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The instability of dust acoustic waves in inhomogeneous dusty plasmas with non-adiabatic dust charge fluctuation*

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This paper investigates the propagation of linear dust acoustic waves in inhomogeneous dusty plasmas due to spatial gradients of dust charge, plasma densities. A linear dispersion relation is obtained with the non-adiabatic dust charge fluctuation and the non-thermally distributed ions. The numerical results show that the inhomogeneity, non-thermal ions and non-adiabatic dust charge fluctuation have strong influence on the frequency and the damping rate of waves.

Keywords: instability of low frequency waves, inhomogeneity, non-adiabatic dust charge variation
PACC: 5235S, 5235

1. Introduction

There is a great deal of interest in the study of coherent and dissipative structures in dusty plasmas for more than a decade.[1−5] The charged dust grains appearing in space and laboratory plasmas are of micrometre or submicrometre size, massive and highly charged. When a dust grain is immersed in the quiescent plasmas it can acquire charge by several mechanisms such as plasma currents, photoelectric emission and other processes.[6−8] The presence of such highly charged dust particles would significantly modify the collective behaviour of plasmas[9−11] and the existing plasma wave spectra, as well as introduce some new eigen modes, called the 'dust ion acoustic' (DIA) waves[1] and the 'dust acoustic' (DA) waves[1] in low frequency and very low frequency oscillations. In truly dusty plasmas, the dust charge is a new dynamic variable $q_{\rm d}$ and its dynamic nature would be important for studying the behaviour of dusty plasmas. In the linear theory, the non-adiabatic ($\tau_{\rm ch}/\tau_{\rm d}$ is small but finite) dust charge variations result in the damping of the linear wave mode,[12−14] where $\tau_{\rm ch}$ is the charging time scale indicating the speed of charging, and $\tau_{\rm d}$ is the hydrodynamical time scale indicating the speed of the change of the hydrodynamical character, whereas, in the nonlinear analysis, the non-adiabatic dust charge variations lead to an anomalous dissipation in plasmas which causes the generation of shock waves in dusty plasmas.[15−17] It is also important to note that most real plasmas are inhomogeneous, and as a wave propagates it can change its characteristics according to the local environment. Recent experiments on observations of dust density perturbation in a DC glow discharge in neon revealed that the phase velocity of the density perturbation varies considerably along the plasma column.[18] Moreover, numerical analysis of these experimental data have indicated that most plasma equilibrium parameters exhibit strong variations that are especially pronounced along the discharge tube. Comparatively few researches have been done about such inhomogeneous dusty plasmas. For example, the propagation of linear waves has been investigated with non-adiabatic dust charge fluctuation and non-thermally distributed ions, but inhomogeneity was not considered.[19] The generalized dispersion describing the coupling of the acoustic modes with the dust-charge relaxation mode and damping of the waves is derived and analysed numerically in homogeneous dusty plasmas.[20] Sorasio *et al* studied the dispersion relation as well as the instability condition in nonuniform dusty plasmas without considering the non-adiabatic dust charge fluctuation and non-thermally distributed ions.[21] It is thus neces-

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sary to investigate plasma waves in inhomogeneous dusty plasmas, taking into account non-adiabatic dust charge fluctuation. Hence, consideration of dissipative properties of the linear waves in inhomogeneous dusty plasmas should be an important and profound issue.[22−24]

In this paper, under the assumption that $\tau_{\rm ch}/\tau_{\rm d}$ is small but finite, we investigate the combined effects of the non-adiabatic dust charge fluctuation, the fast (nonthermal) ions on the propagation of linear DA waves in nonuniform dusty plasmas. It discusses in great detail how the dust charge variation, the presence of non-thermally distributed ions, the temperatures of ions modify the frequency and damping of low frequency mode.

