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The effect of negative ions on the dust acoustic wave in dusty electronegative plasma with positively charged dust grains

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ABSTRACT

The effect of negative ions on the modulational instability properties of nonlinear dust acoustic (DA) waves in the electronegative dusty plasmas was investigated by considering Boltzmann-distributed electrons, negative ions, positive ions as well as positively charged dust grain under the ultraviolet irradiation. It is shown that the modulational instability properties of the DA waves were strongly affected by the temperature and proportion of negative ions. The modulational instability can occur only if the proportion of negative ions was smaller than critical value. The instability growth rate has a maximum value when the proportion of negative ions was a critical one in the unstable region. The effect of photoelectron generated by ultraviolet irradiation on the modulational instability of dust acoustic waves was also discussed by numerical method.

The dusty plasma physics have attracted much attention due to their important application in real cosmic environments, such as Earth's magnetosphere, planetary rings, interplanetary medium, and laboratory environments. In the last decades, different kinds of linear or nonlinear collective excited waves in dusty plasma have been investigated intensively by many researchers. About decades of years ago, the low-frequency dust acoustic (DA) waves was predicted theoretically [1] and confirmed by experiment [2] and extensively studied by many authors [3]. For DA waves the inertia comes from dusty particle mass, while the pressures of inertialess Boltzmann distributed thermal electrons and ions provide the restoring force. Another important wave mode is dust ion acoustic (DIA) waves, which was the extension of usual ion acoustic waves, where the inertia is provided by the ions and the restoring force comes from the inertialess Boltzmann distributed electrons [4].

After the pioneer work of the Rao [1], the linear and nonlinear theoretical studies of DA waves were well proceeded in unmagnetized [5–9] or magnetized [10,11] dusty plasmas. The linear theory was valid only when the amplitude of DA waves was small, while the nonlinearity was not always neglected as the amplitude of DA waves were sufficiently large. The nonlinear propagation of low-frequency DA waves will give rise to solitary waves [12], shock waves [13], or vortices [14], etc., which were considered by many authors during the past few years by considering various effects, such as polarization [15], strong-coupling regime [16], different kinds of electrons and ions [17–22], etc. Then recently the experimental study shows that self-excited DA shock waves have been observed in a dc glow discharge dusty plasma [12]. The nonlinear DA solitary waves were also investigated by an experimental study, which gives that the pulse modulating the discharge voltage with a negative potential can excite a longitudinal DA solitary waves whose velocity increases with the increase of the modulating voltage [13].

Since the dust grain can be charged by many charging process, such as electron and ion collection, secondary electron emission, photoelectron emission, ionization and recombination, etc., the effects of dust grain charge fluctuation on DA waves and DIA waves have attracted much attention [23,24]. When the dust plasma frequency ω_{pd} was far less than the grain charging frequency ν_d, the dust charge may be assumed to be adiabatic one, which were widely studied in plasmas with negatively charged dust grain [25], or positively charged dust grain [26]. Most of the above investigations of the dust charge variation were focused on adiabatic fluctuation. Since the dust charging frequency sometimes was comparable to the frequency of dusty plasmas, the dust charge variation was considered as nonadiabatic one. The dissipative effects caused by nonadiabatic dust charge variation in collisionless dusty plasma were found to the formation of DA shock wave that was governed by a Korteweg–de Vries (KdV)–Burger equation [27]. With the presence of nonisothermal ions in dusty plasmas, the KdV–Burger equation has negative potentials with oscillatory or monotonic shock transition [28]. The modulational instability of DA waves can be governed by a modified nonlinear Schrödinger equation (mNLSE) containing a damping term accounting for the presence of nonadiabatic dust charge variation [29]. In a magnetized dusty plasma DA shock waves can also be described by modified KdV–

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Burger equation [30]. It should be mentioned that dust grains can be positively charged by photoelectron emission, thermionic emission, etc. Shukla investigated DA waves in a thermal plasma with positively charged dust grain because of thermionic and ultraviolet induced photoemissions [31]. Ghosh [32] considered the DA shock wave in a dusty plasma consisting of positively charged dust grains due to thermionic emission, which admitted both compressional oscillatory and monotonic shock wave and was strongly affected by thermionic emission. The presence of streaming ions directly affects DA waves in collisionless dusty plasma, which shows that the damping rate of the slow mode DA solitary wave was dependent on the ion streaming velocity [33]. The modulational instability of DA waves in a dusty plasma consisting of positively charged dust grain can be described by a modified Davey–Stewartson equation, where Wang et al. considered that the ratio of the dust hydrodynamic time to dust charging time was small but finite [34]. Then in this Letter we'll consider another limit, i.e. the ratio of the dust charging time to the dust hydrodynamic time is small but finite. Besides this, the effects of negative ions on the modulational instability of DA waves will be considered here.

