"Physics of Auroral Phenomena", Proc. XXVIII Annual Seminar, Apatity, pp. 104-107 , 2005

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PARAMETRIC GENERATION OF THE ZONAL STRUCTURES BY ALFVEN WAVES IN THE EARTH'S IONOSPHERE

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Abstract. The parametric interaction of the Alfven waves with large-scale zonal structures in the Earth's ionosphere is investigated. It is shown that in the auroral plasma cavity where the Alfven velocity attains its maximum value, the parametric generation is substantially reduced. Our analysis shows that the Alfven waves in the kinetic regime in the upper ionosphere well above the auroral acceleration region at altitudes 3 – 7 R_E (R_E is the Earth radius) are stable with respect to the interaction with the zonal structures. The relevance of our theory to spacecraft measurements in the Earth's ionosphere is discussed.

1. Introduction

The present paper deals with the parametric excitation of low-frequency large-scale convective cells, the so-called zonal structures, by large amplitude Alfven waves in the Earth's ionosphere. Interest in the zonal structures arises from the observational evidence for the existence of large-scale shear motion in the auroral upper ionosphere, the origin of which still remains unclear. These shear motions are of importance in the formation of the three-dimensional auroral current system as they are believed to be the sources of local upward and downward field-aligned auroral currents [see e.g., *Carlson et al.,* 1998; *Marklund et al.,* 2001]. Dynamical models of the coupling between the magnetosphere and the ionosphere make successful use of Alfven waves [*Lysak*, 1990] as carriers of information from the magnetosphere into the auroral ionosphere during substorms, as well as during storms when Alfven waves connect the ring current region to subauroral latitudes. Most of this transport is believed to be due to short-scale Alfven waves [see e.g., *Stasiewicz et al.*, 2000], which contribute to the generation of field-aligned currents, potential drops along the geomagnetic field lines, and particle acceleration. A kinetic formulation of the global problem has been given by *Lysak and Song* [2003] who showed that, when accounting for wave reflection in the ionosphere, stationary Alfvenic structures can evolve along the connecting magnetic field lines, where particles are subject to acceleration in a standing electric wave field. The generation of Alfven waves in these approaches is displaced to the dynamical processes in the magnetosphere, which pump energy into the wave spectrum that is subsequently dissipated in the ionosphere. On the other hand, in order to be dynamically relevant the Alfven waves generated in this way are of large amplitude and thus can decay into other wave modes.

The possibility of zonal structures in magnetized plasma was originally realized from numerical simulations by *Okuda and Dawson* [1973]. *Sagdeev et al.* [1978] were the first to suggest a mechanism of parametric excitation of the zonal structures by finite amplitude Alfven waves. Recently, the interest was shown again in examining the excitation of large-scale zonal structures both in the theory of magnetized plasmas and in geophysical fluid dynamics [*Dubinin et al.,* 1988; *Volokitin and Dubinin,* 1989; *Smolyakov et al.,* 2000; *Shukla and Stenflo,* 2003; *Onishchenko et al.,* 2004a]. The generation and nonlinear evolution of the zonal structures due to the parametric decay of monochromatic inertial Alfven waves (IAWs) in the Earth's ionosphere have recently been discussed by *Pokhotelov et al.* [2003] in the framework of the model adopting a four-wave interaction involving the monochromatic pump Alfven wave, the large-scale convective mode and two sidebands. Furthermore, in this scenario, one can expect efficient particle acceleration along and perpendicular to the geomagnetic filed lines. The IAWs are important in low-β plasmas ($\beta << m_e / m_i$, $m_{e,i}$ the electron and ion masses), i.e., in plasmas where $v_A >> v_{Te}$, with $v_A = B_0 /(\mu_0 n m_i)^{1/2}$ the Alfven velocity, B_0 the ambient magnetic field, μ_0 the permeability of free space, n the plasma number density, $v_{Te} = (2T_e / m_e)^{1/2}$ is the electron thermal velocity and T_e the electron temperature. It has been shown that small-scale Alfven waves parametrically generate larger scale nonoscillating two-dimensional convective vortices familiar under the names of "electrostatic convective cells or zonal structures". They cause the inertial Alfven wave to decay in time and transfer its energy to the zonal structure.

