Features of generation of broadband waves of the ion-cyclotron and the ion-acoustic type in the auroral ionosphere

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Summary

To study instabilities caused by inhomogeneities of the electric field and plasma density in the auroral zone, numerical algorithms are developed and computational modeling are performed for different conditions in the background plasma. It is shown that the dispersion relation has unstable solutions in a wide range of frequencies and wavenumbers. These solutions manifest themselves in satellite observations as a broadband spectrum of electrostatic perturbations. In addition to inhomogeneous energy-density-driven waves of ion-cyclotron type, ionospheric structures are capable of destabilizing oblique ion acoustic waves modified by a shear in the parallel drift of ions.

1. Introduction

Broadband emissions (broadband ELF (extremely low frequency) turbulence or noise) in the magnetosphere-ionosphere system at high latitudes are registered under different conditions in the near-Earth plasma. One of the first attempts to describe generation of electrostatic waves was the theory of the excitation of ion-cyclotron waves by field-aligned currents. The classical theory of the generation of electrostatic ion-cyclotron waves by field-aligned current assumes that the current is constant and uses a local approach [1]. Later, this theory was applied to the ionosphere [2]. But it could not explain the ELF turbulence for several reasons. The theory predicts narrow-band spectrum, and not a broadband. Furthermore, ion heating by broadband turbulence must lead to suppression of ion-cyclotron instability, which is not observed in reality.

Theory of electrostatic ion-cyclotron waves in plasma is the most appropriate for the interpretation of the observed broadband electrostatic noise in the Earth's auroral region. Inhomogeneous localized electric fields and inhomogeneities of the plasma density can destabilize electrostatic ion-cyclotron waves obtained as unstable solutions of nonlocal dispersion equation for ion-cyclotron disturbances and their properties differ significantly from the classical ion-cyclotron waves. Such instabilities can lead to heating of ions in the Earth's ionosphere and the subsequent outflow of ions into the magnetosphere. Two points, regarding the theory of this turbulence, remain unclear [3]. One is the source or sources of free energy which drive the turbulent emissions. The observed ionospheric structures contain various types of inhomogeneities capable of destabilizing electrostatic waves. Their combined effect on the growth of electrostatic instability needs to be quantitatively investigated.

Therefore, to study the instabilities that result from nonuniform distribution of the electric field and the plasma density in the auroral region, computational algorithms are developed in this work and numerical simulations under different conditions of the background plasma are carried out. Nonlocal dispersion equation is analyzed for this purpose, and it is shown that there are unstable solutions in wide range of frequencies and wave numbers which are detected in satellite measurements as broadband spectrum of electrostatic perturbations. Comparison of the two generation mechanisms in the presence of density gradients and of inhomogeneous electric field is performed.

The other point remaining unclear is the branch of the ELF turbulence. Its identification from spacecraft data is somewhat controversial. Some works, based on their observations of close to perpendicular propagation angles, related the observed waves to the electrostatic ion-cyclotron branch. At the same time, in some papers, it was reported on the events of predominantly parallel polarization of electrostatic emissions, which were interpreted in terms of the ion-acoustic branch. In both cases, the broadband character of the electrostatic turbulence in the auroral zone is emphasized. Our numerical analysis shows that in addition to inhomogeneous energy-density-driven waves of ion-cyclotron type, ionospheric structures are capable of destabilizing oblique ion acoustic waves modified by a shear in the parallel drift of ions. In this work, to gain a deeper insight in generation of these waves, numerical algorithm solving the dispersion relation of the instability is developed and computational modeling is performed with various plasma parameters.

2. Governing equations

In this work, we consider nonlocal instabilities in a warm plasma driven by inhomogeneities of plasma density as well as of electric field. The theory of these instabilities is described in detail in the articles [4,5]. Uniform magnetic field is directed along the z-axis, nonuniform electric field is along the x-axis. Plasma is inhomogeneous in the x-direction as well. In general, studying instability in such a plasma configuration requires solving integro-differential equation but in some cases (smallness of dispersion and smallness of the Larmor radius compared to characteristic size of plasma inhomogeneity) it reduces to ordinary differential equation [5]. This results in the nonlocal dispersion relation

