Effect of dust charge inhomogeneity on linear and nonlinear dust–acoustic wave propagation

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Propagation of linear as well as nonlinear dust–acoustic waves (DAWs) in an inhomogeneous dusty plasma consisting of electrons, ions, and dust particles is investigated by taking into account equilibrium dust charge inhomogeneity along with the density inhomogeneity of the plasma and dust particles. For the linear case with harmonic perturbations, coupled equations for self-consistently determining the wave amplitude and the wave number have been derived. On the other hand, nonlinear DAWs are shown to be governed by a Korteweg–de Vries (KdV) type of evolution equation having variable coefficients arising due to charge and density inhomogeneities. Qualitatively, the amplitudes of the linear and nonlinear DAWs are found to decrease (increase) as the waves propagate into regions of increasing (decreasing) dust charge, which is similar to the behavior found in the case with density inhomogeneity alone. Quantitatively, the amplitude of the dust number density perturbation in the linear wave is proportional to $q_d n_d^{1/4}$ for a cold dusty plasma, while in the nonlinear regime it scales as $q_d n_d^{1/14}$. Approximate analytical solutions of the KdV equation have been obtained by making use of a suitable set of coordinate transformations.

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I. INTRODUCTION

Charged dust grains constitute an important component of matter in space and astrophysical systems such as the planetary rings, asteroid zones, cometary tails, interstellar clouds, as well as in the laboratory environments, while trapped dust impurities can lead to serious contamination problems during the industrial manufacture of semiconductor devices using plasma based techniques. Dust grains immersed in ambient plasmas and radiative environments are electrically charged due to various processes, such as plasma (electron and ion) currents, photo-emission, secondary emission and field emission. Charged dust grains react to electromagnetic and gravitational fields, and give rise to a host of low-frequency collective phenomena in dusty plasmas. Over the last decade, the field of dusty plasmas has grown rapidly with applications to space and laboratory systems.

In recent years, a large number of authors have theoretically investigated various aspects of linear and nonlinear wave propagation in homogeneous dusty plasmas. In practical situations, the grain sizes are usually in the micron range, and hence the dust particles are many orders (~10–12) of magnitude heavier than the plasma ions. Consequently, the characteristic time scales associated with the dust and the ions are very widely different and, therefore, it is possible to separate the various plasma normal modes arising due to their dynamics. In fact, dusty plasmas open up an ultra low-frequency regime for the existence of novel types of wave modes, which otherwise are not possible in the usual electron–ion plasmas but with different ion species. For example, the existence of an ultra low-frequency electrostatic acoustic-like mode called the ‘‘dust-acoustic wave’’ (DAW) was first theoretically predicted by Rao et al. by including the dust collective dynamics. Their model consists of Boltzmann distributed thermal electrons and ions which provide the restoring force, while the inertia arises due to the heavier dust component. In the laboratory experiments on dusty plasmas wherein the grain size is about a few microns, the DAW frequency is typically in the range of about ten hertz. They discussed also the nonlinear propagation of DAWs in terms of a generalized Boussinesq equation, which reduces to Korteweg–de Vries (KdV) equation for unidirectional near-sonic propagation. On the other hand, at higher frequencies, Shukla and Silin showed the existence of dust-ion-acoustic waves (DIAWs) wherein the electrons are Boltzmann distributed while the inertia is provided by the ions in the presence of stationary dust grains. Recent laboratory experiments on dusty plasmas have confirmed the existence of DAWs and DIAWs. Furthermore, low-frequency electrostatic ion-acoustic and ion-cyclotron waves have been studied by D’Angelo in a magnetized dusty plasma. Nonlinear propagation of the low-frequency DAWs leads to the formation of coherent structures such as the solitons. Depending on the parameter regimes, it is possible to have negative as well as positive electrostatic potential structures associated with the nonlinear DAW solitons in three component dusty plasmas.

Most of the existing studies on dusty plasmas have focused attention on wave propagation in homogeneous plasmas, whereas in practical situations one encounters plasma inhomogeneities. Some progress has recently been made towards an understanding of wave propagation in inhomogeneous dusty plasmas. The inhomogeneity in the dust number...