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Research paper

Obliquely propagating low-frequency magnetospheric electrostatic solitary waves in the presence of an oxygen-ion beam

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A B S T R A C T

Nonlinear propagation of finite amplitude low-frequency electrostatic solitary waves is examined in a magnetized three-component plasma consisting of a cold singly-charged oxygen-ion beam and Boltzmann distributed background protons and electrons. The theoretical analysis is carried out by assuming the charge neutrality condition at equilibrium. Using parameters determined from satellite observation data for the magnetopause and plasma sheet regions of the Earth's magnetosphere, the model shows the existence of positive polarity soliton structures with amplitudes that decrease as the obliquity of the wave propagation increases.

1. Introduction

Satellite observation [1–5] of broadband electrostatic noise (BEN) has received much attention in the several past decades due to its frequent occurrence in the Earth's magnetosphere. High time resolution measurements have consistently recorded the presence of several ions species (e.g. H^+, O^+ and He^+), including ion beams, in different regions of the Earth's Magnetosphere, such as auroral acceleration region [6–8], plasma sheet boundary layer [9–12], magnetosheath [13,14], magnetopause [15,16], and the outer radiation belts [17]. The energetic ion beams provide the free energy to generates broadband turbulence which includes electrostatic solitary waves having either positive or negative, or both positive and negative electric field potential structures. The occurrence of such nonlinear electrostatic solitary structures has been verified in Laboratory set-ups [18,19]. With regard to the magnetosphere in particular, Ergun et al. [7] have reported the observation of electrostatic solitary waves in the auroral region, as have Mozer et al. [17] more recently in the outer radiation belt.

The consistent observation of BEN has triggered the interest of theoreticians. Many theoretical analyses have been done to explain the nonlinear electrostatic structures observed in various regions of the Earth's magnetosphere in the form of solitons, double layers and supersolitons [20–32]. For the auroral plasma composed of isothermal cold and hot electrons with H^+, O^+ ion beams, Reddy et al. [33] predicted, for wave propagation perpendicular to the magnetic field, the nonlinear excitation of fast and slow hydrogen (as well as oxygen) beam acoustic modes, which can be either rarefactive or compressive solitons or rarefactive double layers. Nakamura [34] investigated one-dimensional electrostatic solitary waves in a three component plasma consisting of electrons, negative ions and a positive ion-beam, using the small amplitude Korteweg-

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de Vries (KdV) technique. In the presence of oxygen and hydrogen ion beams, Lakhina et al. [35] proposed a theoretical explanation in terms of soliton or BGK modes/phase space holes for the solitary pulses associated with bipolar electric field structures observed in the auroral plasma. Ghosh and Lakhina, [36] studied the propagation of large amplitude waves in a four component auroral plasma composed of hydrogen and oxygen ions with two Boltzmann distributed background electrons. The model predicted both positive and negative potential soliton structures using the Sagdeev pseudo-potential technique. Verheest et al. [37] presented a multi-ion plasma model with two electron temperatures to analyze the necessary conditions for the existence of large amplitude low-frequency solitary structures in an unmagnetized plasma. Lakhina et al. [38] predicted the possibilities of obtaining three types of solitary structures namely, low-frequency slow and fast ion-acoustic solitons with positive potential, and both positive and negative potential high-frequency electron-acoustic solitons. Their plasma model composed of background cold electrons and ions, and a hot electron and an ion beam. In a recent study, Rufai [39] presented the existence of obliquely propagating low-frequency solitons and supersolitons in a two-ion species plasma composed of a cold ion fluid, Boltzmann distributed hot protons and non-thermal hot electrons. In a later paper, Rufai et al. [40] showed the coexistence of low-frequency compressive soliton and rarefactive supersoliton structures in a magnetized four-component plasma made up of a cold singly-charged oxygen-ion fluid, Boltzmann distributed hot protons, cool and hot electron species.

In the present study, we consider a magnetized three-component plasma consisting of a cold singly-charged oxygen-ion beam and Boltzmann distributed electron and proton species, and investigate the effect of the oxygen-ion beam velocity on the evolution of nonlinear finite amplitude low-frequency solitary waves in the Earth's magnetosphere, using plasma parameters for the magnetopause and plasma sheet regions as determined by Wang et al. [41] from an analysis of THEMIS data. In Section 2, the theoretical model and localized stationary solutions are presented. The numerical results and discussion follow in Section 3. Finally, the conclusions are presented in Section 4.

2. Theoretical model

We consider a homogeneous, magnetized three-component, collisionless plasma consisting of electrons (N_e, T_e), protons (N_p, T_p) and a cold singly-charged oxygen-ion beam ($N_i, T_i = 0$) drifting along the magnetic field direction $\mathbf{B}_0 = B_0\hat{z}$ with speed v_0, where $N_j(T_j)$ is the density (temperature) of the jth species. Satellite observations have recorded the existence of such a beam [4,8]. Wave propagation is in the (x, z)-plane at an angle θ to $\mathbf{B}_0$. Then, the normalized governing set of fluid equations is given by:

$$\frac{\partial n_i}{\partial t} + \frac{\partial (n_i v_x)}{\partial x} + \frac{\partial (n_i v_z)}{\partial z} = 0 \tag{1}$$

$$\frac{\partial v_x}{\partial t} + \left(v_x \frac{\partial}{\partial x} + v_z \frac{\partial}{\partial z} \right) v_x = -\frac{\partial \psi}{\partial x} + v_y \tag{2}$$

$$\frac{\partial v_y}{\partial t} + \left(v_x \frac{\partial}{\partial x} + v_z \frac{\partial}{\partial z} \right) v_y = -v_x \tag{3}$$

$$\frac{\partial v_z}{\partial t} + \left(v_x \frac{\partial}{\partial x} + v_z \frac{\partial}{\partial z} \right) v_z = -\frac{\partial \psi}{\partial z} \tag{4}$$

where n_i is the oxygen ion density, v_x, v_y and v_z are the components of the oxygen ion velocity along x, y, and z directions, ϕ is the waves electrostatic potential, respectively. The phase velocity of the oscillation is considered to be much less than the electron and proton thermal velocities (i.e $v_\phi \ll v_{te}$, v_{tp}). Then we may use the Boltzmann distribution for the thermal electrons and protons, given respectively as:

$$n_e = \exp(\psi) \tag{5}$$

and

$$n_p = (1 - p)\exp(-\alpha_p \psi). \tag{6}$$

In the above equations, the charge neutrality condition at equilibrium is given by $N_{e0} = N_{i0} + N_{p0}$. The normalization used are: densities are normalized by the electron density N_{e0}, velocities are normalized by the speed $C_s = (T_e/m_i)^{1/2}$ (where m_i is the oxygen ion mass), distance is normalized by the ion Larmor radius, $\rho_i = C_s/\Omega$, time t is normalized by the inverse of oxygen-ion gyro-frequency Ω^{-1} ($\Omega = eB_0/m_i c$), and electrostatic potential ϕ is normalized by T_e/e, with $\psi = e\phi/T_e$. Then, $p = N_{i0}/N_{e0}$ and the temperature ratio $\alpha_p = T_e/T_p$. Our system is closed with the quasi-neutrality condition which is valid for low-frequency phenomena, i.e.

$$n_i + n_p = n_e \Rightarrow n_i = \exp(\psi) - (1 - p)\exp(-\alpha_p \psi). \tag{7}$$