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NUMERICAL SIMULATION OF THE DYNAMICS OF FINE-SCALE IRREGULARITIES IN THE NEAR-EARTH RAREFIED PLASMA

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Abstract. The time evolution of the magnetic field aligned fine-scale irregularities in the electron concentration, existing in the near-earth rarefied plasma, is studied with the help of the model simulation. A two-dimensional mathematical model, developed earlier in the Polar Geophysical Institute, is utilized to investigate the temporal history of the sheetlike irregularity, created initially in the F-region ionosphere, during the period sufficient for the irregularity to decay completely. The utilized model is based on a numerical solution of the Vlasov-Poisson system of equations, with the Vlasov equations describing the distribution functions of charged particles and the Poisson equation governing the self-consistent electric field. The system of equations is numerically solved applying a macroparticle method.

Introduction

Electron density irregularities are often observed in the Earth's ionosphere. These irregularities have a wide range of spatial scales, ranging from a few Debye lengths to thousands of kilometers. The electron density depletions and increases inside irregularities can lie in the range from a few portions to some tens of percents (Fremouw et al., 1977; Martin and Aarons, 1977; Wong et al., 1983; Kersley et al., 1989; Pryse et al., 1991). Not large-scale irregularities are predominately magnetic field aligned. Usually, there are three generic types of their structures: rods, wings, and sheets. Rods are isotropic in the plane perpendicular to the geomagnetic field. Wings and sheets are elongated not only along geomagnetic field but also in the perpendicular plane along a certain direction (Livingston et al., 1982). Small-scale irregularities either are naturally present in the ionosphere, for example radio aurora (Sverdlov, 1982), or maybe artificially produced by high-power, high-frequency radio waves, pumped into the ionosphere (Wong et al., 1983). The purpose of this paper is to investigate numerically the time evolution of the ionospheric plasma sheetlike irregularity whose thickness is much less than the mean free path of particles between successive collisions and commensurable with a Debye length.

Numerical model

At F-layer altitudes, the ionospheric plasma is a rarefied compound consisting of electrons and positive ions in the presence of a strong, external, magnetic field. The studied irregularities are assumed to be geomagnetic field-aligned. In the vicinity of the irregularity, gradients of the plasma parameters in the longitudinal direction are supposed to be much less than those in a plane perpendicular to a magnetic field. Therefore, plasma parameters inside and beyond the irregularity may be considered as independent on the longitudinal coordinate. Hence, it is sufficient to consider a two dimensional flow of plasma in a plane perpendicular to a magnetic field line. The studied sheetlike irregularity has the perpendicular cross-section like a strait strip, with its cross-section sizes being much less than the mean free path of particles between successive collisions. To investigate the time evolution of the studied irregularity a two-dimensional mathematical model, developed earlier in the Polar Geophysical Institute, is utilized. In this model, kinetic processes in the plasma are simulated by using the Vlasov-Poisson system of equations, with the Vlasov equations describing the distribution functions of charged particles and the Poisson equation governing the self-consistent electric field. The Vlasov equations are numerically solved applying a macroparticle method. The Poisson equation is solved using a finite-difference method. More complete details of the utilized mathematical model may be found in the study of Mingalev et al. (2006). In the latter study, the mathematical model has been utilized for numerical simulation of the behavior of small-scale rodlike irregularities existing in the magnetospheric plasma. In the present study, this mathematical model is used to investigate the time evolution of fine-scale sheetlike irregularities, created initially in the F-region ionosphere, during the period sufficient for the irregularities to decay completely.

Presentation and discussion of results

The utilized mathematical model can describe the behavior of the near-earth plasma under various conditions. The results of calculations to be presented in this paper were obtained using the input parameters of the model typical for the nocturnal ionosphere at the level of 300 km. In particular, the value of the non-disturbed electron concentration (equal to the positive ion concentration) is 10^{11} m^{-3}. The electron and ion temperatures are supposed to be equal to 1213 K and 930 K, respectively. The bulk flow velocities of electrons and positive ions are assumed to be zero. The value of the magnetic field is $4.4 \cdot 10^{-5}$ T.