2. Governing equations

We consider an unmagnetized dusty plasma system, which consists of extremely massive, micron-sized, negatively charged dust fluid, nonthermally distributed ions, and Boltzmann distributed electrons. The plasmas are assumed to be inhomogeneous along the vertically oriented tube, chosen as the x-axis. In the steady state, the charge neutrality reads: $n_{\rm i0}(x) = Z_{\rm d0}(x)n_{\rm d0}(x) + n_{\rm e0}(x)$, where $n_{\rm d0}(x)$, $n_{\rm i0}(x)$, and $n_{\rm e0}(x)$ are the unperturbed dust, ion and electron number densities, respectively, and $Z_{\rm d0}(x)$ is the unperturbed number of charges residing on the dust grain measured in units of electron charge. The DA wave dynamics are governed by a set of fluid equation, including continuity, momentum, and Poisson's equations:

$$\begin{aligned}&\frac{\partial n_{\rm d}}{\partial t}+\frac{\partial(n_{\rm d}V_{\rm d})}{\partial x}=0,\\&\frac{\partial V_{\rm d}}{\partial t}+V_{\rm d}\frac{\partial V_{\rm d}}{\partial x}=-q\frac{\partial\phi}{\partial x},\\&\frac{\partial^2\phi}{\partial x^2}=-qn_{\rm d}+n_{\rm e}-n_{\rm i}.\end{aligned}\tag{1}$$

Where $V_{\rm d}$ is the dust fluid velocity normalized to the DA speed $C_{\rm d}=\sqrt{Z_{\rm d0}(0)T_{\rm i}/m_{\rm d}}$ with $T_{\rm i}$ being the ion-temperature (in energy units) and $m_{\rm d}$ being the mass of negatively charged dust particles, $n_{\rm d}$ is the dust grain number density normalized to $n_{\rm d0}(0)$, ϕ is the electrostatic potential normalized to $T_{\rm i}/e$ with e being the magnitude of the electron charge. The time and space variables are normalized by the dust plasma period $\omega_{\rm pd}^{-1}=\sqrt{m_{\rm d}/4\pi n_{\rm d0}(0)Z_{\rm d0}^2(0)e^2}$ and the Debye length $\lambda_{\rm Dd}=C_{\rm d}/\omega_{\rm pd}$, respectively.

The distribution function that was chosen by Cairns *et al*[25] is chosen in order to model an ion distribution with a population of fast particles. Therefore, the ion density $n_{\rm i}$ is directly given by

$$n_{\rm i}=\frac{1}{1-\mu(0)}[1+\beta(\phi+\phi^2)]\exp(-\phi),\tag{2}$$

where $\beta=\dfrac{4\alpha}{1+3\alpha}$, α is a parameter determining the number of fast (nonthermal) ions,

$$n_{\rm e}=\frac{\mu(x)}{1-\mu(0)}\exp(\sigma_{\rm i}\phi),\tag{3}$$

where $\sigma_{\rm i}=T_{\rm i}/T_{\rm e}$, with $T_{\rm e}$ being the electron-temperature (in energy units), $\mu(x)=n_{\rm e0}(x)/n_{\rm i0}(0)$.

The charge $q=Z_{\rm d}e$ (which includes the sign of the charge) is normalized by $Z_{\rm d0}(0)e$ (dust charge at $x=0$). To determine the normalized charge variable q, we consider the following orbital motion-limited[26] charge current balance equation. In normalized form, it reads as:

$$\frac{\tau_{\rm ch}}{\tau_{\rm d}}\left(\frac{\partial q}{\partial t}+V_{\rm d}\frac{\partial q}{\partial x}\right)=\frac{\tau_{\rm ch}}{Z_{\rm d0}(0)e}(I_{\rm e}+I_{\rm i}),\tag{4}$$

where $I_{\rm e}$ and $I_{\rm i}$ are the electron and ion current, respectively. We assume that the dust grain radius (a) $\ll$ the electron gyroradius ($\rho_{\rm e}$). The charging characteristics are not significantly influenced by the existence of external magnetic field, since for $a\ll\rho_{\rm e}$, the curvature effect of the trajectory of an electron (ion) impinging on a dust grain of radius a can be neglected.[27,28] Thus, considering the nonthermally distributed ions, we get the normalized expressions for the electron and ion currents for spherical dust grains with radius a[29]as follows

$$I_{\rm e}=-\pi a^2e\sqrt{\frac{8T_{\rm e}}{\pi m_{\rm e}}}n_{\rm e0}(x)\exp(\sigma_{\rm i}\phi)\exp[zq],\tag{5}$$