$$\frac{d^2\psi}{d\xi^2} + \kappa^2(\xi)\psi = 0, \qquad (1)$$

where $\xi = x / \rho_i$ is the x coordinate normalized to the ion gyroradius,

$$\kappa^2(\xi) = -2\frac{1 + \sum \Gamma(b) A_{ni}(\xi) + \tau(1 + A_{0e})}{\sum \Gamma'(b) A_{ni}(\xi)}, \qquad (2)$$

$$A_{n\alpha} = \frac{\omega_1 + \omega_{2\alpha} - \omega_\alpha^*}{k_z v_{t\alpha}} Z\left(\frac{\omega_1 - \omega_{2\alpha} - n\Omega_\alpha}{k_z v_{t\alpha}}\right). \qquad (3)$$

In expressions (1)–(3), we use the following notation: $\tau = T_i/T_e$ is the ion-to-electron temperature ratio, $v_{t\alpha}$ is the thermal velocity of particles of species α, Ω_α is the gyrofrequency of particles of species α, $\omega_1 = \omega - k_y V_E - k_z V_d$, V_d is magnetic field aligned flow, $\omega_{2\alpha} = k_y V''_E \rho_\alpha^2/2$, $\omega_\alpha^* = k_y \Omega_\alpha \rho_\alpha \varepsilon_n$, $\varepsilon_n = (\rho_\alpha n_0(\xi))/(dn_0(\xi)/d\xi)$, $\Gamma'_n = d\Gamma_n/db$, and Z is the plasma dispersion function.

3. Numerical solution and analysis of the simulation results

In this study, equation (1) is solved numerically by the shooting method. The transverse electric field is approximated by a piecewise-constant function. At each j th interval, $\kappa^2(\xi)$ is constant and $\psi(\xi)$ is represented by the sum of two exponentials, $\psi_j(\xi) = B_j \exp(i\kappa_j\xi) + \tilde{B}_j \exp(-i\kappa_j\xi)$. In the boundary intervals, there is only one exponential and the sign of the root of κ^2 is chosen such that the function ψ vanishes at infinity. At the matching points, continuity conditions are imposed on the function $\psi(\xi)$ and its derivative.

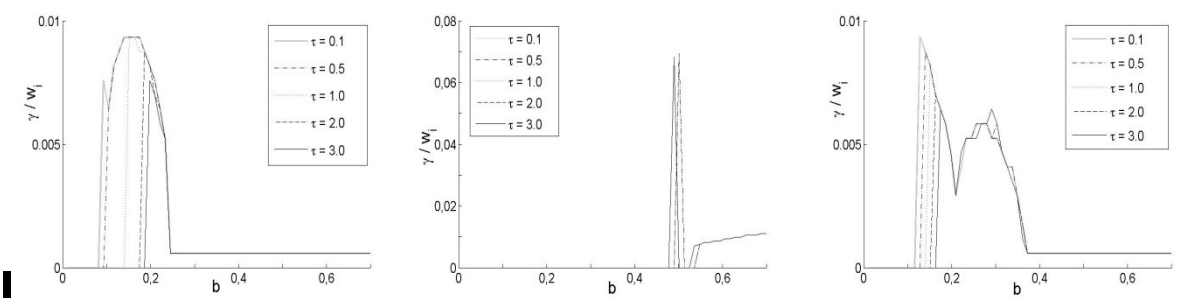

Figure 1. Growth rate of IEDDI (normalized to the gyrofrequency of O+ ions) in the presence of only an inhomogeneous electric field (left), only inhomogeneities of the plasma density (middle), inhomogeneities of both the electric field and the plasma density (right) vs. parameter $b = (k_y\rho_i)^2/2$ for different values of the parameter $\tau = T_i/T_e$: 0.1 (solid gray line), 0.5 (dash-dotted line), 1.0 (dotted line), 2.0 (dashed line), and 3.0 (solid heavy line). The ratio of the longitudinal component of the wave vector to its transverse component is constant, $u = 0.1$, and the other parameters are $\omega_r = 0.98\Omega_i$, $\rho_i = 10$ m, and $V_d = 0.1v_{te}$.