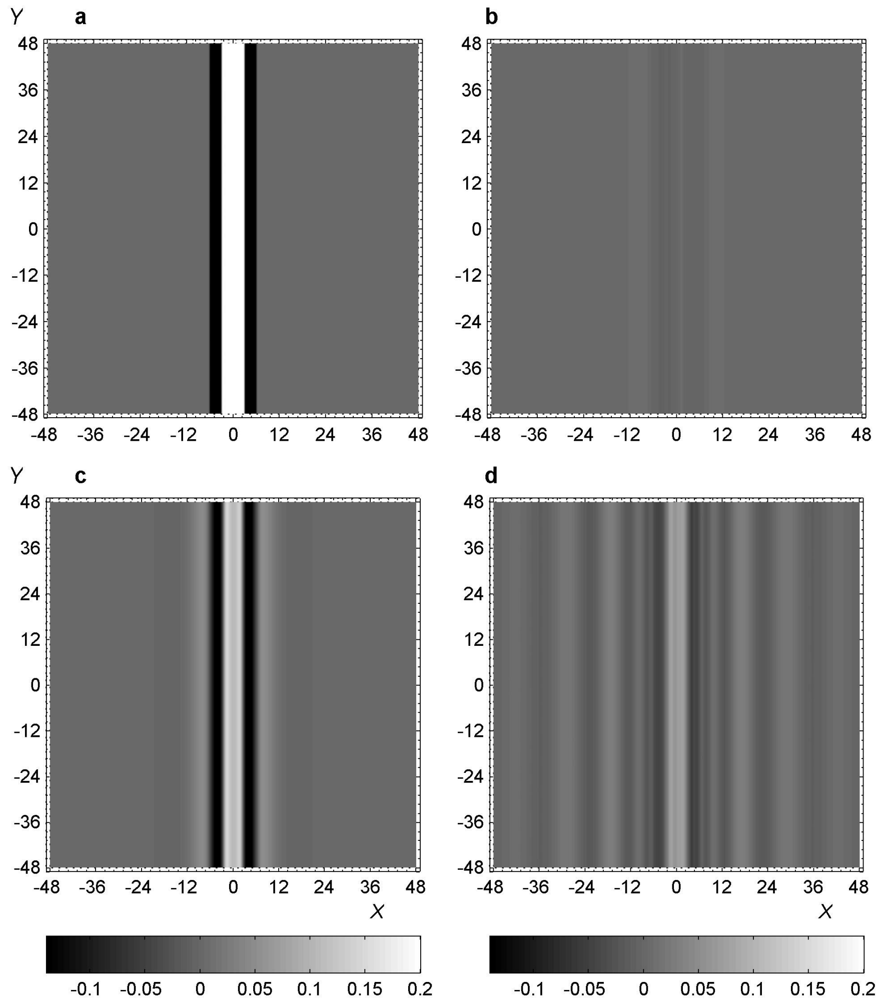

Fig. 1. The calculated spatial distributions of the relative decrease of the electron concentration, $(n_0 - n_e)/n_0$, in the plane perpendicular to the magnetic field. The distances (in the Debye length, $л_{De}^{0}$) from the central point of the simulation region are shown on the horizontal (*X*) and vertical (*Y*) axes. The results are given for the following moments: (a) $t = 0$, (b) $t = 0.74 \cdot u_{pe}^{0}$, (c) $t = 2.2 \cdot u_{pe}^{0}$, (d) $t = 14 \cdot u_{pe}^{0}$.

The above pointed out values yield the following quantities of some physically significant parameters. The equilibrium period of Langmuir oscillations of electrons, u_{pe}^{0}, is equal to $3.52 \cdot 10^{-7}$ s. The Debye length of the plasma, $л_{De}^{0}$, is $7.6 \cdot 10^{-3}$ m. The period of cyclotron oscillations of electrons, q_{ce}, is equal to $8.12 \cdot 10^{-7}$ s, that is, approximately a factor of 2.3 larger than the equilibrium period of Langmuir oscillations of electrons ($q_{ce} \approx 2.3 \cdot q_{pe}^{0}$). The collisional mean free path of charged particles is about 50 m. The mean free time of electron between successive collisions with other particles is larger than the equilibrium period of Langmuir oscillations of electrons by a factor of about 1047.

A two-dimensional simulation region lays in the plane perpendicular to the magnetic field line. The simulation region is a square and its side length is equal to 96 Debye lengths of the plasma. The grid width is equal to one eighth of the Debye length of the plasma. The quantity of the grid cells is 768×768. The time step for the electric field is equal to one hundredth of an equilibrium period of Langmuir oscillations of electrons.

Taking the input parameters of the mathematical model typical for the nocturnal ionosphere at the level of 300 km, we have calculated the time evolution of the distribution functions of charged particles as well as self-consisting electric field for two distinct on principle situations. In these situations, the initial distributions of electric charge density have been different.