$$\begin{aligned}I_{\rm i}=\pi a^2e\sqrt{\frac{8T_{\rm i}}{\pi m_{\rm i}}}\frac{n_{\rm i0}(x)}{(1+3\alpha)}\Bigg[\Bigg(\left(1+\frac{24\alpha}{5}\right)&+\frac{16\alpha}{3}\phi+4\alpha\phi^2\Bigg)-\frac{zq}{\sigma_{\rm i}}\Bigg(\left(1+\frac{8\alpha}{5}\right)\\&+\frac{8\alpha}{3}\phi+4\alpha\phi^2\Bigg)\Bigg]\exp(-\phi),\end{aligned}\tag{6}$$

where $z=z_{\rm d0}(0)e^2/4\pi\varepsilon_0aT_{\rm e}$, $4\pi\varepsilon_0a$ is the capacitance of the spherical dust grain of radius a. $\tau_{\rm d}\left(\approx\omega_{\rm pd}^{-1}\right)$ is the dust hydrodynamical time scale and

$\tau_{\rm ch}\left[\approx (\mathrm{d}q_{\rm d}/\mathrm{d}t)^{-1}\right]$ is the charging time scale given as

$$\tau_{\rm ch} = \left[\frac{a}{\sqrt{2\pi}}\frac{\omega_{\rm pi}^2}{V_{\rm thi}}\frac{5+8\alpha}{5+15\alpha}\left(1+z+\frac{5+24\alpha}{5+8\alpha}\sigma_{\rm i}\right)\right]^{-1}, \tag{7}$$

where $\omega_{\rm pi}$ and $V_{\rm thi}$ are the ion plasma frequency and the ion thermal velocity, respectively. For a typical dusty plasma: $n_{\rm d0}(0) \sim 10^5\,\mathrm{cm}^{-3}$, $n_{\rm i0}(0) \sim 10^9\,\mathrm{cm}^{-3}$, $n_{\rm e0}(0) \sim 10^8\,\mathrm{cm}^{-3}$, $T_{\rm d} \sim 0.05\,\mathrm{eV}$, $T_{\rm i} \sim 0.1\,\mathrm{eV}$, $T_{\rm e} \sim 2\,\mathrm{eV}$, $a \sim 1\,\mu\mathrm{m}$, $m_{\rm d} \sim 10^{-12}g \sim 10^{12}m_{\rm i}$.

3. Dispersion relation

3.1. Inhomogeneity and non-adiabatic dust charge fluctuation

For non-adiabatic charge variation, $\tau_{\rm ch}/\tau_{\rm d}$ is small but finite,[22] we set

$$\frac{\tau_{\rm ch}}{\tau_{\rm d}} = \lambda. \tag{8}$$

In order to investigate the linear propagation of low frequency wave in inhomogeneous dusty plasmas, we shall carry out a normal analysis. We first express the dependent variables $V_{\rm d}$, ϕ, q, and $n_{\rm d}$ in terms of their equilibrium and perturbed parts as $n_{\rm d} = n_{\rm d0}(x) + n'_{\rm d}(x,t)$, $V_{\rm d} = 0 + V'_{\rm d}(x,t)$, $\phi = 0 + \phi'(x,t)$, $q = q_0(x) + q'(x,t)$, and the perturbed quantities are proportional to $\exp[\mathrm{i}(kx-\omega t)]$. Then, substituting Eqs.(2)–(3) and (5)–(8) into Eqs.(1) and (4), and linearizing the Eqs.(1) and (4) with these perturbations, we obtain the following linear dispersion relation:

$$\begin{aligned} &D(\omega,k)\\ &= k^2 - B - \frac{n_{\rm d0}(x)}{\beta_1 - \mathrm{i}\omega\lambda}\left(\beta_2 - \frac{k\lambda q_0(x)}{\omega}\frac{\mathrm{d}q_0(x)}{\mathrm{d}x}\right)\\ &\quad -\frac{kq_0^2(x)}{\omega^2}\left(kn_{\rm d0}(x) - \mathrm{i}\frac{\mathrm{d}n_{\rm d0}(x)}{\mathrm{d}x}\right) = 0, \end{aligned} \tag{9}$$

where

$$B = \frac{\beta - \mu(x)\sigma_{\rm i} - 1}{1-\mu(0)},$$

$$\beta_1 = \frac{1+\delta\sigma_{\rm i}}{(1+zq_0(x))(1+z+\delta\sigma_{\rm i})}\left(\delta = \frac{5+24\alpha}{5+8\alpha}\right),$$

and

$$\beta_2 = \frac{\sigma_{\rm i}}{z(1+z+\delta\sigma_{\rm i})}\left(\frac{zq_0(x)}{\sigma_{\rm i}}\frac{15-16\alpha}{15+24\alpha} - \frac{\delta\sigma_{\rm i} - zq_0(x)}{1+zq_0(x)} - \frac{15-8\alpha}{15+24\alpha}\right).$$

