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Large-scale zonal flow and magnetic field generation due to drift-Alfven turbulence in ionosphere plasma

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ABSTRACT

In the present work, the generation of large-scale zonal flows and magnetic field by short-scale collision-less electron skin depth order drift-Alfven turbulence in the ionosphere is investigated. The self-consistent system of two model nonlinear equations, describing the dynamics of wave structures with characteristic scales till to the skin value, is obtained. Evolution equations for the shear flows and the magnetic field is obtained by means of the averaging of model equations for the fast-high-frequency and small-scale fluctuations. It is shown that the large-scale disturbances of plasma motion and magnetic field are spontaneously generated by small-scale drift-Alfven wave turbulence through the nonlinear action of the stresses of Reynolds and Maxwell. Positive feedback in the system is achieved via modulation of the skin size drift-Alfven waves by the large-scale zonal flow and/or by the excited large-scale magnetic field. As a result, the propagation of small-scale wave packets in the ionospheric medium is accompanied by low-frequency, long-wave disturbances generated by parametric instability. Two regimes of this instability, resonance kinetic and hydrodynamic ones, are studied. The increments of the corresponding instabilities are also found. The conditions for the instability development and possibility of the generation of large-scale structures are determined. The nonlinear increment of this interaction substantially depends on the wave vector of Alfven pumping and on the characteristic scale of the generated zonal structures. This means that the instability pumps the energy of primarily small-scale Alfven waves into that of the large-scale zonal structures which is typical for an inverse turbulent cascade. The increment of energy pumping into the large-scale region noticeably depends also on the width of the pumping wave spectrum and with an increase of the width of the initial wave spectrum the instability can be suppressed. It is assumed that the investigated mechanism can refer directly to the generation of mean flow in the atmosphere of the rotating planets and the magnetized plasma.

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1. Introduction

In recent years, special attention has been paid to the study of the generation of large-scale spatial-inhomogeneous (shear) zonal flows and magnetic field turbulence in the magnetized plasma medium in laboratory devices, as well as in space conditions (Diamond et al., 2005). Such interest firstly is caused by the fact that the excitement of the zonal flows and large-scale magnetic field generation can lead to noticeable weakening of anomalous processes, stipulated by relatively small-scale turbulence and by passage to the modes with improved property of adaptation to the equilibrium state (Diamond et al., 2005; Kamide and Chian, 2007). Zonal flows are the integral parts of the collective activity of the majority of the planetary atmospheres and are manifested in the form of the large-scale low-frequency modes, propagating along the parallels (Busse, 1994; Aubert et al., 2002). The possibility of such generation is intensively studied via some of the basic modes of the turbulence. At the present time, a question about the generation of zonal modes is mostly studied by the electrostatic drift, relatively long-wave modes, characteristic transverse wavelength of which is greater than a Larmor radius of ions according to the electron temperature (Smolyakov et al., 2000; Shukla and Stenflo, 2002) and by some other electrostatic modes (Mikhailovskii et al., 2006a).

The previous authors made the trials of investigations of the special features of the zonal flow generation by means of drift-Alfven type fluctuation on the basis of three sufficiently simplified models, describing nonlinear interaction between these

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modes: the first, a class of the models in which the effect of the ion temperature is negligible and only the effect of the so-called finite Larmor radius of ions according to the electron temperature (Guzdar et al., 2001; Lakhin, 2003) is taken into account; the second model, where both disturbances, the primary small-scale as well as the large-scale zonal disturbances, have characteristic scale less than a Larmor radius of ions ρ_i (Smolyakov et al., 2002); and the third class of the models, where finite Larmor radius of ions are considered neglecting the skin size inertial effects (Lakhin, 2004; Mikhailovskii et al., 2006b; Shukla, 2005). Although in the work (Pokhotelov et al., 2003), generation of the zonal flow was studied by inertial Alfven fluctuations. But, it was made in uniform plasma neglecting finiteness of a Larmor radius of electrons, ions (T_e, $T_i \to 0$).

One of the important wave modes in non-uniform magnetized space (Stasiewicz et al., 2000; Sahraoui et al., 2006; Narita et al., 2007) as well as in laboratory (Gekelman, 1999; Mikhailovskii, 1978) plasma media are electromagnetic small-scale drift-Alfven (SSDA) modes with the transverse wavelengths, small in comparison with a Larmor radius of ions, $k_\perp \rho_i \gg 1$, where $\rho_i = (T_i/m_i \omega_{Bi}{}^2)^{1/2}$ is a Larmor radius of ions, $k_\perp$—transverse (according to external equilibrium magnetic field B_0) wave number, $\omega_{Bi} = eB_0/m_i c$—ion-cyclotron frequency, T_α—the temperature of ions with $\alpha = i$ and electrons with $\alpha = e$, respectively, e—elementary ion charge, m_α—the mass of ion with $\alpha = i$ and electron with $\alpha = e$, respectively, c is the speed of light. These small-scale fluctuations can generate large-scale zonal modes as in the space and as in the laboratory plasma. Moreover, the contemporary theory of anomalous transfers (Kadomtsev, Pogutse, 1984; Aburjania, 2006, 1990) predicts that the anomalous thermal conductivity and diffusion in the plasma medium may be stipulated, in essence, by the processes with the characteristic wavelength $\lambda_\perp$ of the order of collision-less skin length λ_s, $\lambda_\perp = 2\pi/k_\perp \sim \lambda_s = c/\omega_{Pe}$, where $k_\perp$ is transversal (according to external equilibrium magnetic field) wave number of perturbations, $\omega_{Pe} = (4\pi e^2 n_0/m_e)^{1/2}$ is a plasma frequency. In this connection, description of the nonlinear wave processes on the scales $\lambda_\perp \sim \lambda_s < \rho_i$ appears necessary. Therefore, elaboration of the self-consistent system of nonlinear equations, describing the dynamics of SSDA wave processes, with the characteristic scales till to the skin size, i.e., taking into account a finite Larmor radius of ions and inertia processes, represents one of the goals of this work. Further, on the basis of these dynamic equations, an investigation of the special features of the nonlinear development of collective activity in the ionosphere medium on SSDA modes is important.

