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Impact of the Zonal Flows on the Relative Short-Scale ULF Electromagnetic Waves in the Shear Flow Driven Ionosphere

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ABSTRACT

Influence of the large-scale zonal flows and magnetic fields on the relative short-scale ULF electromagnetic waves in the dissipative ionosphere in the presence of a smooth inhomogeneous zonal wind (shear flow) is studied. A broad spectrum of Alfvenic-like electromagnetic fluctuations appears from electromagnetic drift turbulence and evidence of the existence of magnetic fluctuations in the shear flow region is shown in the experiments. In present work one possible theoretical explanation of the generation of electromagnetic fluctuations in DW-ZF systems is given. For shear flows, the operators of the linear problem are non-selfconjugate and therefore the eigenfunctions of the problem are non-normal. The non-normality results in linear transient growth with bursts of the perturbations and the mode coupling, which causes the generation of electromagnetic waves from the drift wave–shear flow system. We show that the transient growth substantially exceeds the growth of the classical dissipative trapped-particle instability of the system. Excitation of electromagnetic fluctuations in DW-ZF systems leads to the Attenuation-suppression of the short-scale turbulence.

Key Words: ULF electromagnetic waves, short-scale turbulence

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 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). Specifically, the experiments indicate that drift turbulence gives rise to a broadband spectrum of electromagnetic waves, which is the subject of the present study. The zonal flow is different from externally imposed shear flow in that the zonal flow is a self-organized turbulence driven phenomena. The fluctuation data show a broad spectrum of electromagnetic waves in the presence of large scale zonal flows. Alfvenic-like fluctuations appear from electromagnetic drift flow driven turbulence in experiments (Horton, 2005; 2009). Generation of broadband electromagnetic fluctuations in drift wave – zonal flow systems is a significant phenomenon because electromagnetic fluctuations can modify the anomalous transport. In addition, the characteristics of these fluctuations indirectly give information about the dynamics of this system. The reported Alfvenic-like fluctuations occur at high shear rates. The fluctuations in flows with high shear rates are strongly non-normal. The strong nonnormality results in linear transient growth with bursts of the perturbations and mode coupling, which indicates the generation of the electromagnetic waves at interaction of the drift waves with the large scale zonal flows.

However, many-year observations (Gekelman, 1999; Grzesiak, 2000; Guzdar et al, 2001) show that at the atmospheric and ionospheric layers the spatially inhomogeneous shear flows permanently exist and are produced by a nonuniform heating of the atmospheric layers by solar radiation. In this connection, it becomes important to investigate the problem at the presence of inhomogeneous shear winds.

The interest in shear flows exist, generally speaking, due to their occurrence both in the near-earth space (as has been mentioned above) and astrophysical objects (galaxies, stars, jet outbursts, the world ocean and so on) and in the laboratory and engineering equipment (oil and gas pipelines, plasma magnetic traps, magnetodynamic generators and so on). A flow velocity shear is a powerful source of various energy-consuming processes in a solid medium. Though these processes have been studied in the course of many years, their theoretical interpretation is difficult even in terms of linear approximation. The canonical (modal) investigation of linear wave processes (spectral expansion disturbances with respect to time followed by analysis of the eigenvalues) in shear flows does not take into account a highly important physical process, namely, the mutual transformation of wave modes (Chagelishvili et al, 1996; Gogoberidze et al, 2004).

Nonmodal approach correctly describes transient exchange of energy between basic shear flow and perturbations. The energy transfer channel is resonant by nature and leads to energy exchange between different wave modes (chagelishvili et al, 1996; Gogoberidze et al, 2004). The mutual transformation of different kinds of waves is studied numerically and analytically in (Aburjania et al, 2006; Aburjania, 2006) in detail for the ULF electromagneic Rossby type waves. The mutual transformation occurs at small shear rates if the dispersion curves of the wave branches have pieces nearby one another. Other possibility of energy transfer channel is nonresonant vortex and wave mode characteristic times are significantly different and nonsymmetric a vortex mode is able to generate a wave mode but not vice versa. This channel leads to energy exchange between vortex and wave modes, as well as between different wave modes. We concentrate on this channel of mode coupling because it is important at high shear rates.

