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3D model of small-scale density cavities in the auroral magnetosphere with field-aligned current

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ABSTRACT

We propose a 3D model of small-scale density cavities stimulated by an auroral field-aligned current and an oscillating field-aligned current of kinetic Alfvén waves. It is shown that when the field-aligned current increases so that the electron drift velocity exceeds a value of the order of the electron thermal velocity, the plasma becomes unstable to the formation of cavities with low density and strong electric field. The condition of instability is associated with the value of the background magnetic field. In the case of a relatively weak magnetic field (where the electron gyro-radius is greater than the ion acoustic wavelength), the current instability can lead to the formation of one-dimensional cavities along the magnetic field. In the case of a stronger magnetic field (where the ion acoustic wavelength is greater than the electron gyro-radius, but still is less than the ion gyro-radius), the instability can lead to the formation of 3D density cavities. In this case, the spatial scales of the cavity, both along and across the background magnetic field, can be comparable, and at the earlier stage of the cavity formation they are of the order of the ion acoustic wavelength. Rarefactions of the cavity density are accompanied by an increase in the electric field and are limited by the pressure of bipolar electric fields that occur within them. The estimates of typical density cavity characteristics and the results of numerical solutions agree with known experimental data: small-scale structures with a sufficiently strong electric field are observed in the auroral regions with strong field-aligned current.

1. Introduction

There are field-aligned currents in the auroral regions of the Earth's magnetosphere which are strong enough for the plasma turbulence excitation (Akasofu and Chapman, 1972). The field-aligned current achieves $(1-3)\cdot 10^6$A. Typically, these currents are closed through ionospheric areas with sufficient transverse conductivity.

Transverse inhomogeneity of the field-aligned currents may cause instabilities leading to the excitation of kinetic Alfvén waves (KAW) and inertial Alfvén waves (IAW) (Kozlovsky and Lyatsky, 1997; Wu and Seyler, 2003). Electrical currents of KAW and IAW can be comparable with the original field-aligned currents and sometimes exceed them. The largest current density in KAW is associated with the waves propagating nearly perpendicular to the background magnetic field and can achieve $\underset{\sim}{j} \sim \underset{\sim}{B}\omega_{pe}/\mu_0 c$, where $\underset{\sim}{j}$ and $\underset{\sim}{B}$ are the current density and the magnetic field in the Alfvén wave, ω_{pe} is the electron plasma frequency (Bespalov et al., 2006; Bespalov and Misonova, 2011). According to the FAST data, the current density in KAW is often of the order of $16\,\mu\text{A/m}^2$, whereas a typical density of the original field-aligned current is of the order of $1\,\mu\text{A/m}^2$ (Nakajima et al., 2007).

Small-scale plasma structures are observed in the auroral zone with field-aligned currents and electric currents of KAW and IAW (Stasiewicz et al., 2000a; Carlson et al., 1998; Chaston et al., 1998, 2000, 2004; Wygant et al., 2002; Genot et al., 2004). Observations onboard FAST spacecraft performed with a high spatial and temporal resolution have demonstrated the existence of density cavities with scale length of the order of several hundred meters. (Chaston et al., 2000, 2003a, 2003b, 2004). Small-scale density cavities were also observed from FREJA. The density depletion is deep enough: minimum density in structures related to the background density can be less than 0.5 (Louarn et al., 1994) and sometimes less than 0.1 (Chaston et al., 2000), in solitary structures can reach value 0.27 (Wu and Chao, 2004).

Sometimes the density deplation is more than 50% of the background density (Wu and Chao, 2004). These structures are

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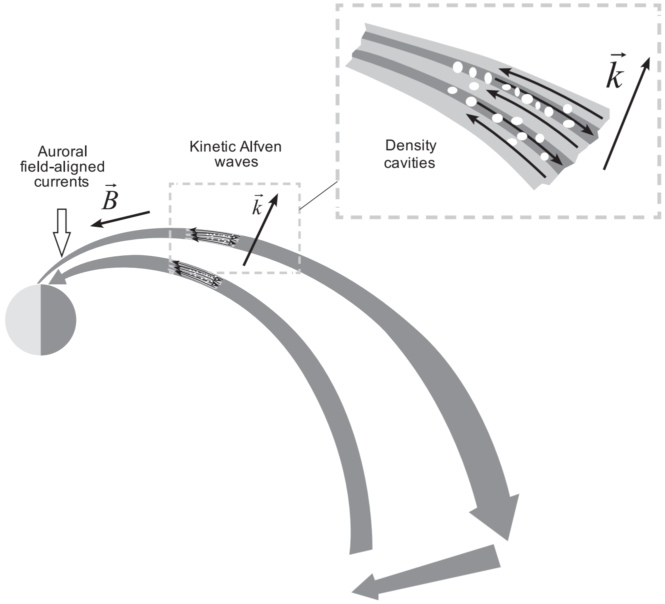

Fig. 1. Sketch of small-scale density cavities in the zone of auroral field-aligned currents and varying field-aligned currents of kinetic Alfvén waves propagating nearly perpendicular to the magnetic field $\boldsymbol{B_0}$.

associated with sufficiently strong (hundreds of mV/m) nonstationary spikes of the electric field (Louarn et al., 1994; Chaston et al., 2003a; Genot et al., 1999; Wu and Chao, 2004). Recent observations onboard VAN ALLEN PROBES spacecraft have shown the existence of electron holes of several hundred meters scales with antisymmetric electric field (Azmane et al., 2016). Small-scale density cavities in the regions with field-aligned electric currents of KAW are schematically shown in Fig. 1.

