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Influence of superthermal plasma particles on the Jeans instability in self-gravitating dusty plasmas with dust charge variations

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ABSTRACT

A theoretical analysis of the dust acoustic waves in the self-gravitating dusty plasmas is presented within the consideration of the superthermal electrons, ions and dust charge variations. For this purpose, the current of electrons and ions to the dust surface is calculated, and then the dispersion relation for the dust acoustic waves is obtained. It is shown that by increasing the number of superthermal particles, the growth rate of the instability increases, the dust acoustic waves frequency decreases, and the instability region is extended to the smaller wavelengths. Moreover, it is found that the ratio of the electric force to the self-gravitational force is decreased in the presence of the superthermal particles, and dust charge variations.

1. Introduction

Since the early 1990s, dusty plasmas have become an essential part of the general field of plasma physics [1,2]. Dusty plasmas are of interest in laboratory, industrial plasma processing, astrophysical and space environments such as, interplanetary space, interstellar or molecular clouds, comets, planetary rings, earth's environments etc [3–8]. The dust grains come in all sizes, in an almost continuous range going from macromolecules to rock fragments and asteroids [9]. When dust particles are immersed in plasma, they inevitably become charged (usually negatively because of the greater mobility of electrons) by collecting electrons and ions from the background plasma [1,2,5–8].

For certain dusty plasmas containing rather heavy charged grains, it is assumed that the gravitational intergrain interactions could become important, therefore the name "self-gravitating dusty plasma" is appropriate for these plasmas.

It is well known that, self-gravitating systems are subjected to the Jeans instability [10] provided that the square of the Jeans frequency exceeds the square of the sound frequency [11]. Physically, the Jeans instability arises because of an imbalance between the self-gravitational force and the incompressibility of the fluid [12]. This instability has been found to play a crucial role in the formation of many astrophysical objects such as galaxies, stars etc. It is now well established that astrophysical objects contain a significant amount of electrically charged dust grains. On these grains, the electric and gravitational forces could be comparable, at least within an order of magnitude [13]. In other words, $Gm_d^2/q_d^2 \approx O(1)$, where G is the gravitational constant, m_d is the dust mass, and q_d is the charge on the dust grain surface. Because of this interplay between the electric and gravitational forces, there are interesting deviations from the Jeans instability attributes of a neutral fluid, which has been the subject of many investigations [14–17].

In reality, the charge on the dust grain varies both with space and time, due to electron and ion currents flowing into or out of dust grain, as well as other spatial and temporal variations in the surrounding plasma properties [18–23], such as change in the electric potential, or electron temperature [24,25]. The effect of dust charge variations on the Jeans instability has been studied recently [26].

In space plasmas, it has been observed that particle velocity distributions have a significant high-energy (superthermal) excess, when compared to an equilibrium Maxwell–Boltzmann distribution. This high-energy tail can be well modeled by a "κ distribution" (a generalized Lorentzian distribution) which was first proposed by Vasyliunas [27]. Since then, kappa (κ) distributions have been utilized in numerous studies of space plasmas, namely in solar wind [28–31] and planetary magnetospheres [32–34], in the outer heliosphere and inner heliosheath [35–37], and in other various plasma-related analyses [38–41]. Recently, an interesting

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investigation was made by Livadiotis [42], regarding the statistical background and properties of kappa distributions in space plasmas.

For three-dimensional isotropic case, the κ distribution function is given by

$$f_k(v) = n\left[\pi\left(\kappa - \frac{3}{2}\right)\theta^2\right]^{-\frac{3}{2}}\left(\frac{\Gamma(\kappa+1)}{\Gamma(\kappa-\frac{1}{2})}\right) \times \left(1 + \frac{1}{\kappa-(3/2)}.\frac{v^2}{\theta^2}\right)^{-(\kappa+1)}, \quad (1)$$

where n is the particle number density, κ is the spectral index, $\Gamma(x)$ is the gamma function, and $v^2 = v_x^2 + v_y^2 + v_z^2$ denotes the square norm of the particle velocity $\vec{v}$. The coefficient is determined so that $\int f_\kappa(v)d^3v = n$. The parameter θ is the thermal speed which is defined as

$$\theta = \sqrt{\frac{2k_BT}{m}}, \quad (2)$$

where T is the particle temperature, m is the mass of the particle, and k_B is the Boltzmann constant.

In order to avoid the confusion about the definition of temperature in Lorentzian distribution function [43], we used the above notation (Eq. (2)) in which the temperature and thermal speed are defined independent of kappa index [42,44].

Kappa is a parameter that describes the extent to which the distribution departs from Maxwellian distribution. It follows from Eq. (1) that, one requires to have $\kappa > 3/2$, as otherwise the distribution function cannot be defined. At very large values of the spectral index ($\kappa \to \infty$), the kappa distribution function approaches a Maxwellian distribution

$$f_M(v) = n\left(\frac{m}{2\pi k_BT}\right)^{3/2}\exp\left(\frac{-mv^2}{2k_BT}\right). \quad (3)$$

Low values of κ, represent distributions with a relatively large component of particles with speed greater than thermal speed. These particles, are so called "superthermal particles" and form the tail of the kappa velocity distribution function. It is worthwhile to note that, for $v \gg \theta$, the high velocity tail decreasing with v as a power law [$f_\kappa(v) \propto v^{-2(\kappa+1)}$], and when the velocity, v, is smaller than or comparable [45] to θ, the kappa velocity distribution function is close to the Maxwellian having the same thermal speed v_{th}.