2. Model Equations

We describe the dynamics of the drift Alfven waves by the following theoretical model –fluid equations (Aburjania et al. 2006):

$$\frac{d_0}{dt}\left(\frac{1}{\delta}\Delta_\perp A - A\right) - \frac{\partial\varphi}{\partial z} - \chi\frac{\partial A}{\partial y} + \nabla_\parallel A = 0, \qquad (1)$$

$$\frac{d_0}{dt}(\Delta_\perp\varphi - 0.5\sigma\Delta_\perp^2\varphi) + \nabla_\parallel\Delta_\perp A = 0, \qquad (2)$$

$$\frac{d_0 N}{dt} - \chi\frac{d\varphi}{dy} + \nabla_\parallel\Delta_\perp A = 0. \qquad (3)$$

Here the density perturbation, N, is normalized to the reference value of the background density value, n_0 - $N = \ln(n_0/n)$, the electrostatic potential, φ, to T_e/e , the parallel component of the vector potential, A, to $(c/c_A)(T_e/e)$; c_A is the Alfven velocity. Time derivative d_0/dt and space derivative along the total magnetic field, $\nabla_\parallel$, imply

$$\frac{d_0}{dt} = \frac{\partial}{\partial t} + V_{oz}(x)\nabla, \quad \nabla_\parallel = \frac{\partial}{\partial z} - \mathbf{e_z}[\nabla A\times\nabla]_z . \qquad (4)$$

In this model the ion and electron temperatures are assumed to be uniform (∇T_e , $\nabla T_i = 0;\ T_e \geq T_i$) and the temperature gradients are neglected. The perturbations are considered to be quasi-neutral, $N_e \sim N_i = N$.

Electric and magnetic fields are given as:

$$\mathbf{E} = -\nabla\boldsymbol{\varphi} - \frac{1}{c}\frac{\partial A_z}{\partial t}\mathbf{e_z}\ ,\ \mathbf{B}_\perp = [\nabla A_z\times\mathbf{e_z}], \qquad (5)$$

$B_z \gg B_\perp$ at $\beta \ll 1$.

We got:

$$\left(\frac{\partial}{\partial t} + V_0(x)\frac{\partial}{\partial z}\right)(\Delta_\perp\varphi + \sigma\Delta_\perp N - \frac{\sigma}{2}\Delta_\perp^2\varphi) + \frac{\partial}{\partial z}\Delta_\perp A + \Delta_\perp\varphi + \sigma\Delta_\perp N - 0.3\sigma D_2\Delta_\perp^2\varphi = 0, \qquad (6)$$

$$\left(\frac{\partial}{\partial t} + V_0(x)\frac{\partial}{\partial z}\right)A + \left(\frac{\partial}{\partial z} + S\frac{\partial}{\partial y}\right)\varphi - \chi\frac{\partial A}{\partial y} - \frac{\partial N}{\partial z} = 0. \qquad (7)$$

$$\left(\frac{\partial}{\partial t}+V_0(x)\frac{\partial}{\partial z}\right)N+\frac{\partial\Delta_\perp A}{\partial z}-\chi\frac{\partial\varphi}{\partial y}+V'\frac{\partial A}{\partial y}+\Delta_\perp(\varphi-N)=0. \qquad (8)$$

Here, φ, A, N are perturbations of the scalar electrostatic potential, vector potential of the magnetic field and the density, respectively.

Hereafter, we use nondimensional variables and physical quantities. Spatial scales are normalized to the length scale of perturbations along the magnetic field $L_{\parallel}\sim 1/k_{\parallel}$ and time is normalized to the Alfvén wave time $\tau_A\sim 1/k_{\parallel}V_A$, shear flow is given as following:

$$\mathbf{V}_0(z)=v_0(z)\,\mathbf{e_x}\;=A\cdot z\cdot\mathbf{e_x},$$

$$x_1=x-azt,\quad y_1=y,\quad t_1=t, \qquad (9)$$

or

$$\frac{\partial}{\partial t}=\frac{\partial}{\partial t_1}-az\frac{\partial}{\partial x_1},\quad \frac{\partial}{\partial x}=\frac{\partial}{\partial x_1},\quad \frac{\partial}{\partial z}=\frac{\partial}{\partial z_1}-at_1\frac{\partial}{\partial x_1}. \qquad (10)$$

$$\tau\Rightarrow\omega_g t_1;\quad V_{x,z}\Rightarrow\frac{\tilde{V}_{x,z}}{\omega_g H};\quad \rho\Rightarrow\frac{\tilde{\rho}}{\rho_0};\quad P\Rightarrow\frac{-i\tilde{P}}{\rho_0\omega_g^2H^2};$$

$$(x,z)\Rightarrow\frac{(x_1,z_1)}{H};\ S\Rightarrow\frac{A}{\omega_g};\ \ k_{x,z}\Rightarrow k_{x_1,z_1}H;\ \ k_z=k_z(0)-k_xS\tau;$$

$$k^2(\tau)=(k_x^2+k_z^2(\tau));\ b_0\Rightarrow\frac{\sigma_P B_0^2}{\rho_0\omega_g};\ \ b_y\Rightarrow\frac{\sigma_P B_y^2}{\rho_0\omega_g};$$

