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Effect of hot ion temperature on obliquely propagating ion-acoustic solitons and double layers in an auroral plasma

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ABSTRACT

Properties of obliquely propagating ion-acoustic solitons and double layers in a magnetized auroral plasma composed of hot adiabatic ions and two types of, cool and hot Maxwellian electrons are studied using Sagdeev pseudo-potential technique and assuming the quasi-neutrality condition. The new and surprising result which emerges from the model is that in contrast to the case of cold ions where ion-acoustic solitons and double layers are found for subsonic Mach numbers only, the hot ions case allows these nonlinear structures to exist for both subsonic and supersonic Mach number regimes. The double layers exist at lower angle of propagation as hot ion temperature is increased. The soliton electric field amplitudes are increased but their width and pulse duration are decreased with the increase in hot ion temperature. For the auroral zone parameters, the maximum electric field amplitude, width, pulse duration and speed for the solitons come out to be in the range $\sim$ (0.3–15) mV/m, $\sim$ (195–455) m, (7–20) ms and (22–26) km/s, respectively. The results seem to be in agreement with the Viking satellite observations in the auroral zone.

1. Introduction

The fact that space is occupied with nonlinear wave phenomena has attracted many researchers. Soliton and double layer formation and propagation are among the most interesting and challenging problems in space plasmas. Washimi and Taniuti [1] investigated the properties of the Kortweg-deVries (KdV) equation of small amplitude nonlinear ion-acoustic solitary waves in a cold collisionless plasma. Using the fluid equations, Sagdeev [2] described the properties of solitons in a plasma consisting of hot isothermal electrons and cold ions. More extensive investigations on laboratory experiment [3,4] and theoretical analysis [5–9] have been done on the existence and behaviours of ion-acoustic solitary waves in various plasmas. Later, the observations of solitary waves propagating along the auroral magnetic field lines were reported by the several spacecraft missions: S3-3 [10], Viking [11], FREJA [12], POLAR [13,14] and FAST [15–17] satellites.

The existence of ion-acoustic solitary waves and double layers in a plasma consisting of two electron temperatures have been investigated by many authors in the past [18–23]. Small amplitude ion-acoustic double layers and solitons in auroral magnetized plasma consisting of hot and cold electrons and two ions (oxygen-hydrogen) have been studied by Reddy and Lakhina [24]. Their analysis predicted either negative potential double layers, or negative potential solitons or positive potential solitons in distinct parametric space. Reddy et al. [25] extended the analysis to include any number of ion beams and found that the fast and slow hydrogen (as well as oxygen) beam-acoustic modes can be generated which can be either

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rarefactive double layers or rarefactive or compressive solitons. Sayal et al. [26] studied the propagation characteristics of ion-acoustic rarefactive soliton in a two electron temperature unmagnetized plasma with two cold ions, using kinetic and fluid models for both the ion species. Motivated by the measurements performed by FREJA [12] and Swedish Viking satellites at low altitudes region of auroral plasma, Cairns et al. [27] predicted the coexistence of ion-acoustic solitons with both density peaks and density depressions in plasma consisting of ions and electrons. Berthomier et al. [28] described the characteristics of ion acoustic solitary waves and weak double layers in the presence of two electron species in an unmagnetized plasma with finite ion temperature. Using a model consistent with satellite observations, Kourakis and Shukla [29] presented the theoretical and numerical analysis for ion-acoustic solitary waves in an unmagnetized, collisionless, three-component plasma, composed of positive cold ion fluid moving in a background of two thermalized electron population. Ghosh and Lakhina [30] exploited the measurements by POLAR satellite to explain the width-amplitude variation of rarefactive ion-acoustic solitary waves in the auroral plasma. Employing the Sagdeev pseudo-potential technique, they investigated analytically solitary structures in both unmagnetized and magnetized multi-ion plasmas with two electrons temperature. Verheest et al. [31] discussed the necessary conditions for large amplitude ion acoustic solitons in unmagnetized multi-ion plasma with two electron temperatures. Recently, Lakhina et al. [32,33] highlighted the possibilities of the existence of three types of solitary waves, depending on the Mach number regime e.g., slow ion-acoustic, ion-acoustic and electron-acoustic solitons. These were predicted in their proposed model for arbitrary amplitude nonlinear ion- and electron-acoustic solitary waves in an unmagnetized multi-component plasma consisting of cold background electrons and ions, hot electron and ion beams. In a recent study, Lakhina et al. [34] showed the possibilities of ion-acoustic, slow and fast electron-acoustic soliton/double layer, depending upon the plasma parameters. The results were related to the observations of the electrostatic solitary waves (ESWs) observed in the Earth's magnetosphere by the Cluster satellite. More recently, Rufai et al. [35] extended the work of Berthomier et al. [28] and Baluku et al. [36] by assuming magnetized ion species. They investigated the finite amplitude ion-acoustic solitary wave and double layer structures in a magnetized plasma consisting of cold ions and two-temperature electrons and applied their results to Viking satellite observations in the auroral region.