Equation (9) represents a dispersion relation for low frequency waves in nonuniform dusty plasmas consisting of extremely massive, micron-sized, negatively charged dust fluid, non-thermally distributed ions, and Boltzmann distributed electrons. It is seen from Eq.(9) that the dispersion relation is dependent on inhomogeneity, non-adiabatic dust charge variation and non-thermally distributed ions.

Now we return to the determination of roots of the dispersion relation. The explicit dispersion relation in this case may be obtained by Eq.(9) in the form $D(\omega,k) \equiv D_{\rm r}(\omega,k) + \mathrm{i}D_{\rm i}(\omega,k) = 0$. where

$$D_{\rm r} = \beta_1 k^2 - n_{\rm d0}(x)\left(\beta_2 - \frac{k\lambda q_0(x)}{\omega}\frac{\mathrm{d}q_0(x)}{\mathrm{d}x}\right) - \frac{\beta_1 k^2 q_0^2(x) n_{\rm d0}(x)}{\omega^2} + \frac{\lambda k q_0^2(x)}{\omega}\frac{\mathrm{d}n_{\rm d0}(x)}{\mathrm{d}x} - \beta_1 B, \tag{10}$$

$$D_{\rm i} = -\omega\lambda k^2 + \frac{\beta_1 k q_0^2(x)}{\omega^2}\frac{\mathrm{d}n_{\rm d0}(x)}{\mathrm{d}x} + \frac{\lambda k^2 q_0^2(x) n_{\rm d0}(x)}{\omega} + \omega\lambda B. \tag{11}$$

In Eq.(10), for $\omega \equiv \omega_{\rm r} + \mathrm{i}\omega_{\rm i}$, with $|\omega_{\rm i}| \ll |\omega_{\rm r}|$, the real frequency is obtained by setting $D_{\rm r}(\omega,k) \equiv 0$.

$$\begin{aligned} &(\beta_1 k^2 - \beta_2 n_{\rm d0}(x) - \beta_1 B)\omega_{\rm r}^2\\ &+\left(\lambda k n_{\rm d0}(x) q_0(x)\frac{\mathrm{d}q_0(x)}{\mathrm{d}x}\right.\\ &\left.+\lambda k q_0^2(x)\frac{\mathrm{d}n_{\rm d0}(x)}{\mathrm{d}x}\right)\omega_{\rm r}\\ &-\beta_1 k^2 n_{\rm d0}(x) q_0^2(x) = 0. \end{aligned} \tag{12}$$

Thus we obtain the real frequency,

$$\omega_{\rm r} = -\frac{b}{2} \pm \frac{\sqrt{b^2-4c}}{2}, \tag{13}$$

where $b = \dfrac{\lambda k n_{\rm d0}(x) q_0(x)\dfrac{\mathrm{d}q_0(x)}{\mathrm{d}x} + \lambda k q_0^2(x)\dfrac{\mathrm{d}n_{\rm d0}(x)}{\mathrm{d}x}}{\beta_1 k^2 - \beta_2 n_{\rm d0}(x) - \beta_1 B}$, and $c = -\dfrac{\beta_1 k^2 n_{\rm d0}(x) q_0^2(x)}{\beta_1 k^2 - \beta_2 n_{\rm d0}(x) - \beta_1 B}$. The damping rate $\omega_{\rm i}$ is calculated from the condition $\omega_{\rm i} = -D_{\rm i}/(\partial D_{\rm r}/\partial\omega_{\rm r})$, Thus, the damping rate is given by

$$\omega_{\rm i} = \frac{-\omega\lambda k^2 + \dfrac{\beta_1 k q_0^2(x)}{\omega^2}\dfrac{{\rm d}n_{\rm d0}(x)}{{\rm d}x} + \dfrac{\lambda k^2 q_0^2(x) n_{\rm d0}(x)}{\omega} + \omega\lambda B}{2\omega(k^2\beta_1 - \beta_2 n_{\rm d0}(x) - \beta_1 B) + \lambda k\left(n_{\rm d0}(x)q_0(x)\dfrac{{\rm d}q_0(x)}{{\rm d}x} + q_0^2(x)\dfrac{{\rm d}n_{\rm d0}(x)}{{\rm d}x}\right)}. \quad (14)$$

