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Small amplitude ion acoustic solitons in a weakly magnetized plasma with anisotropic ion pressure and kappa distributed electrons

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Abstract

The Zakharov–Kuznetzov (ZK) equation is derived for nonlinear electrostatic waves in a weakly magnetized plasma in the presence of anisotropic ion pressure and superthermal electrons. The anisotropic ion pressure is defined using Chew–Goldberger–Low (CGL) while a generalized Lorentzian (kappa) distribution is assumed for the non-thermal electrons. The standard reductive perturbation method (RPM) is employed to derive the two dimensional ZK equation for the dynamics of obliquely propagating low frequency ion acoustic wave. The influence of spectral index (kappa) of non-thermal electron on the soliton is discussed in the presence of anisotropic ion pressure in plasmas. It is found that ion pressure anisotropy and superthermality of electrons affect both the width and amplitude of the solitary waves. On the other hand the magnetic field is found to alter the dispersive property of the plasma only, and hence the width of the solitons is affected while the amplitude of the solitary waves is independent of external magnetic field. The numerical results are also presented for illustrations.

Keywords: Solitary waves; Anisoptropic ion pressure; Kappa distribution

1. Introduction

Nonlinear ion acoustic waves with Maxwell–Boltzmann distributed electrons have been studied by a number of authors. However, there are evidences that non-Maxwellian distributed particles can exist in space and laboratory plasmas due the long tails in their distribution function (Vasyliunas, 1968; Hasegawa et al., 1985; Christon et al., 1988; Pierrard and Lemaire, 1996; Pierrard et al., 2004). Such distributions can be modeled by kappa or generalized Lorentzian velocity distributions functions. The generalized Lorentzian distribution explains many astrophysical and space plasmas, such as auroral zone plasma (Singh et al., 2011; Olsson and Janhune, 1998) magnetosphere (Christon et al., 1989), interstellar medium (Leubner and Voros, 2005) and solar wind (Shrauner and Feldman, 1977). Non Maxwellian energetic plasma particles are also observed on laboratory scale such as Hellberg et al. (2000) and Goldman et al. (2007). The use of the kappa distribution function was first predicted by Vasyliunas, 1968to fit OGO 1 and OGO 2 solar wind data. This is an empirical fit to the observed particle distributions. and it has been extensively studied by various researchers (Sultana et al., 2012; Devanandhan et al., 2011a,b, 2012; Choi et al., 2011; Sahu, 2011; Shah and Saeed, 2011) to see the effect of superthermal electron distributions on linear and nonlinear regimes of ion and dust acoustic modes.

In the presence of ambient magnetic field, plasma behaves differently in the parallel and perpendicular

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directions relative to the magnetic field, and known as anisotropic plasmas (Baumjohann and Treumann, 1997). In such anisotropic plasma case, one needs two energy equations for the evaluation of ion pressure $p_{\parallel i}$ and $p_{\perp i}$. Chew–Goldberger–Low presented a theory in 1956 known as (CGL) or double adiabatic theory, which can be applied to such anisotropic plasma case (Baumjohann and Treumann, 1997; Parks, 1991). The CGL theory is applicable to magnetized anisotropic plasma, when there is no coupling between the parallel and perpendicular degrees of freedom of the system. For isotropic plasma case, there exist a strong coupling between parallel and perpendicular degrees of freedom due to wave-particle interactions and dissipative effect (Denton et al., 1994).

In order to capture the physical processes of interest in case of real magnetized plasma, there are various theoretical models based on different assumptions and simplifications. Ion pressure anisotropy naturally develops in low density magnetized plasma, when the gyro-motion (motion in perpendicular plane) and the$B$-field aligned motion are not coupled by collisions. The magnetic field provides the preferred orientation while the collisional effects (particles collisions, etc.) tend to drive the plasma isotropic by evenly distributing the parallel and perpendicular momenta with respect to the magnetic field. For small enough collisional effects, the ion parallel and perpendicular pressure with respect to the magnetic field can be different, however this difference is bounded by instabilities, like firehose, mirror and cyclotron instabilities (Seough et al., 2013). Our primary interest is to study space plasma phenomenon, which are mostly collisonless and hence ion pressure anisotropy can play an important role.