We present the following perturbations in a linear approximation:

$$\begin{Bmatrix}\varphi\left(k_{x_1},k_{y_1},t_1\right)\\ A\left(k_{x_1},k_{y_1},t_1\right)\\ N\left(k_{x_1},k_{y_1},t_1\right)\end{Bmatrix}=\begin{Bmatrix}\varphi_k(\tau)\\ A_k(\tau)\\ N_k(\tau)\end{Bmatrix}\times e^{(ik_{x_1}x_1+ik_{y_1}z_1+iy_1)} \qquad (11)$$

with

$$k_{\mathbf{x}}(\tau)=k_{\mathbf{x}}(0)-S\cdot k_{\mathbf{z}}\cdot t,$$

The wavenumbers of the SFH modes vary in time along the flow shear. In the linear approximation, SFH “drift” in the **K**-space in wavenumber space.

For each Fourier harmonics we will have:

$$(1+\frac{\sigma}{2}k_\perp^2)\frac{\partial\varphi}{\partial\tau}=-i\sigma\chi k_y\phi-ik_z(1+\sigma k_\perp^2),$$

$$\frac{\partial A}{\partial\tau}=-ik_z\phi+i\chi k_yA+ik_zN, \qquad (12)$$

$$\frac{\partial N}{\partial\tau}=-i\chi k_y\phi+ik_zk_y^2A,$$

With $k_\perp^2(\tau)=k_{\mathbf{x}}^2(\tau)-k_{\mathbf{z}}^2$,

This system of equations corresponds to spectrally stable DWs. In fact, low frequency DWs are subject to the trapped-particle instability.

In the simulations below, the quadratic form of (spectral energy density) for a separate SFH as a measure of its intensity is

$$E(\tau)=E_A(\tau)+E_\phi(\tau)+E_n(\tau) \qquad (13)$$

In the present analysis, this stretching physics is contained in the wave-number vector **K** time dependence induced by the shear flow parameter *S*. The effect is relatively easy to understand: convection of the initial structures stretches them in the direction of the sheared flow. This occurs for structures of all three fields:

vorticity, density, and magnetic flux. This time-dependent stretching induces a coupling between the three fields.

3. Linear Spectrum of the perturbations

The dispersion equation of our system may be obtained in the shearless limit *S*=0 using the full Fourier expansion of the variables, including time (Horton et al, 2009). Although the roots of the dispersion equation obtained in the shearless limit do not adequately describe the mode behavior in the shear case, we use this limit to understand the basic spectrum of the considered system. Hence, using Fourier expansion of the field vector we derive for the shearless limit the cubic dispersion relation:

$$(1+\frac{\sigma}{2}k_\perp^2)\omega^3+(k_y(1+\frac{\sigma}{2}k_\perp^2)-\sigma\chi k_y)\omega^2+(k_z^2(1+\sigma k_\perp^2)-\chi^2\sigma k_y^2-k_z^2k_y^2(1+\frac{\sigma}{2}k_\perp^2))\omega+ \\ -\chi k_y k_z^2(1+\sigma k_\perp^2)+\sigma\chi k_y k_z^2 k_\perp^2=0, \quad (14)$$

This third order dispersion equation describes three different modes of perturbations: two high frequency kinetic Alfvén waves and a low frequency DW. Due to the nonzero electron skin depth scale the Alfvénic-like fluctuations are dispersive with ω dependent on K_x. This fact is very important for mode coupling since K_x is time dependent in nonuniform flow, which, in turn, makes ω also time dependent. The dispersion equation is solved numerically for the parameters taking *S*=0 and the real parts of the dispersive curves, respectively, are plotted in Fig. 1.The plots show that the magnitude of the frequencies of Alfvénic-like fluctuations differ substantially from the DW frequency for all values of K_x. Consequently, the Alfvénic-like and DWs are linearly coupled solely by the nonresonant channel at sizeable shear flow rates.

