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Effect of ion nonthermality on nonlinear dust acoustic wave propagation in a complex plasma in presence of secondary electron emission

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In this paper we have investigated the effect of ion nonthermality on nonlinear dust acoustic wave propagation in a complex plasma in presence of secondary electron emission considering equilibrium dust charge positive. In space and astrophysical plasmas presence of nonthermal ions have been detected by satellite observations. This ion nonthermality modifies propagation characteristics of dust acoustic waves when dust grains are charged by secondary electron emission mechanism. In case of dust charging by secondary electron emission process two stable equilibrium dust charge states exist out of which one is negative and the other is positive. Here we have considered positive equilibrium dust charge state and both adiabatic and nonadiabatic dust charge variation. Our investigation shows that characteristics of both dust acoustic soliton and dust acoustic shock depend on the strength of the ion nonthermality along with secondary electron yield. Increase in both ion nonthermality and secondary electron yield help to retain the shape of compressive dust acoustic soliton when dust charge variation is adiabatic and to maintain oscillation of the dust acoustic shock when dust charge variation is nonadiabatic. [http://dx.doi.org/10.1063/1.4985747]

I. INTRODUCTION

Wave propagation in dusty plasmas has become an important field of plasma research since early nineties of the last century. Both linear and nonlinear theories of dust acoustic and dust ion acoustic wave propagation have been extensively studied by several authors in different physical situation.[1,2] In most of these studies dust grains were charged by plasma current, no electron emission from dust grains were considered. In such cases only one equilibrium dust charge state exists which is negative.[3]

On the other hand if primary electrons are energetic enough they excite material electrons of dust grains. Those excited electrons then leave material surfaces and are called secondary electrons. The ratio of such emitted electrons to incident electrons is termed as secondary electron yield. In case of secondary electron emission, dust grains possess two stable equilibrium dust charge states out of which one is negative and the other is positive.[3–6] The negative equilibrium state exists for low value of the secondary electron yield whereas the positive equilibrium state exists for its high value.

Another important grain charging process in which electrons emit from dust grains is photoemission process that causes positive grain charging. This photoemission process starts with optical excitation. In this process photons, as light quanta $h\nu$ are absorbed by an electron and transmits all its energy. This energy transfer is definite which is not the case when excitation is made by electrons or ions. This is the basic difference between the secondary emission process and the photoemission process. Using a cesiated p-type GaN sample Yater et al[7] shown that photoelectrons had a substantially

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narrower energy distribution than the secondary electrons. Also their measurements revealed that the photoelectron distributions were not as uniform as the secondary electron distribution.

In space plasma positively charged dust (ice) particles were observed by rocket measurement[8] even during night hours when photoelectric emission of electrons from the ice is not operable. The cause of this positive charging may be due to secondary electron emission process. Thus in the study of wave propagation in a complex plasma presence of positively charged dust is important when dust grains are charged by secondary electron emission process.

Non thermal ions were observed by the Vella satellite from the earth's bow shock[9] as well as in and around earth's foreshock.[10] The Aspera experiment on Phobos-satellite detected nonthermal ion fluxes from the upper ionosphere of Mars.[11] Due to the absence of strong magnetic field, the impact of the solar wind with the planetary atmosphere results in nonthermal ion fluxes. There are many other sources which produce nonthermal ions. Thus to study the effect of nonthermal ions on dust acoustic wave propagation is an important task of dusty plasma research.

Linear theories of dust acoustic wave propagation in presence of secondary electron emission were studied earlier by considering both negatively and positively charged dust grains.[12–16] Since early nineties presence of non thermal ions in the study of wave propagation in dusty plasma were considered by several authors[17–25] but no one considered the presence of secondary electrons in their study. Presence of nonthermal ions along with secondary electrons was first time considered by us to study the linear theory of dust acoustic wave propagation in self gravitating dusty plasmas.[26,27] Presence of nonthermal electrons was also later considered to study the linear theory of dust acoustic waves.[28] Nonlinear theory of dust acoustic wave propagation in presence of secondary electron emission has been recently reported by us considering both adiabatic and non adiabatic dust charge variation with Boltzmann distributed electrons (primary and secondary) and ions.[29] Presence of nonthermal ions along with Boltzmann distributed primary and secondary electrons and positively charged inertial dust grains will be considered in this paper to study nonlinear evolution of dust acoustic waves. Both adiabatic and nonadiabatic dust charge variation will be taken into account.

In our present investigation we have used reductive perturbation technique which shows the existence of dust acoustic soliton for adiabatic dust charge variation and dust acoustic shock for nonadiabatic dust charge variation. Both amplitude and width of this dust acoustic soliton depend on the nonthermal parameter a and the secondary electron yield δ_M. Similarly for nonadiabatic dust charge variation the dissipation-dispersion ratio is also function of these two parameters a and δ_M. Hence ion nonthermality influences propagation characteristics of both dust acoustic soliton and dust acoustic shock wave for fixed as well as varying δ_M. Nature of its dependence has been investigated numerically.