The Alfven velocity in the Earth's ionosphere increases sharply towards the magnetosphere and attains its maximum value at an altitude of the order of the Earth's radius. According to observations [*Chaston et al.,* 2003a, b], the Alfven velocity in this region is of the order of 2×10^5 km/s or larger and thus becomes relativistic, i.e., comparable to the speed of light. Recently, *Onishchenko et al.* [2004b] generalized the theory of the IAW parametric instability developed by *Pokhotelov et al.* [2003] for the case of low-density plasma, accounting for the effects of a nonzero ratio between the Alfven velocity and the speed of light. In the linear approximation the IAWs are described by the dispersion relation $\omega_k = k_z v_A \beta_A^{1/2} \Lambda_I^{-1/2}$, where ω_k is the wave frequency,

$\beta_A = 1/(1+v_A^2/c^2)$ accounts for the effect of the ratio between the Alfven velocity and the speed of light, $\Lambda_I = 1+\lambda_e^2 k_\perp^2$ the factor accounting for the wave dispersion due to the nonzero collisionless electron skin depth $\lambda_e = c/\omega_p$, c the speed of light, $\omega_p = (ne^2/\varepsilon_0 m_e)$ the electron plasma frequency, e the elementary charge, ε_0 the permittivity of free space, k_z and $k_\perp$ the components of the wave vector along and perpendicular to the ambient magnetic field.

At larger distances from the Earth in the upper ionosphere, the β exceeds the electron-to-ion mass ratio [*Goertz and Boswell*, 1979], and the inertial Alfven waves turn into the kinetic Alfven waves (KAWs) [e.g., *Hasegawa and Chen*, 1975] with perpendicular wavelengths of the order of the ion Larmor radius. In the linear approximation the KAWs are described by dispersion relation $\omega_k = k_z v_A \Lambda_K^{1/2}$, where Λ_K accounts for the effects of finite ion-acoustic and ion Larmor radii $\rho_s = (T_e/m_i)^{1/2}/\omega_{ci}$, $\rho_i = \rho_s (T_i/T_e)^{1/2}$, respectively. Here T_i is the ion temperature, $\omega_{ci} = eB_0/m_i$ the ion gyro-frequency, $\Lambda_K = k_\perp^2\rho_s^2 + z/[1-\Gamma(z)]$, $\Gamma(z) = \exp(-z) I_0(z)$, $z = k_\perp^2 \rho_i^2$ and $I_0(z)$ the modified Bessel function. In the long wavelength approximation $k_\perp^2\rho_i^2 << 1$ we have $\omega_k = k_z v_A [1 + k_\perp^2 \rho_s^2 (1+3T_i/4T_e)]$ [for a detailed review see, e.g., *Stasiewicz et al*, 2000]. Recently, it has been found [Pokhotelov et al., 2004; Onishchenko et al., 2004c] that KAWs do not generate zonal structures.

2. Basic model

2.1 Parametric interaction of IAWs. The parametric instability of IAWs can be qualitatively investigated in the framework of the following simple considerations. Using the Laplace equation $\nabla^2\phi = -\varepsilon_0^{-1} e n^c$, where ϕ is the electrostatic potential of the electrostatic convective cell, $n^c = n_i^c - n_e^c$, n_i^c and n_e^c are the ion and electron number density perturbations in the convective cells, respectively, we obtain equation for the generation of electrostatic convective cells

$$\partial_t n^c = -\frac{\beta_A v_A^2}{c^2}\nabla\cdot(\mathbf{Q}_i - \mathbf{Q}_e). \qquad (1)$$