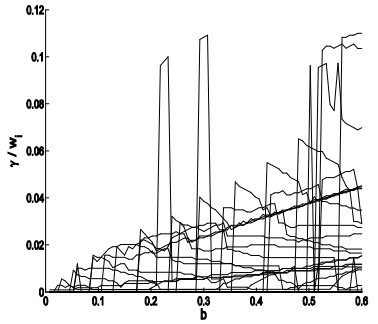

Figure 2. Unstable solutions for IEDDI waves obtained for 40 values of the real frequency ω_r near the ion gyrofrequency Ω_i for ω_r/Ω_i from 0.8 to 1.2. Inhomogeneities of both the plasma density and the localized electric field were taken into account.

The problem is reduced to a system of homogeneous linear equations for the coefficients before exponentials. It can be written in the matrix form as $M \times h = 0$, where h is the column vector composed of the coefficients B_j and $\tilde{B}_j$ and the matrix M is defined by the matching conditions. A nontrivial solution to this system exists if $\det M = 0$. As a result, we obtain a dispersion relation that allows one to find a set of eigenvalues for each set of plasma parameters. The values of the electric field and plasma density for the background configuration were taken from [6], where observational data from the *Freja* satellite were used. When solving the problem, it was assumed that the plasma consists of electrons and oxygen ions.

Figure 1 illustrates the unstable solutions obtained for different values of the ion-to-electron temperature ratio $\tau = T_i/T_e$ at $u = 0.1$. Here, the solid gray line corresponds to $\tau = 0.1$; the dash-dotted line, to $\tau = 0.5$; the dotted line, to $\tau = 1.0$; the dashed line, to $\tau = 2.0$; and the black heavy line, to $\tau = 3.0$. It is clearly seen that the domain where solutions exist narrows with increasing ion-to-electron temperature ratio. This is because, as T_i increases, the wave phase velocity falls in the region of the ion distribution function where ion Landau damping is stronger. Since, in this case, additional energy supply is required to maintain instability, its development is suppressed. It should be noted that, if only plasma density inhomogeneities are included, the domain where solutions exist is narrower than in the case where there are only inhomogeneities of electric field. We can see that the excitation domain is wider considering inhomogeneities of both the electric field and the plasma density than in the cases where inhomogeneities of only the electric field or only the plasma density are taken into account.

Figure 2 shows unstable solutions for IEDD waves obtained for 40 values of the real frequency ω_r near the ion gyrofrequency Ω_i. The ratio ω_r/Ω_i takes values from 0.8 to 1.2 with a step of 0.01. The parameters of the background plasma used in the numerical solution are as follows: $\rho_i = 10$ m, $V_d = 0.1v_{te}$, $\tau = 0.5$, and $u = 0.1$. In these runs, we took into account inhomogeneities of both plasma density and electric field. It is seen from Fig. 2 that there are a lot of different roots, i.e., unstable solutions exist in a wide range near the first cyclotron resonance.

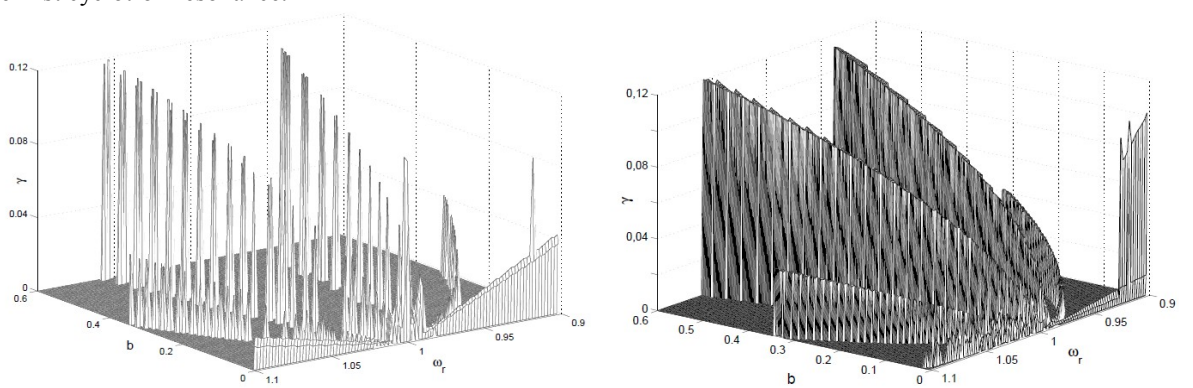

Figure 3. The growth rate of the IEDD instability normalized by gyrofrequency of oxygen ion depending on parameter *b* and real part of wave frequency. Only inhomogeneous electric field is considered. Model distribution with maximum 0.1 mV/m (left) and 100 mV/m (right) is used.