It is obvious from Eqs.(13) and (14) that the frequency and the damping of the low frequency are influenced by the dust charge variation, the presence of non-thermally distributed ions, the temperature of ions, and the inhomogeneity.

3.2. Non-adiabatic dust charge fluctuation

In this case, we assume that the equilibrium quantities are constant, i.e, $n_{\rm d0}$, q_0, μ do not vary with x coordinate, and that the ratio $\tau_{\rm ch}/\tau_{\rm d} \neq 0$, i.e., the ratio is a finite and small quantities. Therefore, the dispersion relation of the low frequency waves becomes

$$D(\omega, k) = k^2 - B - \frac{\beta_2 n_{\rm d0}}{\beta_1 - {\rm i}\omega\lambda} - \frac{k^2 n_{\rm d0} q_0^2}{\omega^2} = 0. \quad (15)$$

According to the same method, we obtain the real ($\omega_{\rm r}$) and imaginary ($\omega_{\rm i}$) parts of the frequency, respectively

$$\omega_{\rm r} = \left(\frac{\beta_1 k^2 n_{\rm d0} q_0^2}{\beta_1 k^2 - \beta_2 n_{\rm d0} - \beta_1 B}\right)^{1/2}, \quad (16)$$

$$\omega_{\rm i} = \frac{-\lambda k^2 + \lambda B + \dfrac{\lambda k^2 q_0^2 n_{\rm d0}}{\omega^2}}{2(k^2\beta_1 - \beta_2 n_{\rm d0} - \beta_1 B)}. \quad (17)$$

It is obvious from Eqs.(15), (16) and (17) that the dispersion relation becomes simpler when the inhomogeneity is neglected, and that the non-adiabatic dust charge fluctuation and the non-thermally distributed ions have effect on the propagation of the low frequency waves.

3.3. No charge fluctuation

In this case we assume that the charges on the dust grains are fixed. Therefore, the dispersion relation of the low frequency waves in the presence of non-thermally distributed ions becomes

$$D(\omega, k) = k^2 - B - \frac{k^2 n_{\rm d0} q_0^2}{\omega^2} = 0. \quad (18)$$

It is seen from Eq.(18) that the frequency of the low frequency waves does not include the imaginary part, which means that the waves is stable when the dust charges are constant and the dust plasmas are homogeneous.

4. Numerical results and discussion

We now investigate the influence of the inhomogeneity, the dust charge variation, the presence of non-thermally distributed ions, and the temperature of ions on the propagation of the low frequency mode by using the general dispersion relation, viz. Eq.(9). To make further progress we need to find a plasma model that can easily be discussed throughout. Although there are a number of measurements and computer simulations of inhomogeneous profiles for dusty plasma parameters, all of them are related to specific experiments and often the plasma date just contradicts each other. This means that the general behaviour of the inhomogeneous structure of dusty plasmas is far from being clearly understood. It is instructive to go to the simplest model, that can easily be discussed throughout and allows one to ascertain the main physical features. Evident reduction in complexity can be obtained when all the functions $n_{\rm d0}(x)$, $q_0(x)$, $\mu(x)$, are characterized by exponential profile, namely

$$\begin{aligned} n_{\rm d0}(x) &= n_{\rm d0}(0)\exp(\alpha_{\rm d}x) \\ q_0(x) &= q_0(0)\exp(\alpha_{\rm q}x), \\ \mu(x) &= \mu(0)\exp(\alpha_\mu x). \end{aligned} \quad (19)$$

Inserting Eq.(19) in Eq.(9), we can numerically investigated the propagation of the DA waves in nonuniform dusty plasmas with dust charge fluctuation and fast ions.