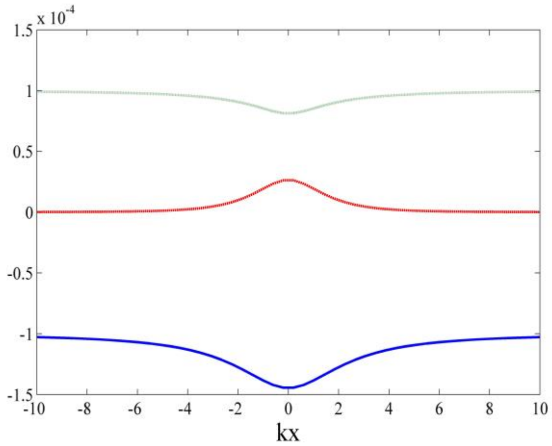

Fig. 1. Dispersion Curves.

Figure 1 shows that maximum values of frequency for the least stable DW mode are achieved at $K_X/K_Z \sim 1$. Thus, and the trapped-particle instability has no significant influence on the dynamical phenomena.

According to Eq. 14 in the shearless limit, when the axial vector potential is comparable to the electrostatic potential i.e., at $K_X/K_Z \gg 1$, DWs have a small electromagnetic component that arises from the parallel plasma current. However, as K_X/K_Z, $R_d \rightarrow 0$, DWs become electrostatic. As to the other two modes, they are Alfvénic-like with high frequency and have dominant magnetic fluctuations for all K_X. Next we will analyze the coupling of the DW mode with these Alfvénic-like modes.

4. **TRANSIENT GROWTH AND MODE COUPLING**

Spectral Fourier harmonics dynamics are studied by numerically solving the three complex time evolution equations 8, 9, and 10. Separation of the fields into the real and imaginary parts is made in the following way (Aburjania et al, 2006):

$$\varphi_k=\varphi_1+i\varphi_2, \quad A_k=A_1+iA_2, \quad N_k=N_1+iN_2, \quad (15)$$

For each Fourier harmonics we will have:

$$(1+\frac{\sigma}{2}k_{\perp}^{2})\frac{\partial\varphi}{\partial\tau}=-i\sigma\chi k_{y}\phi-ik_{z}(1+\sigma k_{\perp}^{2}), \quad (16)$$

$$\frac{\partial A}{\partial\tau}=-ik_{z}\phi+i\chi k_{y}A+ik_{z}N, \quad (17)$$

$$\frac{\partial N}{\partial\tau}=-i\chi k_{y}\phi+ik_{z}k_{y}^{2}A \quad (18)$$

Equations 16–18, together with the appropriate initial values, pose the initial value problem describing the dynamics of a perturbation SFH. The character of the dynamics depends on which mode SFH is initially imposed in the equations: pure DW SFH, one of the Alfvénic wave SFH or, or a mixture of these wave SFHs. Let us concentrate on the linear dynamics when we initially insert in Eqs. 16–18 a SFH nearly corresponding to a DW perturbation with wavenumbers satisfying the condition $K_X(0)/K_Z >> 1$. The numerical simulations are performed using the MATLAB numerical ordinary differential equation solver. Note that the action of the flow shear on the dynamics of DW SFH at wavenumbers $K_X(0)/K_Z >> 1$ is negligible.

