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Q1 Generalized polarization force acting on dust grains in a dusty plasma

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HIGHLIGHTS

- Polarization force is generalized.
- Tsallis statistical mechanics is considered.
- Modifications arising in dust-acoustic waves, and dust sheath formation are analyzed.

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ABSTRACT

The polarization force acting on dust particles in a dusty plasma is revisited within the theoretical framework of the Tsallis statistical mechanics. The generalized nonextensive polarization force expression is derived. As application, the modifications arising in the propagation of dust-acoustic solitary waves, and dust sheath formation are analyzed. Our results should be of wide relevance to explain and interpret the sheath formation and its structure in nonequilibrium plasmas related process such as surface treatments and ion implantation.

1. Introduction

During the last two decades, a great deal of interest has been devoted to the new and fascinating field of dusty plasmas. A dusty plasma is a normal electron–ion plasma with an additional highly charged component of extremely massive particulates (dust grains). Dusty or complex plasmas occur in quite a number of space plasmas, such as interstellar clouds, cometary plasma tails, planetary rings, and the ionosphere of the Earth and other planets [1–7]. Significant amount of dust particles is also frequently encountered in industrial reactors for semiconductor manufacturing, in processing discharges for etching, sputtering, ion implantation etc. [8–14], and in the chambers of fusion devices [15]. Besides, dust particles are thought to be a leading cause of degradation of laboratory devices yields. These dust particles may have sizes ranging from tens of nanometers to hundreds of microns, are typically billions of times more massive than protons, and can have between one thousand and several hundred thousand elementary charges. The presence of dust grains can significantly alter the properties and behavior of a plasma in which they are immersed [16,17]. It affects all kinds of plasma wave modes and, remarkably, gives rise to new, very low-frequency dust modes. The most well studied of such modes is the so-called "dust

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acoustic wave" (DAW) [18] which arises due to the restoring force provided by the plasma thermal pressure (electrons and ions) while the inertia is due to the dust mass.

Charged dust particles embedded in a plasma are subject to various forces acting on them. Probably, the most important one is the electric force $\mathbf{F}_e = q_d\mathbf{E}$ ($\mathbf{E}$ is the electric field and $q_d = -eZ_d$ the dust charge, with Z_d being the number of electrons residing on the dust grain surface). The electric force is mainly responsible for the confinement of the negatively charged particles in the positive plasma potential. Due to the quasi-neutrality of the bulk plasma, the electric field is usually much weaker than the electric field in the sheath region. Another force acting on the dust is the polarization force which is due to the deformation of the Debye sheath around the particulates in the background of non-uniform plasmas. The non-uniformity is related to the non-zero gradient of the local electron and ion density in the plasma. The polarization force F_p is given by [19]

$$\mathbf{F}_p = -q_d^2 \nabla\lambda_D / 2\lambda_D^2 \tag{1}$$

where $\lambda_D = \lambda_{Di}/\sqrt{1 + (\lambda_{Di}/\lambda_{De})^2}$ is the linearized Debye length, with $\lambda_{Di(e)} = \sqrt{\varepsilon_0 T_{i(e)}/n_{i(e)}e^2}$ being the ion (electron) Debye length, $T_{j=i,e}$ is the temperatures in energy unit, and $n_{j=i,e}$ stands for the number density. In the presence of an external electric field E, expression (1) becomes

$$\mathbf{F}_p = q_d\mathbf{E} - \frac{q_d^2}{2}\frac{\nabla\lambda_D}{\lambda_D^2}. \tag{2}$$

It may be useful to note that in Ref. [19], the authors have assumed Boltzmannian electrons and ions.

Expression (1) (or (2)) has been also derived in the case of a dusty plasma with finite ion flows [20]. In Ref. [20], Hamaguchi and Farouki have extended their earlier results [19] to obtain the total force exerted on a charged particulate in a nonuniform plasma under the influence of finite ion flows. They have rigorously demonstrated, in the context of a fluid approximation of the plasma, that the expression for the polarization force given in Ref. [19] is a good approximation, unless the ion flow velocity is comparable to the ion thermal velocity. Moreover, expression (1) has been used in the case of a dusty plasma with nonthermal ions [21], with adiabatic electrons and adiabatic ions [22], with nonthermal electrons [23]. Expression (1) has been also used to study the influence of dust charge fluctuation and polarization force on radiative condensation instability of magnetized gravitating dusty plasma [24] with thermal ions and fluid electrons. It has been also used to study the radiative-condensation instability in gravitating strongly coupled dusty plasma [25] having thermal ions and fluid electrons.

As shown by Khrapak et al. [26] for Boltzmannian electrons and ions, the polarization force can be written as $F_p = \frac{1}{16\pi\varepsilon_0}(|q_d|\, e/\lambda_D T_i)(1 - T_i/T_e)q_d\nabla\phi$, or $F_p = Rq_d\nabla\phi$, where $R = \frac{1}{16\pi\varepsilon_0}(|q_d|\, e/\lambda_D T_i)(1 - T_i/T_e)$ represents the effects of plasma-particle polarization interaction, and ϕ is the electrostatic potential. Regardless of the sign of the dust charge, the polarization force is therefore always in the direction of decreasing Debye length, and acts in the direction opposite to the electrical force. Using such a model form of the polarization force, Khrapak et al. [26] demonstrated that the polarization effect can play an important role in the propagation characteristics of the linear low-frequency DAW. In particular, the polarization effect causes a decrease of the wave phase velocity. This decrease is more effective for larger dust grains. Later, Bandyopadhyay et al. [27] showed that an enhancement of the polarization force for a given Mach number, leads to an increase in the amplitude and a reduction in the width of the solitary DAW. Note that some recent theoretical work focused on the effect of the polarization force on different collective processes in dusty plasmas [26,27,21–30].

Nevertheless, the derivation of the polarization force in Refs. [19–26] has been limited to situations which might be inadequate for the description of systems endowed with long-range interactions, such as plasma and gravitational systems, where nonequilibrium stationary states exist.

We recall that over the last few years, there has been a renewed interest in nonextensive plasmas, covering different plasma modes, instabilities, collisions of solitary waves, and other collective phenomena effects see Refs. [31–35] and references therein for an actual view of the theory and its breadth of use. This interest has been mainly motivated by the fact that during the last two decades, it has been proven that systems endowed with long-range interactions, long-time memory, fractality of the corresponding space–time/phase-space, or intrinsic inhomogeneity are untractable within the conventional Boltzmann–Gibbs (BG) statistics. To overcome this shortcoming, Tsallis [36], in a celebrated and influential paper, proposed a nonextensive generalization of the BG entropy. This generalization has made remarkable progress and found wide applicability in different disciplines (information theory, solid state physics, plasma physics, nonequilibrium systems, etc.). A one particular parameter, the entropic index q which measures the degree of nonextensivity, has been introduced ($q = 1$ corresponds to the standard, extensive, Boltzmann–Gibbs (BG) statistics). The q-nonextensive formalism has been successfully applied to systems endowed with long range interactions [37,38], as usually happens in astrophysics and plasma physics. Owing to an increasing amount of experimental and theoretical evidence showing that the BG formalism fails to describe systems with long-range interactions and memory effects, Tsallis proposed the following q-entropy [36]

$$S_q = k_B \frac{1 - \sum_i p_i^q}{q - 1} \tag{3}$$

where k_B is the Boltzmann constant, p_i is the probability of the ith microstate, and q a parameter quantifying the degree of nonextensivity. For $q = 1$, S_q reduces to the habitual standard BG entropy. A very important property of

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