The processes associated with field-aligned current regions are also of great theoretical interest. For example, some mechanisms have been proposed to explain the properties of the double layers (Langmuir, 1913; Carlqvist, 1972; Kan et al., 1979; Kan and Lee, 1980; Belova et al., 1980; Borovsky and Joyce, 1983; Gurevich et al., 1985; Yadav et al., 1994). Large-scale density cavities associated with ponderomotive effects and Joulean heating have been studied in (Volosevich and Galperin, 1999) and (Stasiewicz et al., 2000b). Nonlinear electric field structures including large-amplitude ion cyclotron waves in the upward current region, and intense, spiky bipolar electric fields in the downward current region, were reported in (Ergun et al., 1998). A two-dimensional model of the nighttime auroral ionosphere has been developed to study the effects of the auroral current systems (Zettergren and Semeter, 2012). The model of magnetosphere-ionosphere coupling was considered in (Russell et al., 2015). In their model, the strong electric field associated with an intense downward field-aligned current, is a signature of the ionospheric plasma depletion caused by the downward current. The density distribution and electric potential structure inside the auroral density cavity in the auroral acceleration region were studied using CLUSTER data in (Alm et al., 2013, 2014, 2015a,b).

In our previous papers (Bespalov and Misonova, 1998, 2001, 2002), a model of small-scale structures with a fairly strong electric field was used to explain some properties of the accelerated charged particle fluxes in the auroral region. In (Bespalov and Misonova, 2002, 2011; Bespalov et al., 2006), this model was developed for the one-dimensional case. It has been shown that if the electron drift velocity along the magnetic field exceeds the electron thermal velocity (Bunemann's instability condition), then the plasma becomes unstable to the formation of density cavities. This leads to the formation of cavities with low density and a fairly strong electric field. In Bespalov and Misonova (2002) and Bespalov et al. (2006), we have shown that such cavities can effectively accelerate charged particles and have examined the properties of the accelerated fluxes. In Bespalov and Misonova (2011), we have considered the problem of anomalous plasma conductivity associated with density cavities.

In this paper, we propose a three-dimensional model of the formation of small-scale density cavities. In Section 2, we find a 3D equation governing the processes of the density cavity formation in a relatively strong background magnetic field and low background plasma frequency (2.1) and ascertain the condition of small-scale density perturbation instability (2.2). In Section 3, we analyze the instability growth caused by the ion acoustic perturbation (3.1), give a typical numerically computed solution (3.2), and estimate the main characteristics of the density cavity (3.3). The estimates and the results of numerical solutions agree with known experimental data. We mention that three-dimensional small-scale structures can appear in strong electric current regions where the electron gyro-frequency exceeds the electron plasma frequency. Such conditions can be realized in the auroral density cavity constituting the boundary between a dense cold ionospheric plasma and a hot plasma sheet. Inside the cavity, the electron density is often lower than 0.3 cm^{-3}(Alm et al., 2013, 2014, 2015a, 2015b).

2. Instability of small-scale density perturbations in the regions with strong field-aligned currents

2.1. The 3D equations governing the processes of density cavity formation in a relatively strong background magnetic field

We now consider the stability of the regions of strong field-aligned current to the formation of small-scale density cavities. To describe the cavity formation process, we use the equations of two-fluid magnetohydrodynamics for a fully ionized plasma (Artsimovich and Sagdeev, 1979), in which we neglect the Coloumb collisions and assume that the plasma pressure obeys the polytropic law. Thus, we write

$$\frac{\partial n_{e,i}}{\partial t} + \mathrm{div}\left(n_{e,i}\vec{u}_{e,i}\right) = 0, \tag{1}$$

$$m_{e,i}n_{e,i}\left(\frac{\partial \vec{u}_{e,i}}{\partial t} + (\vec{u}_{e,i}, \nabla)\vec{u}_{e,i}\right) = \mp e n_{e,i}\left(\vec{E} + \left[\vec{u}_{e,i}, \vec{B}_0\right]\right) - \nabla p_{e,i}, \tag{2}$$

$$p_{e,i}/n_{e,i}^{\gamma_{e,i}} = \text{const},\ \ p_{e,i} = n_{e,i}k_B T_{e,i}. \tag{3}$$

In these expressions, $m_{e,i}$ are the masses, $n_{e,i}$ are the number densities, $p_{e,i}$ are the partial pressures, $u_{e,i}$ are the individual bulk velocities, $\gamma_{e,i}$ are the politropic indices, e is the electron charge, and k_B is Boltzmann's constant. The indices e and i and the «$\mp$» signs in Eq. (2) correspond to the electron and ion components, and $\vec{B}_0$ is the background magnetic field. Taking into account that the typical velocity of the processes of interest is much less than the speed of light and thus considering the electric field as a potential, we complete the system of Eqs. (1)–(3) by the Gaussian equation

$$\frac{e(n_i - n_e)}{\varepsilon_0} = \mathrm{div}\left(\vec{E}\right),\quad \vec{E} = -\nabla(\varphi). \tag{4}$$

We use also the following assumptions:

1. the characteristic ion velocity is much less compared with the