About 50 years ago, Vasyliunas [27] found that, the kappa distribution provided a good description of the electron energy distribution over the full range of energies. Since then, the κ distribution is widely used to fit the velocity distribution observed in space plasmas, often with $2 < \kappa < 6$. Examples include the observations in the earth's foreshock ($3 < \kappa_e < 6$) [46], the measurements of ion and electron distributions ($\kappa_i = 4.7$, $\kappa_e = 5.5$) in the plasma sheet [47], and development of the Lorentzian ion exosphere model and associated solar wind model with coronal electrons satisfying $2 < \kappa_e < 6$ [48,49]. Although there is no completely satisfactory theory for the persistence and apparent ubiquity of κ distributions in space, works by Treumann and co-workers [50,51], Collier [52], and Leubner [39], provided heuristic explanations toward a full explanation.

The Jeans instability of the self-gravitating dusty plasmas with Lorentzian electrons and ions, and constant dust charge are studied in some papers [16,53–55]. In this work, we adopt the fluid model to obtain the dispersion relation for the dust acoustic waves in the self-gravitating Lorentzian dusty plasma in which, the dust charge is variable and depends on the plasma potential. The current of the superthermal electrons and ions flowing onto the dust grain surface is calculated by using the orbit-limited motion (OLM) approach [56,57]. Then it is investigated that, how the presence of the superthermal plasma particles can affect the gravitational stability of the dusty plasma.

2. Basic equations

Consider an infinite, unmagnetized, isotropic and self-gravitating dusty plasma consisting of electrons, singly ionized positive ions, and micron-sized negatively charged dust grains which are spatially uniform at equilibrium. The grains are spherical with equal radii and very massive as compared to electrons and ions. Therefore, it is reasonable to assume that the gravitational potential is mainly due to the dust grains. Moreover, we consider a nonthermalized plasma where the dust grains are much colder than the electrons and ions, i.e., ($T_d \ll T_e, T_i$). In this paper, the subscripts i, e, and d, are used to show ion, electron, and dust species respectively. Also, the charge and mass of the dust grains are in the range where $Gm_d^2/q_d^2 \approx O(1)$.

In what follows, we used the fluid model to describe the dynamics of the dust grains

$$\frac{\partial \vec{v}_d}{\partial t} + (\vec{v}_d \cdot \nabla)\vec{v}_d = -\frac{q_d}{m_d}\nabla\phi - \nabla\psi - \frac{k_BT_d}{m_dn_d}\nabla n_d, \quad (4)$$

$$\frac{\partial n_d}{\partial t} + \nabla \cdot (n_d\vec{v}_d) = 0, \quad (5)$$

where n_d is the dust number density, $\vec{v}_d$ is the dust fluid velocity, and ψ, ϕ are the gravitational potential of dust grains, and the electric potential respectively. In Eq. (6), the effect of the collision between the dust grains and neutral components is ignored.

The dust grains can be charged by absorbing electrons and ions flowing onto their surface. Due to the large mobility of electrons compared with that of ions, the dust particles usually acquire a negative charge. Therefore, $q_d = -Z_de$ where Z_d is the number of electrons residing on the dust grain surface, and e is the magnitude of a electron's charge. In energetic or radiative plasma environments some mechanisms such as secondary and photoelectric emission, contribute to grain charging and can lead to positively charged grains [1,58]. In this paper, we assume that the dusty plasma is far from a radiative source, such as a supernova, and the collection of plasma particles has the main role in the charging of dust grains.

Livadiotis [59] investigates the theory and formulations of the kappa distributions that describe particle systems characterized by a nonzero potential energy. Both the ions and electrons are assumed to follow a generalized three-dimensional kappa distribution, given by

$$f_j(v_j) = n_{j0}\left[\pi\left(\kappa_j - \frac{3}{2}\right)\theta_j^2\right]^{-\frac{3}{2}}\left(\frac{\Gamma(\kappa_j+1)}{\Gamma(\kappa_j-\frac{1}{2})}\right) \times \left[1 + \frac{1}{\kappa_j-(3/2)}\left(\frac{v_j^2 + \frac{2q_j\phi}{m_j}}{\theta_j^2}\right)\right]^{-(\kappa_j+1)}, \quad (6)$$

where $j = i, e$, and n_{j0} is the equilibrium number density of species j (the subscript zero denotes the equilibrium value of the quantities).

It is worthwhile to note that, in Eq. (6) the gravitational energy of the electrons and ions in comparison with their electric energy, has been ignored. This is reasonable because of the small ratio of the electrons and ions mass to the grains mass ($q_dm_j/q_jm_d \ll 1$).

The gravitational potential and electric potential can be obtained from Poisson's equation

$$\nabla^2\psi = 4\pi Gm_dn_d, \quad (7)$$

$$\nabla^2\phi = -4\pi[e(n_i - n_e) + q_dn_d]. \quad (8)$$

Here, n_e and n_i are the electron and ion number densities, which can be obtain by integrating the kappa distribution function over velocity space

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