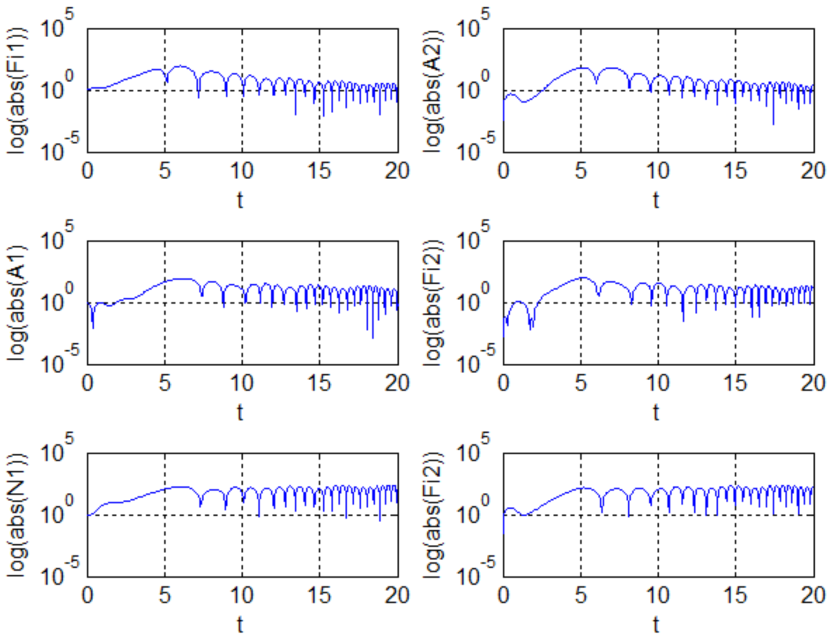

Fig. 2. The evolution of a single SFH

The simulations reveal a novel linear effect - the excitation of Alfvénic-like fluctuations - that accompanies the linear evolution of DW mode perturbations in the ZF. Mathematically, the problem is equivalent to time-dependent scattering theory in quantum mechanics. By using a 3x3 matrix representation of the system, formal solutions can be written in terms of the time ordering operator and exponentials of matrices.

The evolution of the initial DW SFH according to the dynamic equations (12) for the ionospheric parameters is presented in Fig. 2. Recall that K_X changes in time according to Eq. 14: the shear flow sweeps K_X to low values and then back to high values but with negative K_X/K_Z. While $K_X/K_Z >> 1$, the DW SFH undergoes substantial transient growth without any oscillations and the magnetic fluctuations are small. Significant magnetic field fluctuations appear when $K_X/K_Z = 1$. While $K_X/K_Z = 1 < 0$, the DW SFH generates the related SFH of Alfvénic-like wave modes through the second channel of the mode coupling. This generation of Alfvénic-like wave modes is especially prominent, where significantly higher frequency oscillations of all the fields are clearly seen at times when $K_X/K_Z = 1 < 0$. A substantial transient burst of the electron thermal energy, electron density of fluctuations is evident and an appearance of Alfvénic like fluctuations.

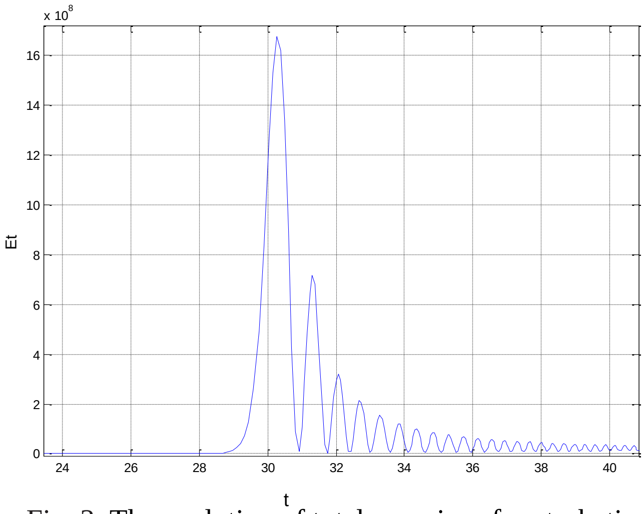

Fig. 3. The evolution of total energies of perturbation SFH

Figure 3 shows the related dynamics of the different energies. It indicates a substantial transient burst of the electron thermal energy of fluctuations and an appearance of Alfvénic like fluctuations.

4. CONCLUSIONS AND DISCUSSION

Drift-Alfvén waves are investigated in plasma with a significant level of background sheared flow. Magnetically confined plasmas in laboratory experiments, space physics, and coronal loops are examples where sheared flows occur.

We show that the linear dynamics of DWs are qualitatively changed by the presence of sheared flows when the shear normalized parameter *S* approaches unity and, consequently, there is strong excitation of magnetic fluctuations by the drift wave–shear flow system. The shear flow induces transient growth/bursts along with complex temporal wave forms and generates Alfvénic-like fluctuations from DWs. We show that the trapped-particle or any classical DW instability is far slower than these transient bursts and has no notable influence on the dynamic processes for the ionospheric parameter values. The frequency of the bursts is determined by the frequency of the generated Alfvénic-like waves Fig. 1. The frequency of the bursts depends only on the value of velocity shear parameter.

The complex linear dynamics are a result of the shear flow continually sweeping the wavenumber of the DW SFH K_X to low values and then back to high values. In this time-dependent sweeping of K_X, the DW SFH undergoes substantial transient growth and, when $K_X / K_Z < 0$, it generates the related SFH of Alfvénic-like wave modes illustrated in Fig. 2. The linear mode coupling channel universally leads to energy exchange between different perturbation modes at high shear rates. Flow non-normality induced mode coupling is related to the abrupt changes in magnetic turbulence during *L-H* transitions.