Figures 1–4 illustrate the numerical solutions of Eq.(9) for both the frequency ($\omega_{\rm r}$) and the growth rate ($\omega_{\rm i}$) of the DA waves for different α (the number of the non-thermal ions), $\sigma_{\rm i}$ (the temperature of ions), λ (the effect of the non-adiabatic dust charge variation),

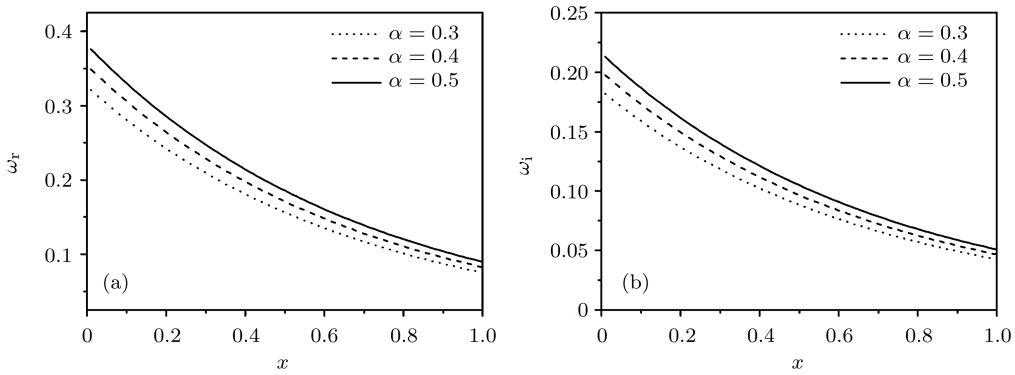


Fig.1. The frequency (a) and the damping rate (b) against x for different α and $\sigma_i = 0.1$, $\lambda = 0.01$, $k = 0.6$, $z = 2$.

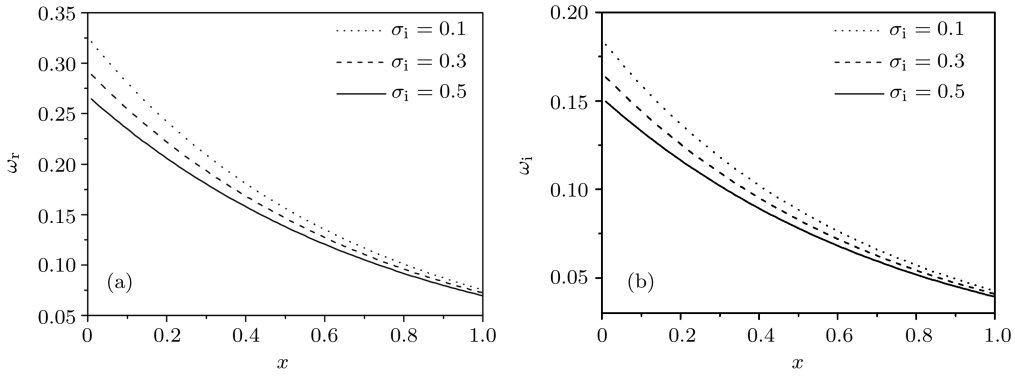


Fig.2. The frequency (a) and the damping rate (b) against x for different σ_i and $\alpha = 0.3$, $\lambda = 0.01$, $k = 0.6$, $z = 2$.

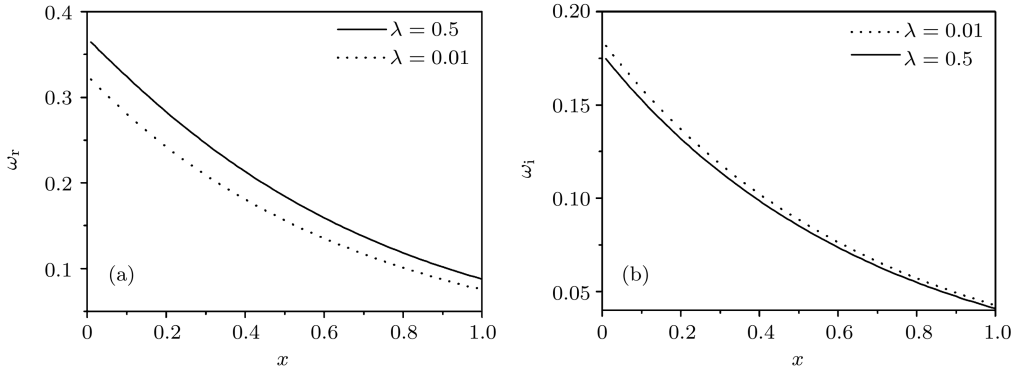


Fig.3. The frequency (a) and the damping rate (b) against x for different λ and $\alpha = 0.3$, $\sigma_i = 0.1$, $k = 0.6$, $z = 2$.