Due to great potential applications of negative ions in microelectronic or photoelectronic industries and the high power fusion devices such as ITER, negative-ion-rich dusty plasma are extensively studied in most space and laboratory plasma [35]. Negative ions can also be produced by electron attachment to neutral particles or may be injected from external sources. The effects of negative ions on DA or DIA waves [36] and the dust grain charging [37] were considered by many authors. Recently, the role of negative ions on Jeans instability in a self-gravitating dusty plasma has been investigated, which shows that the growth rate of this Jeans instability decreases with the increasing of negative ion temperature [38]. The arbitrary amplitude solitary waves and double layers were investigated in a dusty electronegative plasma containing Boltzmann electrons, Boltzmann negative ions and mobile positive ions [39]. More recently, the dusty negative ion-acoustic shock waves in dusty plasmas was investigated theoretically [40, 41] and observed experimentally [42], which shows that the negative ion-acoustic shock waves were observed when the negative ion density was larger than a critical value. Since the presence of negative ions in the dusty plasma is very important from both the theoretical and experimental points of view, in this Letter we'll investigate the effects of negative ions on the modulational instability of DA waves.

As mentioned above the dusty plasmas can have a positively charged dust grain due to the ultraviolet irradiation [43,44]. Then we will consider a positively charged dust grain due to the ultraviolet irradiation in our work. Since the dust charge variation in the dusty plasma is very important for the properties of the DA waves, we'll investigate the effects of dust charge variation, negative ions and ultraviolet irradiation on the modulational instability properties of DA waves, which is important in the dispersive medium [4]. For the positively charged dust grain, the fluid equations and Poisson's equation are given in the normalized form,

$$\frac{\partial n_d}{\partial t}+\frac{\partial}{\partial x}(n_d \mathrm{v}_{dx})=0, \tag{1}$$

$$\left(\frac{\partial}{\partial t}+\mathrm{v}_{dx}\frac{\partial}{\partial x}\right)\mathrm{v}_{dx}=-Q_d\frac{\partial\phi}{\partial x}, \tag{2}$$

$$\frac{\partial^2\phi}{\partial x^2}=\mu(n_e+\alpha n_p+\beta n_n)-\mu_i n_i-Q_d n_d, \tag{3}$$

where n_s is the number density, $s=e,p,n,i,d$ denotes electrons, photoelectron, negative ions, positive ions, and dust grain, respectively, which were given by $n_e=\exp(\phi)$, $n_p=\exp(\sigma_p\phi)$, $n_n=\exp(\sigma_n\phi)$, and $n_i=\exp(-\sigma_i\phi)$ with $\sigma_p=T_e/T_p$, $\sigma_n=T_e/T_n$ and $\sigma_i=T_e/T_i$, where T_p, T_n and T_i are photoelectron, negative ion and positive ion temperature, respectively. v_{dx} is the dust fluid velocity, and Q_d is the charge residing on the dust grains, ϕ is the electrostatic potential. Eqs. (1)–(4) were normalized by the following conditions, $\mathrm{v}_{dx}/C_d\to\mathrm{v}_{dx}$, $n_s/n_{s0}\to n_s$, $Q_d/eZ_{d0}\to Q_d$, $e\phi/T_e\to\phi$, $t\omega_{pd}\to t$, $x/\lambda_{Dd}\to x$, T_e is the electron temperature, $\lambda_{Dd}=(T_e/4\pi n_{d0}Z_{d0}e^2)^{1/2}$ is Debye length. The other parameter are $\mu=n_{e0}/n_{d0}Z_{d0}$, $\alpha=n_{p0}/n_{e0}$, $\beta=n_{n0}/n_{e0}$, and $\mu_i=\mu(1+\alpha+\beta)-1$, where n_{e0}, n_{p0}, n_{n0}, n_{i0}, n_{d0} are the equilibrium electron, photoelectron, negative ion, positive ion and positively charged dust grain number densities, respectively, which satisfy the charge neutrality at equilibrium $n_{e0}+n_{p0}+n_{n0}=n_{d0}Z_{d0}+n_{i0}$. The dust grain charge is determined by [45]

