Dust-acoustic solitary waves in dusty plasmas with non-thermal ions

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Most studies on dusty plasmas have assumed that electrons and ions follow Maxwellian distributions. However, in the presence of energetic ions, the distribution of ions tends to be non-Maxwellian. It is shown here that the existence of non-thermal ions would increase the phase velocity of a dust-acoustic wave. It is also found that the change in the phase velocity profoundly affects the characteristics of a dust-acoustic solitary wave. © 2013 American Institute of Physics.

I. INTRODUCTION

Dusty plasma refers to plasma consisting of ions, electrons, and micron to sub-micron sized charged dust. The collective behavior of massive dust particles can lead to propagation of a low frequency mode called the dust-acoustic wave (DAW), where the dust grains oscillate against the thermalized background of electrons and ions, which provide the necessary restoring force.

Following the theoretical prediction of a dust-acoustic wave by Rao et al.,1 experimental observation of low frequency oscillation around 12 Hz in dusty plasma was reported by Chu et al.2 in a radio frequency discharge system. Negatively charged silicon dioxide (SiO2) particles were produced through a gas-phase reaction and suspended in a SiH4/Ar discharge. When the density and the size of dust particles reached certain threshold values at low pressure, coupling between the particles and the background plasma caused large-amplitude low frequency fluctuations of the dusty plasma. D'Angelo3 categorized this as the first laboratory observation of dust-acoustic waves. Following this pioneering work, DAWs have been observed in several laboratory experiments using different devices, and their characteristics have been examined using different approaches.4–11

The dispersion relation for dust-acoustic waves was first derived by Rao et al.,1 and there were numerous theoretical studies to generalize this model by considering more realistic assumptions. Among the various models, one can include studies on the effects of dust charge fluctuations,12–14 collisions with neutral particles,15 forces such as ion drag force,16 electron drag force,17 and polarization force,18 magnetic field,19 and also the role of dust size distribution.20

Most of the studies on the formation and propagation of dust-acoustic waves were based on the assumption that electrons and ions follow Maxwellian distributions. However, there are physical systems such as Earth’s bow shock21 or the moon’s atmosphere,22 in which the ions follow a Cairns distribution,23 and that take into account the existence of the non-thermal or energetic ions. In our recent investigation24 on non-thermal ions, we developed a model to explain the experimental data reported by Heinrich et al.25 on the laboratory observation of self-excited dust-acoustic shock waves.

In this paper, the effect of non-thermal ions on the phase velocity of dust-acoustic wave is investigated. Detailed analysis of how this would affect the basic characteristics of the dust-acoustic solitary wave, namely its amplitude and width, is also presented.

II. MODEL EQUATIONS

Propagation of a dust-acoustic wave in unmagnetized dusty plasma whose constituents are negatively charged inertial dust particles, electrons, and ions is described in this section. For very low frequency waves such as dust-acoustic waves, electrons and ion inertia can be neglected. Their number densities are governed by nearly Maxwellian distributions for the electrons and non-Maxwellian distributions for the ions, such that they can be written as

\[ n_e = n_{e0} \exp\left(\frac{-e\phi}{k_B T_e}\right) \]

and

\[ n_i = n_{i0} \left[ 1 + \beta + \rho \left( \frac{e\phi}{k_B T_i} \right) + \rho \left( \frac{e\phi}{k_B T_i} \right)^2 \right] \exp\left(-e\phi/k_BT_i\right), \]

respectively. Here, \( T_e \) is the electron temperature, \( T_i \) is the ion temperature, \( k_B \) is the Boltzmann constant, and \( \beta = 4\nu/(1 + 3\nu) \), where \( \nu \) represents the population of the non-thermal ions.26 Consider the following system of equations that describe the dynamics of dust particles of uniform mass \( m_d \). The dust particle density \( n_d \) is governed by the continuity equation

\[ \frac{\partial n_d}{\partial t} + \frac{\partial}{\partial x} (n_d u_d) = 0, \tag{1} \]

and the mean velocity \( u_d \) obeys

\[ \frac{\partial u_d}{\partial t} + u_d \frac{\partial}{\partial x} u_d = \frac{z_d e}{m_d} \frac{\partial}{\partial x} \phi, \tag{2} \]

where \( \phi \) is the electrostatic potential, \( z_{d0} \) is the dust charge number, and \( e \) is the electric charge. The Poisson’s equation for the system can be written as

\[ \frac{\partial^2}{\partial x^2} \phi = 4\pi e (n_e + z_{d0} n_d - z_i n_i), \tag{3} \]

where \( n_d = n_{d0} + \tilde{n}_d \). Here, \( n_{d0} \) is the equilibrium number density and \( \tilde{n}_d \) is the perturbation of the number-density of

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