and k (wave number) against x, respectively. In a general way, the non-adiabatic dust charge variation results in the dissipation of the waves. Plasma densities exponentially decrease with x, thus the waves should increase with x. It is shown from these figures that the growth rate decreases with x, because the dissipative effect of non-adiabatic dust charge fluctuation is stronger than the effect of the inhomogeneity. Moreover, it is indicated from theses figures that the frequency of the DA waves also decreases with x. From Figs.1–4, we can see that the frequency of the DA waves increases when the values of λ, the number of non-thermal ions (α), and the wave number (k) increase, but decreases when the temperature of ions (σ_i) increases, and the damping rate increases with α, decreases with σ_i, λ. Figure 2 depicts that when the values of x are lower, i.e., the plasmas densities are larger, the temperature of ions (σ_i) has effect on the frequency and the damping rate of the DA waves, significantly, however, for higher values of x, the frequency and the damping rate of the DA waves vary with the temperature of ions (σ_i) slowly. It is clear

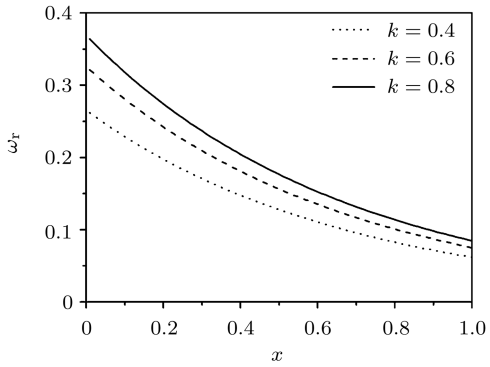


Fig.4. The frequency against x for different k and $\alpha = 0.3$, $\lambda = 0.01$, $\sigma_{\rm i} = 0.1$, $z = 2$.

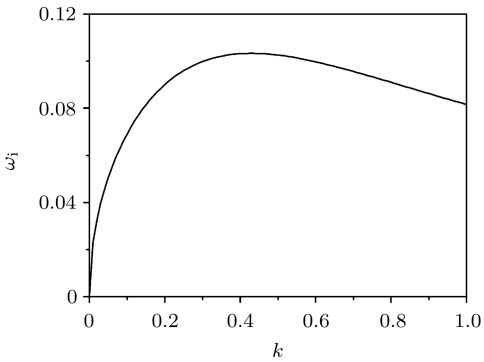


Fig.5. The damping rate against k for $\alpha = 0.3$, $\lambda = 0.01$, $\sigma_{\rm i} = 0.1$, $z = 2$.

from Fig.3 that the frequency and the damping of the DA waves vary with λ, indistinctively. Furthermore, according to the numerical experiment, the damping rate of the DA waves is nonlinear with the wave number (k). Figure 5 indicates how the damping rate varies with the wave number (k). It can be seen from Fig.5 that for lower values of k, the damping rate of the DA waves obviously increases as the wave number increases, however, for higher values of k, i.e. $k_{\rm c} > 0.4$, with the increase of the wave number, the damping rate decreases slowly.

5. Conclusion

In summary, the instability of the DA waves is investigated by the kinetic dispersion relation in nonuniform dusty plasmas, which consists of extremely massive, micron-sized, negatively charged dust fluid, nonthermally distributed ions, and Boltzmann distributed electrons. The effects of some parameters such as the number of fast ions, the non-adiabatic dust charge variation, the temperature of ions, and the number of waves on the instability of the DA waves were investigated in great detail. With reference to the present study, we can obtain more profound understanding of the properties of DA wave. Furthermore, we expect that the present investigation would be useful for future experiments on DA waves.

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