At present, there prevails the point of view, according to which, the spontaneous generation of large-scale zonal modes (or convective cells) are the result of the secondary instability of plasma fluctuations (Diamond et al., 2005). At the basis of instability, there lies the nonlinear interaction of the primary fluctuations (pumping of one of the types of relatively short drift waves, swinging by some known linear or nonlinear mechanisms), which results in the zonal flow generation. Positive feedback is ensured by modulation of the amplitudes of primary plasma fluctuations by secondary large-scale shear zonal mode, and instability can be related to the class of parametric (or modulation) instabilities. The generation of such large-scale (in comparison with the small-scale primary modes) structures can substantially increase energy transfer via medium particles.

According to investigation methods of the above-mentioned nonlinear processes, the works already existing in this direction can be divided into two groups. To the first group can be attributed the works which are based on ideas and methods of the classical theory of coherent parametric instabilities (Oraevskii, 1984) and frequently called the "parametric" approach. In them, the interaction processes of the finite number of waves are examined: pumping waves; the shear flows (wave with the low, sometimes with zero frequency) and one or two satellites of the pumping wave (Sagdeev et al., 1978; Guzdar et al., 2001; Smolyakov et al., 2002; Mikhailovskii et al., 2006c). The second and alternative group includes the works Smolyakov et al. (2000); Lakhin (2003, 2004), in which there lies an assumption about the separation of the scales of turbulence into small-scale and the zonal flow (large-scale), developed at the time in the work (Vedenov, Rudakov, 1964). In this approach, the small-scale turbulence is described by the wave kinetic equation, in which the influence of zonal flow is considered. In the work Smolyakov et al. (2002), it is shown that given the initial approximations the above-mentioned approaches lead to the identical results.

In this work, for investigation of the zonal flow generation by means of skin scale SSDA fluctuations in the ionosphere plasma, we use the "parametric" approach, which, as already is mentioned above, goes back to the method used in the theory of convective cell generation (Sagdeev et al., 1978). The method of this approach has been improved in recent works (Mikhailovskii et al., 2006b, c) in the sense that, instead of the separate monochromatic packet of primary modes, the spectrum of these modes with arbitrary width is investigated. In our opinion, this approach is more visual and more adequate for this problem. Consequently, this work is organized as follows. Initial nonlinear equations for our task are represented in Section 2. There on the basis of the analysis of the linear stage of disturbance propagation, we determine frequency spectrum of those investigated by us SSDA skin scale pumping waves. In Section 3, we introduce the excited values, which characterize the primary small-scale modes (pumping), secondary small-scale modes (satellites) and the zonal flows. Further in Section 3, initial equations for amplitudes of the pumping waves, satellites and the zonal modes are formulated. Here, also, the solution of these equations is conducted and expressions for the amplitudes are determined. Dispersion equation for the large-scale zonal flow and the magnetic field for the arbitrary continuous spectrum of pumping are obtained in Section 4. The analysis of this equation for the monochromatic small-scale (of order of a skin size) and relatively large-scale waves, and also for the different practically important spectra of the pumping waves is carried out in Section 5. Here, the correspondent growth increments and the criterion of zonal flow generation are determined. Section 6 is concerned with investigating the influence of the non-monochromaticity of different pumping waves on the zonal flow instability development. Finally, in Section 7, the basic results of this investigation are assembled.

2. Initial dynamic equations

The equilibrium state of the ionosphere plasma we characterize with electron density ne_0, the single-charged ions n_{i0}, non-uniform along the axis x in the Cartesian coordinate system ($\nabla n_{j0} \| e_x$, $j = e$, i, where e_x is unit vector along the x axis), uniform temperature of the electrons T_e and the ions T_i (∇T_e, $\nabla T_i = 0$; $T_e \geq T_i$). Here, we introduce Cartesian local coordinate system, in which the x axis is directed along the parallel, y axis—along the meridian, and z axis—vertically up. Non-uniform equilibrium density ($n_0(x) = n_{e0}(x) = n_{i0}(x)$) is supported by external sources (for example, external electric field, volumetric forces and others). External equilibrium magnetic field B_0 we consider uniform and directed along the z axis, ($B_0 \| z$).

For electron's description let us use a electron continuity equation in a drift approximation

$$\frac{\partial n_e}{\partial t} + V_E \cdot \nabla n_e - \frac{1}{cB_0}(B \cdot \nabla)J_\| = 0, \tag{1}$$

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