The first situation corresponds to homogeneous spatial distributions of the electron and positive ion concentrations at the initial moment inside the simulation region, with the plasma being electrically neutral and the electric charge density being equal to zero.

The second situation corresponds to homogeneous spatial distribution of the positive ion concentration only. The spatial distribution of the electron concentration, at the initial moment, contains an irregularity like a strait straight strip intersecting the simulation region across its center. Inside the irregularity, the electric neutrality of the plasma is broken whereas, beyond it, the plasma is electrically neutral at the initial moment.

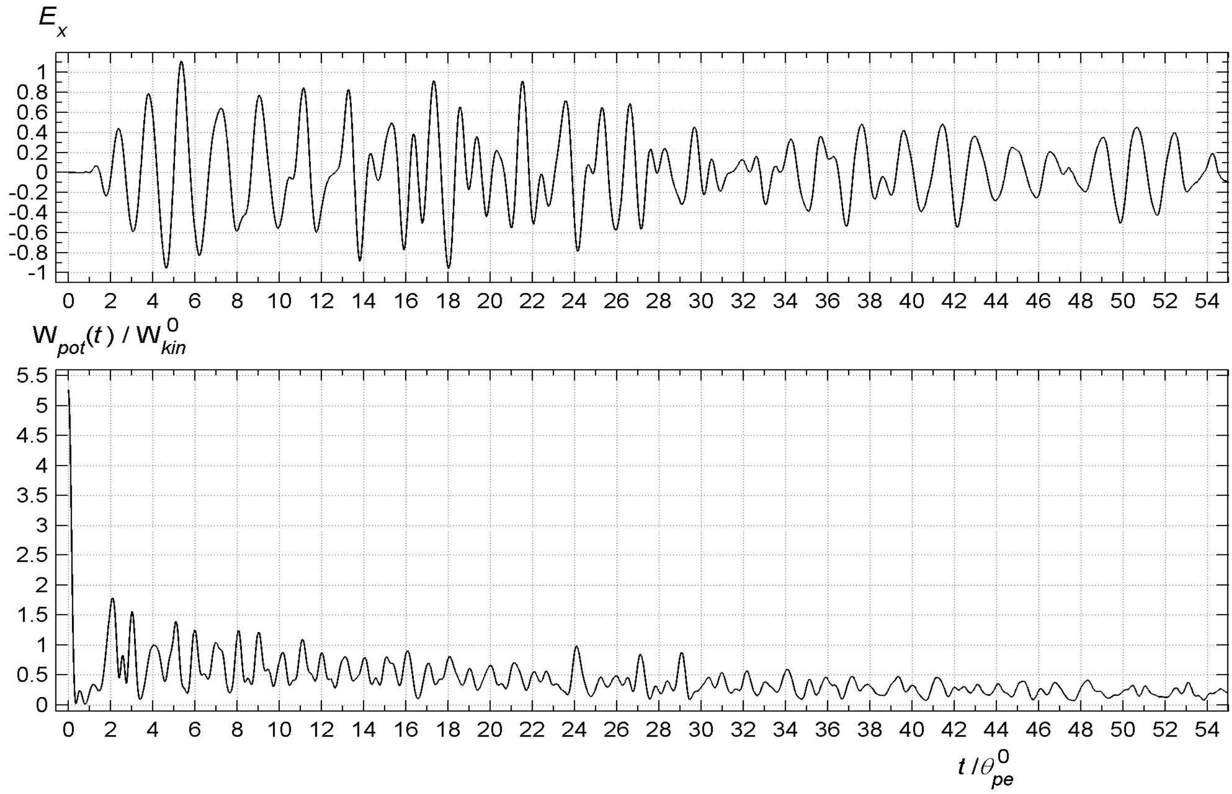

Fig. 2. The time variations of the electric field component, directed along the *X* axis, at the point, displaced from the center of the simulation region in the *X* direction for a distance of sixteen Debye lengths $\left(16 \cdot л_{De}^{0}\right)$, (top panel) and of the normalized potential energy of the plasma filling up all simulation region, $W_{pot}(t)/W_{kin}^{0}$, (bottom panel). The time in units of the equilibrium period of Langmuir oscillations of the electrons, u_{pe}^{0}, is shown on the horizontal axes.