The energy evolution is easily produced by integrating the linear system of coupled field equations (see fig. 3). For sufficiently low values of the shear flow, the coupling becomes weak and the usual Doppler-shifted, well-separated modes of the linear system are recovered.

In space physics the effect is associated with sheared Earthward flows in the nightside plasma sheet that are driven by enhanced solar winds with southward embedded solar magnetic field components. Spacecraft in the plasma sheet measure high speed sheared flows driven by the convection electric field. Enhanced magnetic fluctuations associated with these flows are also observed. It remains to make a quantitative analysis of the magnetospheric problem. Finally, note that nonlinear simulations showing the growth of vortex structures out of the linear transients. Further nonlinear studies are being planned for the laboratory and space physics settings of this qualitatively new phenomenon.

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დიდმასშტაბიანი ზონალური დინებების ზეგავლენა შედარებით მცირემასშტაბიანი ულტრა დაბალი სიხშირის ელექტრომაგნიტურ ტალღებზე წანაცვლებით დინებიან იონოსფეროში

ხ. ჩარგაზია

რეზიუმე

ნაშრომში შესწავლილია დიდმასშტაბიანი ზონალური დინებებისა და მაგნიტური ველებს გავლენა შედარებით მცირემასშტაბიანი ულტრა დაბალი სიხშირის ელექტრომაგნიტურ ტალღებზე წანაცვლებით დინებიან დისიპაციურ იონოსფეროში. გამოვლენილია ალფენის მსგავსი ელექტრომაგნიტური ფლუქტუაციების ფართო სპექტრი, რომლებიც დაიმზირება ექსპერიმენტებში. წარმოდგენილ ნაშრომში წარმოდგენილია ელექტრომაგნიტური ფლუქტუაციების გენერაციის თეორიული ახსნა დრეიფულ ტალღა - ზონალური დინების სისტემაში. წანაცვლებითი დინებისათვის წრფივ ამოცანაში შემავალი ოპერატორები არარიან

თვით-შეუღლებადი და ამასთან, საკუთარი ფუნქციებიც - -არაორთოგონალური. აღნიშნული არაორთოგონალურობა განაპირობებს ფლუქტუაციების იმპულსურობას და მოდების ურთიერთკავშირს, რაც თავის მხრივ იწვევს ელექტორმაგნიტური ტალღების გენერაციას დრეიფული ტალღა - წანაცვლებითი დინების სისტემაში. ჩვენ ვაჩვენეთ, რომ მოდების ტრანზიენტული ზრდა მნიშვნელოვნად აღემატება სისტემის კლასიკურ დისიპაციურ წარტაცებული ნაწილაკების არამდგრადობას. ელექტრომაგნიტური ფლუქტუაციების გენერაცია აღნიშნულ სისტემაში იწვევს მცირე მასშტაბიანი ტურბულენტობის მილევას.

Влияние крупномасштабных зональных течений на сравнительно мелкомасштабных ультра низкочастотных (УНЧ) электромагнитных волн в ионосфере в присутствии неоднородных зональных ветров

Х.Чаргазиа

Резюме

Изучена влияние крупномасштабных зонального течения и магнитного поля на сравнительно мелкомасштабного ультра низкочастотных (УНЧ) электромагнитных волн в диссипативной ионосфере в присутствии неоднородных зональных ветров. В экспериментах показана появление широкого спектра Альвеновских флюктуации от электромагнитной дрейфовой турбулентности и возможность магнитных флюктуаций в сдвиговых течениях. В данной работе описана одна теоретическая возможность генерации электромагнитных флюктуации в ЗТ (зональное течение) – ДВ (дрейфовая волна) системе. При сдвиговых течениях операторы линейных задач не являются взаймно сопряженными и в следствии, соответствуюшие собственные функции не являются ортогональным. Неортогональность вызывает линейный транзиентный рост возмущений с пучками и взаймную трансформацию волновых мод, что приводит к генерацию электромагнитных волн в ЗТ– ДВ системе. Показано, что транзиентный рост волновых возмущений существенно превосходит классический диссипативный рост неустойчивости захваченных частиц системы. Излучение электромагнитных флюктуаций в ЗТ– ДВ системе приводит к затуханию мелкомасштабной турбулентности.