For purposes of clarity, three-dimensional plots in the coordinates ω_r, $b = (k_y\rho_i)^2/2$, γ are presented in this work. These plots allow us to show dependence of governing parameters of the problem more elaborately. We use parabolic dependence on coordinate x for model distributions of electric field and plasma density. In Fig. 3, computational results with model distributions of electric field with maximum values of 0.1 mV/m and 100 mV/m are presented. Background plasma parameters adopted in the run are the following: $\rho_i = 20$ m, $V_d = 0.9v_{te}$, $\tau = 0.5$, and $u = 0.1$ Replacement of complex experimental dependence of electric filed by the model distribution with the same characteristic value of electric field has only a weak effect on the IEDDI solution. As inferred from comparison of Fig.3 (left) and Fig.3 (right), the instability generation diminishes with

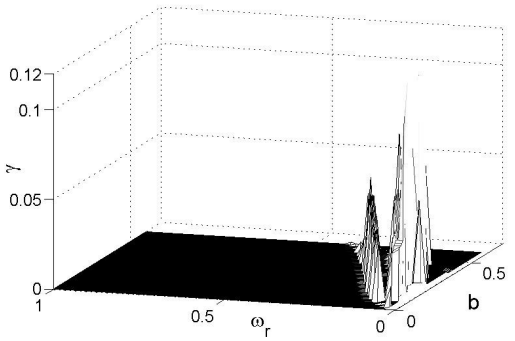

Figure 4. Possibility oblique ion acoustic modes modified by a shear in the parallel drift of ions exist in auroral ionosphere

decreasing gradient of electric field. Also, we conclude that inhomogeneities of plasma density do affect instability generation but this influence is smaller than the influence of electric field inhomogeneities. This result is in accordance with the fact that inhomogeneities of plasma density have a higher order of smallness than inhomogeneities of electric field in equation (1).

Our numerical analysis shows that in addition to inhomogeneous energy-density-driven waves of ion-cyclotron type, ionospheric structures are capable of destabilizing oblique ion acoustic waves modified by a shear in the parallel drift of ions. Figure 4 shows unstable solutions obtained for oblique ion-acoustic modes. The parameters of the background plasma used in the numerical solution are as follows: $\rho_i = 10$ m, $\tau = 0.1$, and $u = 0.1$. Figure 4 demonstrates existence oblique ion acoustic modes in auroral ionosphere. It is shown that only the inhomogeneities of field-aligned current can excite oblique ion-acoustic waves. It is demonstrated that in contrast to the ion-cyclotron mode, gradient of the field-aligned current has a significant influence on the excitation of ion-acoustic mode.

5. Conclusions

We have shown that, in contrast to the earlier concepts, electrostatic waves with an inhomogeneous energy density distribution can be excited not only by localized inhomogeneous electric fields, but also by plasma density inhomogeneities. When inhomogeneities of both electric field and plasma density are taken into account, the domain where solutions exist is getting wider, i.e., these two mechanisms of electrostatic wave excitation in the auroral zone operate jointly. We have shown that broadband electrostatic noise in the auroral zone can be identified as a kind of electrostatic ion-cyclotron waves excited due to the onset of IEDDI. For this kind of instability to develop, localized inhomogeneous electric fields and/or inhomogeneities of the plasma density are required. It was shown that the form of detailed distributions of electric field, as well as of plasma density, is of minor importance for instability generation. The amplitude of inhomogeneity is a more important factor. The instability is generated in some range of u values, which characterizes the direction of wave propagation. The ionospheric structures are effective in destabilizing the transverse velocity-shear-assisted (or IEDD) waves as well as ion-acoustic waves modified by shear in the parallel drift of ions. The observational fact that different branches may dominate the electrostatic turbulence in different conditions can be explained by the interplay of various destabilizing factors inside a particular structure. In our study, we have shown that oblique ion-acoustic waves modified by a shear in the parallel drift of ions can be generated and only the inhomogeneities of field-aligned current can excite oblique ion-acoustic waves in auroral zone.

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6. References

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