_i/T_e$.

Equations (5)–(7) are our new nonlinear equations that govern the nonlinear dynamics of coupled electrostatic drift-ion-cyclotron (EDIC) waves in a nonuniform magnetoplasma containing equilibrium density and velocity gradients. They describe the nonlinear behavior of fully developed EDIC wave turbulence that is created by the parallel ion velocity gradient. When the wave frequency is much smaller than ω_{ci}, eq. (6) can be solved in a perturbative manner and the solution substituted in (5) to derive a set of nonlinear partial differential equations which is similar to that presented in Ref. [3].

In the following, we examine the linear instability of coupled EDIC waves in a nonuniform magnetoplasma and discuss the ion acceleration by the ponderomotive force of the EIC waves.

In order to study the instability of coupled waves, we derive a local dispersion relation from (5)–(7) by neglecting the nonlinear terms, and assuming that the wave potential and the ion velocity perturbations are proportional to $\exp(ik_y y + ik_z z - i\omega t)$. The resultant dispersion relation reads

$$(\omega^2 - \omega_{ci}^2)\omega^2 - \omega_{e*}^2\omega_{ci}\omega - \omega^2 k_y^2 v_s^2 = k_z^2 v_s^2(\omega^2 - \omega_{ci}^2) + k_y k_z v_s^2 \omega_v \omega_{ci}, \tag{8}$$

where $\omega >> k_z v_{i0}$, $\omega_{e*}^2 = k_y \kappa_n v_s^2, \kappa_n = (\partial n_0/\partial x)/n_0, v_s = [T_e(1+\sigma)/m_i]^{1/2}$, and $\omega_v = \partial v_{i0}/\partial x \equiv V_{i0}'$.

Several comments are in order. First, in the absence of the density gradient, Eq. (8) yields

$$\omega^4 - \omega_{ic}^2\omega^2 + k_z v_s^2 \omega_{ci}^2 - k_y k_z v_s^2 \omega_v \omega_{ci} = 0, \tag{9}$$

where $\omega_{ic}^2 = \omega_{ci}^2 + k^2 v_s^2$ and $k^2 = k_y^2 + k_z^2$. Equation (9) predicts an oscillatory instability of the EIC waves. For $\omega >> \omega_{ci}$, Eq. (9) gives

$$\omega^2 = \frac{1}{2}k^2 v_s^2 \pm \frac{1}{2}\left[k^4 v_s^4 + 4k_y k_z v_s^2 \omega_v \omega_{ci}\right]^{1/2}, \tag{10}$$

which admits an oscillatory instability for $V_{i0}' < 0$ and $|\omega_v| > k^4 v_s^2/4k_y k_z \omega_{ci}$.

Second, for $\omega << \omega_{ci}$, we obtain from (8)

$$\omega^2 + \omega\omega_* = \omega_a^2 - \frac{k_y k_z v_s^2 S_i}{1+b_s}, \tag{11}$$

where $\omega_* = k_y \kappa_n \rho_s^2 \omega_{ci}/(1+b_s), b_s = k_y^2 \rho_s^2, \rho_s = v_s/\omega_{ci}, \omega_a = k_z v_s/(1+b_s)^{1/2}$, and $S_i = V_{i0}'/\omega_{ci}$. Equation (11) predicts an oscillatory instability [3] provided that $S_i > (\omega_*^2 + 4\omega_a^2)(1 + b_s)/4k_y k_z v_s^2$. Finally, we note that (8) can be numerically analyzed to obtain the complete unstable spectra and the associated growth rate of the PIV gradient instability.

The PIV driven electrostatic waves acquire finite amplitudes. Large amplitude EIC waves exert a ponderomotive force on the ions and electrons and produce a space charge field which accelerates the ions along and across the external magnetic field lines. The ion acceleration $m_i d_t \mathbf{v}_i$ is thus caused by the ponderomotive force $\mathbf{F} = \mathbf{F}_\perp + \hat{\mathbf{z}} F_\parallel$, where, for our purposes, the perpendicular (to $\hat{\mathbf{z}}$) and parallel components of the EIC ponderomotive force are [5]

$$\mathbf{F}_\perp = -\frac{e^2}{m_i(\omega^2-\omega_{ci}^2)}\left(\nabla_\perp + \frac{\omega_{ci}}{\omega}\hat{\mathbf{z}}\times\nabla\right)\left(\frac{\omega^2}{\omega^2-\omega_{ci}^2} < |\mathbf{E}_\perp|^2 > + < |\mathbf{E}_\parallel|^2 >\right), \qquad (12a)$$

and

$$F_\parallel = -\frac{e^2}{m_i\omega^2}\nabla_\parallel\left(\frac{\omega^2}{\omega^2-\omega_{ci}^2} < |\mathbf{E}_\perp|^2 > + < |\mathbf{E}_\parallel|^2 >\right), \qquad (12b)$$

where $\mathbf{E}_\perp$ and $\mathbf{E}_\parallel$ are the perpendicular and parallel components of the electric field vector of the EIC wave, and where $\sigma << 1$ has been assumed. The angular bracket stands for the ensemble average. It follows that the ponderomotive force accelerates the ions as well as the electrons both parallel and perpendicular to the geomagnetic field lines, as an ambipolar electric field is build up due to the charge separation effect. For electric fields of the order of one tenth V/m and EIC wavelengths comparable to the ion gyroradius, the ion energies can be of the order of several hundreds eV over characteristic acceleration lengths of a few kilometers in the auroral region [1, 2].

To summarize, we have derived a set of nonlinear equations that govern the dynamics of low-frequency (in comparison with the electron gyrofrequency), long wavelength (in comparison with the ion gyroradius) electrostatic waves in a nonuniform magnetoplasma containing an equilibrium density gradient and equilibrium sheared plasma flows. It is shown that the latter can excite a broad spectrum of electrostatic waves covering frequencies below, comparable, or higher than the ion gyrofrequency. Finite amplitude EIC waves exert a ponderomotive force on the ions and cause consequently differential acceleration along and across the magnetic field lines. Thus, we have presented a mechanism by which nonlinear EIC wave structures are created. The charged particle acceleration in the auroral region is basically produced by the ponderomotive force of these intense localized electric field structures.

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