Here $\partial_t \equiv \partial/\partial t$, $\mathbf{Q}_i$ and $\mathbf{Q}_e$ are the fluctuation induced ion and electron fluxes, respectively

$$\mathbf{Q}_i = n\overline{\mathbf{v}_P} = \frac{\overline{\mathbf{j}_\perp}}{e} = -\frac{\overline{\{\psi, \nabla_\perp\psi\}}}{\mu_0 v_A^2 e B_0} \qquad (2)$$

and

$$\mathbf{Q}_e = -\frac{\overline{\mathbf{B}_\perp j_z}}{eB_0} = -\frac{\overline{\nabla_\perp^2 A(\nabla A\times\hat{\mathbf{z}})}}{\mu_0 e B_0}. \qquad (3)$$

The over bar denotes the averaging over the fast time $\propto 1/\omega_k$ and over short spatial interval $\propto 1/k_z$ Alfvenic perturbations. Here $\mathbf{v}_P = \omega_{ci}^{-1} d_t(\mathbf{E}_\perp/B_0)$ is the ion polarization drift velocity, $\mathbf{E}_\perp = -\nabla_\perp\psi$ and $\mathbf{B}_\perp = \nabla A\times\hat{\mathbf{z}}$ are perpendicular components of the electric and magnetic fields of high frequency Alfvenic perturbations, ψ and A are the electrostatic potential and the z-component of the vector potential $\mathbf{A}$, $\nabla_\perp = \nabla - \hat{\mathbf{z}}\times\nabla$, $\hat{\mathbf{z}}$ the unit vector along the ambient magnetic field $\mathbf{B}_0$, $d_t = \partial_t + \mathbf{v}_E\cdot\nabla = \partial_t + B_0^{-1}\{\psi,...\}$ the convective time derivative, $\mathbf{v}_E = B_0^{-1}\hat{\mathbf{z}}\times\nabla\psi$ the $\mathbf{E}\times\mathbf{B}$ drift velocity, $\{\varphi,\chi\} = \partial_x\varphi\partial_y\chi - \partial_y\varphi\partial_x\chi$ denotes the Poisson bracket, $\partial_x \equiv \partial/\partial x$ and $\partial_y \equiv \partial/\partial y$, $\mathbf{j}_\perp$ and j_z are the perpendicular and parallel components of the electric current. The ion and electron fluxes have different physical meaning and, thus, a different impact on the IAW parametric instability. The ion flux is due to the Reynolds stresses associated with the ion advection force $ne\mathbf{v}_E\cdot\nabla\mathbf{v}_E$ whereas the electron flux is due to the Maxwell stresses induced by the Lorentz force, $\mathbf{j}\times\mathbf{B}$. Using equations (2) and (3) and equations describing the coupling of IAWs, one can express the ion and electron fluxes through n^c and potentials ψ and A,

$$\partial_t \nabla \cdot \mathbf{Q}_i = \frac{c^2}{v_A^2} \frac{\beta_A}{B_0^2} \overline{\{\psi, \{\psi, n^c\}\}} \tag{4}$$

and

$$\partial_t \nabla \cdot \mathbf{Q}_e = \frac{c^2}{B_0^2} \overline{\{A, \{A, n^c\}\}}. \tag{5}$$

Substituting (4) and (5) into (1), we obtain

$$\partial_t^2 n^c = -\frac{\beta_A}{B_0^2} [\beta_A \overline{\{\psi, \{\psi, n^c\}\}} - v_A^2 \overline{\{A, \{A, n^c\}\}}], \tag{6}$$