$$\frac{\omega_{pd}}{\nu_d}\left(\frac{\partial}{\partial t}+\mathrm{v}_{dx}\frac{\partial}{\partial x}\right)Q_d=\frac{1}{\nu_d eZ_{d0}}(I_e+I_n+I_i+I_p) \tag{4}$$

where $\omega_{pd}=(m_d/4\pi n_{d0}Z_{d0}^2e^2)^{-1/2}$ is the dusty plasma frequency, ν_d is the dust grain charging frequency and will be given in the following. Z_{d0} is the equilibrium number of charges measured in units of e residing on the dust grains and e is the magnitude charge of electron. According to the orbit motion limited theory [45], the Boltzmann-distributed electrons, negative ions and positive ions currents I_e, I_n and I_i for the positively charged dust grains are given by

$$I_e=-4\pi r^2e\left(\frac{T_e}{2\pi m_e}\right)^{1/2}n_{e0}e^{\phi}(1+zQ_d), \tag{5}$$

$$I_n=-4\pi r^2e\left(\frac{T_n}{2\pi m_n}\right)^{1/2}n_{n0}e^{\sigma_n\phi}(1+\sigma_n zQ_d), \tag{6}$$

$$I_i=4\pi r^2e\left(\frac{T_i}{2\pi m_i}\right)^{1/2}n_{i0}e^{-\sigma_i(\phi+zQ_d)}, \tag{7}$$

where $z=e^2Z_{d0}/rT_e$, r is the radius of the dust grain, m_e, m_n, and m_i are the mass of electron, negative ion, and positive ion, respectively. The photoemission current for positively charged dust grains is given by [45]

$$I_p=\pi r^2eJ_pY_pe^{-\sigma_p zQ_d}, \tag{8}$$

where J_p is the photon flux and Y_p is the yield of photoelectrons and σ_p is the ratio of photoelectrons temperature to electrons one. The dust grain charging frequency ν_d appearing in the normalized dust charging balance equation (4) can be given as

$$\nu_d=\frac{r}{\sqrt{2\pi}}\frac{\omega_{pi}^2}{V_{ti}}\frac{e^{-\sigma_i z}}{\sigma_i}\times\left(\frac{1}{1+z}\frac{1}{\Gamma}+\frac{\sigma_n}{1+\sigma_n z}\frac{\Gamma_n}{\Gamma}+\sigma_p\frac{\Gamma_p}{\Gamma}+\sigma_i\right), \tag{9}$$

where $\omega_{pi}=(4\pi n_{i0}e^2/m_i)^{1/2}$ and $V_{ti}=(T_i/m_i)^{1/2}$ are the ion plasma frequency and the ion thermal velocity, respectively. The other parameters are

$$\Gamma=1+\Gamma_n-\Gamma_p, \tag{10a}$$

$$\Gamma_n=\sqrt{\frac{m_e}{\sigma_n m_n}}\frac{n_{n0}}{n_{e0}}\frac{1+\sigma_n z}{1+z}, \tag{10b}$$

$$\Gamma_p=\sqrt{\frac{\pi m_e}{8T_e}}\frac{JY}{n_{e0}}\frac{1}{1+z}e^{-\sigma_p z}. \tag{10c}$$

Here we have used the currents equilibrium condition $I_{e0}+I_{n0}+I_{i0}+I_{p0}=0$ to obtain the dust grain charging frequency. The coupled equations (1)–(4) is the basic equations of our system for investigation of modulational instability of DA envelope solitary wave in the dusty plasmas consisting positively charged dust grains with the effects of ultraviolet irradiation under the assumption of nonadiabatic dust charge variation when the ratio of the