In this paper, we investigate electrostatic solitary waves and double layer structures in a magnetized plasma consisting of an adiabatic ions fluid and two Maxwellian electron populations. Our present investigation extends the recent work of Rufai et al. [35] by including the effect of a finite ion temperature through the adiabatic condition. The inclusion of finite ion temperature pushes the limits of both minimum and maximum Mach numbers for solitons to higher sides. Section 2 present the basic set of equations governing the dynamics of plasma system. In Section 3, we obtain the localized solution of nonlinear finite amplitude waves, using the Sagdeev potential technique for solitons and double layers. Detailed numerical results are presented in Section 4 and discussion and conclusions are drawn in Section 5.

2. Theoretical model

We consider the collisionless, homogeneous plasma with adiabatic ions and two temperature electrons, in presence of an external static magnetic field ($B_o = B_o\hat{z}$), along the z-direction and waves are propagating in the (x, z)-plane. The two group of electrons, cool electrons (N_c, T_c) and hot electrons (N_h, T_h) are assumed to follow Boltzmann distribution, i.e.,

$$N_c = N_{c0}\exp\left(\frac{e\phi}{T_c}\right) \tag{1}$$

$$N_h = N_{h0}\exp\left(\frac{e\phi}{T_h}\right) \tag{2}$$

while the adiabatically heated ions are governed by the fluid equations. The phase velocity of the ion-acoustic wave is assumed much less than the thermal velocities of the cool and hot electrons, i.e., $\frac{\omega}{k} \leqslant v_{tc},\ v_{th}$, where $v_{tc,h} = (T_{c,h}/m_e)^{1/2}$ are thermal velocities of the cold and hot electrons, m_e is the electron mass. Then, the adiabatic ions are described by the fluid equations given below,

Continuity equation:

$$\frac{\partial N_i}{\partial t} + \nabla.(N_i\mathbf{V_i}) = 0. \tag{3}$$

Momentum equation:

$$\frac{\partial \mathbf{V_i}}{\partial t} + \mathbf{V_i}.\nabla\mathbf{V_i} = -\frac{e\nabla\phi}{m_i} + e\frac{\mathbf{V_i}\times\mathbf{B_o}}{m_i c} - \frac{1}{N_i m_i}\nabla P_i. \tag{4}$$

Pressure equation:

$$\frac{\partial P_i}{\partial t} + \mathbf{V_i}.\nabla P_i + \gamma P_i.\nabla\mathbf{V_i} = 0 \tag{5}$$

where N_i V_i and m_i are the number density, fluid velocity and mass of the ions, e is the magnitude of the electron charge, c is the speed of the light in vacuum and the ion pressure P_i is given by the balance pressure Eq. (5). further, ion pressure can be written as yields