$\partial_t^2 \equiv \partial^2 / \partial t^2$. In the linear approximation the high-frequency potentials are connected through the relation $\psi_k = v_A \beta_A^{1/2} \Lambda_I^{1/2} A_k$. Using this relation, we obtain in the limit of a narrow wave packet of Alfven waves the zonal structure density oscillations

$$\partial_t^2 n^c - 2\frac{q^2 k^2}{B_0^2} | \psi_k |^2 \left(\beta_A^2 - \frac{1}{\Lambda_I} \right) n^c = 0, \tag{7}$$

where ψ_k is the Fourier amplitude of the Alfven wave, q is the wave number of the zonal structure. It is accepted that $\mathbf{q} \perp \mathbf{k}$. Equation (7) shows that the instability exists when $\lambda_e^2 k^2 / (1 + \lambda_e^2 k^2) + \beta_A^2 > 1$ that corresponds to the case when the electron flux is larger than the ion flux. In the limit $v_A^2 / c^2 << 1$ the instability thus appears when $\lambda_e^2 k^2 / (1 + \lambda_e^2 k^2) > 2 v_A^2 / c^2$. Therefore, the most favorable conditions for the parametric instability of IAWs are realized in the lower ionosphere, far below the maximum of the Alfven velocity.

2.2 Parametric interaction of KAWs. In the high-latitude ionosphere the transition from low $\beta < m_e / m_i$ to finite $\beta > m_e / m_i$ plasmas occurs at altitudes $(2-3)R_E$. At those altitudes the electron inertia is small and the dominant dispersion effect is due to the finite ion Larmor radius effect (FLR). Under such condition the equation for the generation of electrostatic convective cells analogous to equation (1) can be represented as

$$(\hat{\Gamma} - 1)\partial_t \phi = -B_0^{-1} (\{\psi, \hat{\Gamma} \psi\} - v_A^2 \rho_i^2 \{A, \nabla_\perp^2 A\}), \tag{8}$$

where the operator $\hat{\Gamma} = \exp(\rho_i^2 \nabla_\perp^2) I_0 (-\rho_i^2 \nabla_\perp^2)$ accounts for the FLR effect in the so-called Pade approximation. The first and second terms on the right-hand side of equation (8) proportional to the fluctuation induced ion and electron fluxes, $\mathbf{Q}_i$ and $\mathbf{Q}_e$. It has been shown [*Pokhotelov et al.*, 2004*; Onishchenko et al.* 2004c] that in contrast to the parametric interaction of IAWs the ion flux that plays a stabilizing role is larger than that of the electron one that leads to the stability of KAWs with respect to the interaction with zonal structures.

3. Conclusions

According to the FAST measurements [*Chaston et al.*, 2003a, b], the value of the parameter v_A / c in the maximum of the Alfven velocity (the so-called Dessler's maximum) differs substantially for the day- and nighttime conditions. During the daytime, this ratio is of the order of 0.1-0.2, whereas during the nighttime, v_A / c becomes of the order of unit. Thus, under the nighttime conditions, the parametric instability can be suppressed. It is the case of nighttime ionosphere that is of the most interest for our study. The IAW generation (e.g., as a result of feedback instability) is the most favorable during this time [*Trakhtengertz and Feldstein*, 1991].

Observations provided by the IC-Bulgaria 1300 [*Chmyrev et al.*, 1988; 1992] and FAST [*Stasiewicz et al.*, 2000; *Chaston et al.*, 2003a,b] satellites in the auroral zone, below the maximum of the Alfven velocity, indeed give the evidence of the existence in the ionosphere of damping large-amplitude (up to 100 nT) Alfven waves and large-scale electrostatic convective perturbations. At higher altitudes, where the Larmor radius is larger than the skin depth, the appearance of convective cells, according to the Polar data [*Wygant et al.*, 2000], was not noticed. These facts indirectly confirm the results of our analysis of the parametric instability of KAWs in a finite-pressure plasma [*Pokhotelov et al.*, 2004; *Onishchenko et al.*, 2004c].

Acknowledgements. This research was partially supported by the Russian Fund for Basic Research through the Grant No. 04-05-64657, by ISTC under Research Grant No. 2990, and by the Russian Academy of Sciences through the Grant "Physics of the Atmosphere: electrical processes and radiophysical methods".

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