Simulation results, obtained for the first situation when the process started from the completely electrically neutral state, indicate that the spatial distributions of the electron and positive ion concentrations tend to retain a homogeneity and electrical neutrality of the plasma. However, short-scale non-regular fluctuations of the calculated parameters of the plasma arise near their initial values, with amplitudes of these fluctuations being very little. The presence of the short-scale non-regular fluctuations of the calculated parameters of the plasma, referred to as a discrete noise, is due to the specific character of the applied macro-particle method, with the fluctuation amplitudes being conditioned by the number of macro-particles used in the calculations. It should be emphasized that the amplitudes of the fluctuations, obtained for the first situation when process started from the completely electrically neutral state, characterize the accuracy of the applied numerical method that cannot be exceeded in following calculations.

In the second situation, at the initial moment, the spatial distribution of the electron concentration contains an irregularity like a strait straight strip intersecting the simulation region across its center, with the spatial distribution of the positive ion concentration being homogeneous in all simulation region. Calculations were made for the case in which the initially created irregularity has the thickness of $12л_{De}^{0}$, where $л_{De}^{0}$ is the Debye length of the plasma. Inside this irregularity, a part of electrons traveled from the internal strip, having the thickness of $6л_{De}^{0}$, into the external strips, surrounding the internal strip. Calculations were performed for the case in which the relative decrease of the electron concentration $(n_0 - n_e)/n_0$, is equal to 0.2 in the internal strip at the initial moment. In other words, 20 percent of electrons were displaced from the center of the irregularity to its periphery. As a consequence of this displacement, an excess of positive charge appeared in the internal strip of the irregularity, while an excess of negative charge appeared in the strips surrounding it. The configuration of the initial irregularity in the plane perpendicular to the magnetic field is presented in Fig. 1a.

Simulation results, obtained for the second situation, indicate that, after initial moment, the spatial distribution of the electron concentration changes essentially while the positive ion concentration is retained practically invariable. It turns out that the initially created irregularity vanishes completely during a short period, with the plasma becoming electrically neutral in all simulation region at the moment near to the equilibrium period of Langmuir oscillations of the electrons. Figure 1b illustrates this condition. Further calculations indicate that the changes in the electron concentration are continued and, after a short period, the irregularity arises again to a moment of about $(2.2-2.3)\,u_{pe}^{0}$. This fact is illustrated by Fig. 1c. It can be seen that the recovered irregularity almost completely coincides with the initial one presented in Fig. 1a. Later, the cycle of vanishing and recovering of the irregularity is repeated again and again (Fig. 1d). Thus, the time evolution of the initially created irregularity is accompanied by periodic vibrations. After the first vibration, the period of these vibrations is equal to the equilibrium period of Langmuir oscillations of electrons. In the course of time, the amplitudes of the vibrations of the electron concentration and other parameters decrease smoothly, with the irregularity decaying little by little.

One of the parameters, characterizing the plasma, is a normalized potential energy of the plasma, filling in a spatial volume V, which may be defined as $W_{pot}(t)/W_{kin}^{0}$, where $W_{pot}(t)$ is the potential energy of the plasma, and W_{kin}^{0} is the initial kinetic energy of all particles filling in the volume V. Results of simulation indicate that the normalized potential energy of the plasma can fluctuate. Examples of fluctuating parameters of the plasma are presented in Fig.2.

Results of simulation indicate that, during the time interval of about 35 periods of Langmuir oscillations of electrons, the considered irregularity lost almost completely its initial structure, was diffused, and decayed.

It is of interest to note that, in the process of evolution, additional almost symmetrical alternate strips with an excess of charge of different sign begin to appear around the initial irregularity (Fig. 1d). In the course of time, these additional strips begin to fill up all simulation regions.

It can be noticed that we have made calculations for other cases in which the irregularity thickness and the initial relative decrease of the electron concentration inside the central strip of the irregularity were different. In essence, simulation results for these cases turn out to be qualitatively analogous to the results, obtained for the basic case, described above in this study, and presented in Figs. 1-2.

Conclusions

Results of numerical simulations were presented of the dynamics of the magnetic field aligned fine-scale irregularities in the electron concentration, created initially in the F-region ionosphere. The irregularities like sheet were considered which have the initial thickness equal to a few Debye lengths. The results were obtained by applying the earlier developed two-dimensional mathematical model, based on numerical solving the Vlasov-Poisson system of equations by using the macroparticle method. The simulation results indicated that, in the course of time, the irregularity decays accomplishing periodic damped vibrations, with the period of these vibrations being equal to the equilibrium period of Langmuir oscillations of electrons. The time interval of about 35 periods of Langmuir oscillations of electrons was sufficient for the irregularity to decay completely.

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