Mamun (1997) studied the effects of ion temperature on the electrostatic solitary waves in a nonthermal plasma using pseudo-potential approach while Saini et al. (2009) investigated the ion acoustic solitary excitations in the presence of superthermal electrons using the same pseudo-potential method. They showed that for a fixed Mach number the profile of the nonlinear structure is steeper, and have a larger amplitude than the usual structures occurring in plasma. Zaheer et al. (2004) reported a comparative study of the electrostatic modes, such as Langmuir excitations, dust ion acoustic waves and dust acoustic waves using non-Maxwellian velocity distribution functions. Kadijani et al. (2011) studied the behavior of solitary waves in magnetized electron–ion plasma with Lorentzian velocity distribution. Arbitrary and small amplitude ion acoustic waves are studied in electron–positron–ion (e–p–i) plasma by El-Awady et al. (2010). They showed the dependence of superthermal parameter of electrons on nonlinear structures. Ahmad-i-hojatabad et al. (2010) elaborated the effects of kappa distributed and trapped electrons on solitary structures in magnetized plasma. Chatterjee et al. (2010) derived the Korteweg–de Vries (KdV) equation by employing Poincare–Lighthill–Kuo method and explained the head-on collisions of ion acoustic solitary waves in an unmagnetized e–p–i plasma with kappa distributed electrons. Using reductive perturbation technique nonlinear Schrödinger equation has been derived in the presence of superthermal electrons and positrons by Sabry et al. (2011). They reported that the superthermal parameter increases the modulation instability of the solitary excitations. Recently Singh et al. (2013) investigated the effect of ion temperature on ion acoustic waves in a magnetized superthermal plasma using Sagdeev potential approach. They showed that, for auroral plasma region their results are in good agreement with Viking observations. The kappa distribution is more suitable in explaining various space observational data (Vasyliunas, 1968; Hasegawa et al., 1985; Christon et al., 1988; Pierrard and Lemaire, 1996; Pierrard et al., 2004). Recently the measurements in the laboratory also have nice agreements with kappa theory (Hellberg et al., 2000; Goldman et al., 2007; Sarri et al., 2010).

The model described in this paper has been motivated by a series of magnetosheath observations made from two spacecrafts namely AMPET/CCF and AMPET/IRM as described by Denton et al. (1994). Pressure anisotropy also has an essential role in the turbulent intracluster medium (ICM) as discussed by Nakwacki et al. (2012). They showed that in a low density collisionless medium, such as ICM the thermal pressure become anisotropic with respect to the magnetic field orientation and lead to the evolution of the turbulent gas. The favorable condition for ion pressure anisotropy in such plasma environments is that the ion gyrofrequency is much larger than the ion–ion collision frequency. In this paper, we are studying the Zakharov–Kuznetsov (ZK) electrostatic solitons in a weakly magnetized plasma with anisotropic ion pressure and superthermal electrons. It is organized in the following fashion: In Section 2, we have presented the basic set of dynamic equations and dispersion relation is obtained by assuming small amplitude sinusoidal perturbations. In Section 3, ZK equation is obtained using the well-known reductive perturbation method in the presence of anisotropic ions and Lorentzian velocity distributed electrons. In Section 4, small amplitude two dimensional electrostatic soliton solution is presented using tanh method. The numerical results and discussion are presented in the last Section 5.

2. Set of governing equations

We are considering the propagation of electrostatic waves in magnetized, collisionless plasma containing ions and superthermal electrons. The ions are considered to be inertial and exhibit pressure anisotropy with respect to the external magnetic field, whereas the electron's inertia can be neglected in the low frequency limit. The anisotropic ion pressure is defined using double adiabatic or Chew–Golberger–Low (CGL) theory (Chew et al., 1956). The ambient magnetic field is taken along the $\hat{x}$-axis i.e. $\mathbf{B} = B_0\hat{x}$. The equations describing the dynamics of ions