II. FORMULATION OF THE PROBLEM

Since we are studying characteristics of nonlinear propagation of low frequency dust acoustic waves the plasma under our consideration consists of Boltzmann distributed primary and secondary electrons, nonthermal ions and inertial positively charged dust grains satisfying the quasineutrality condition,

$$n_{io} + z_{d0} n_{d0} = n_{eo} + n_{so} \tag{1}$$

where n_{io}, n_{eo}, n_{so} and n_{d0} are equilibrium number densities of ions, primary electrons, secondary electrons and dust grains respectively and z_{d0} is the number of charges on dust grains in equilibrium. The nonthermal ions satisfies the velocity distribution[30]

$$F_i(v_i) = F_i(v_x, v_y, v_z) = \frac{n_{i0}}{1+3a}\left(\frac{1}{2\pi v_{ti}^2}\right)^{3/2}\left[1 + 4a\left(\frac{1}{2}\frac{v_x^2}{v_{ti}^2} + \frac{\Phi}{\sigma_i}\right)^2\right]\exp\left(-\frac{v_x^2+v_y^2+v_z^2}{2v_{ti}^2} - \frac{\Phi}{\sigma_i}\right) \tag{2}$$

where v_{ti} is the ion thermal velocity, a is the ion nonthermal parameter, $\sigma_i = \frac{T_i}{T_e}$ is the ion-electron temperature ratio, $\Phi = \frac{\mathrm{e}\phi}{\mathrm{T_e}}$ is the normalized plasma potential and v_x, v_y, v_z are x, y, and z components of ion velocity.

Thus normalized nonthermal ion density calculated from the distribution function (2) will be

$$N_i = \left[1 + \frac{4a}{1+3a}(\frac{\Phi}{\sigma_i} + \frac{\Phi^2}{{\sigma_i}^2})\right]\exp(-\Phi/\sigma_i) \tag{3}$$

On the other hand normalized number densities of Boltzmann distributed primary and secondary electrons are,

$$N_e = \exp(\Phi) \tag{4}$$

$$N_s = \exp\left(\frac{\Phi}{\sigma_s}\right) \tag{5}$$

Inertial dust grains satisfy the normalized continuity and momentum equations,

$$\frac{\partial N_d}{\partial T} + \frac{\partial}{\partial X}(N_d V_d) = 0 \tag{6}$$

$$\frac{\partial V_d}{\partial T} + V_d \frac{\partial V_d}{\partial X} = -\frac{Q_d}{\alpha_d}\frac{\partial \Phi}{\partial X} \tag{7}$$

whereas the variable dust charge obeys the normalized grain charging equation

$$(\frac{\omega_{pd}}{\nu_d})(\frac{\partial Q_d}{\partial T} + V_d \frac{\partial Q_d}{\partial X}) = \frac{1}{\nu_d}(\frac{\bar{I}_i + \bar{I}_e + \bar{I}_e^s}{z_{do} e}) \tag{8}$$

The Poisson equation satisfied by the normalized electric potential is,

$$\frac{\partial^2 \Phi}{\partial X^2} = -\frac{1}{(1+\frac{\delta_i}{\sigma_i}+\frac{\delta_s}{\sigma_s})}\left[\delta_i\left\{1+\frac{4a}{1+3a}(\frac{\Phi}{\sigma_i}+\frac{\Phi^2}{{\sigma_i}^2})\right\}\exp\left(-\frac{\Phi}{\sigma_i}\right) - \exp(\Phi) + \delta_s \exp\left(\frac{\Phi}{\sigma_s}\right) + (1-\delta_i+\delta_s)Q_d N_d)\right] \tag{9}$$

Here the ion, primary electron, secondary electron, and dust number densities n_i, n_e, n_s and n_d, dust fluid velocity u_d, electrostatic potential energy $e\phi$, dust charge q_d and the independent space variable x and time variable t are normalized in the following way,

$$\mathrm{N_i = n_i/n_{i0};\ N_e = n_e/n_{e0};\ N_s = n_s/n_{s0};\ N_d = n_d/n_{d0};\ V_d = u_d/c_d;\ \Phi = \frac{e\phi}{T_e};}$$
$$Q_\mathrm{d} = q_d/\mathrm{ez_{d0}},\ \mathrm{X = x/\lambda_d;\ T = \omega_{pd} t};\ q_{do} = z_{do} e, \tag{10}$$

where $\omega_{pd} = \left(\frac{4\pi n_{d0} z_{d0}^2 e^2}{m_d}\right)^{1/2}$ is the dust plasma frequency, $c_d = \sqrt{\frac{z_{d0} T_{eff}}{m_d}}$ is the dust acoustic speed, $\lambda_D = \left(\frac{T_{eff}}{4\pi z_{d0} n_{d0} e^2}\right)^{1/2}$ is the dusty plasma Debye length, m_d is mass of the dust grains and z_{d0} is the grain charge number in equilibrium. The effective temperature T_{eff} is defined by

$$\frac{1}{T_{eff}} = \frac{1}{z_{do} n_{do}}(\frac{n_{io}}{T_i} + \frac{n_{eo}}{T_e} + \frac{n_{so}}{T_s}) \tag{11}$$

Here T_i, T_e, T_s are ion, primary electron and secondary electron temperatures respectively, and $\delta_i = \frac{n_{io}}{n_{eo}}$, $\delta_s = \frac{n_{so}}{n_{eo}}$, $\sigma_i = \frac{T_i}{T_e}$, $\sigma_s = \frac{T_s}{T_e}$, $\alpha_d = \frac{(1-\delta_i+\delta_s)}{(1+\frac{\delta_i}{\sigma_i}+\frac{\delta_s}{\sigma_s})}$, $z = z_{d0} e^2/r_0 T_e$, r_0 is the grain radius.

The non dimensionalized expressions for ion current $\bar{I}_i$ has been calculated from the nonthermal ion distribution (3) in the form,[19]

$$I_i = \pi {r_0}^2 e\sqrt{\frac{8T_i}{\pi m_i}}\frac{n_{i0}}{1+3a}\exp(-\frac{\Phi}{\sigma_i}) \times \left[(1+\frac{24a}{5}) + \frac{8a\Phi}{3\sigma_i}(2+\frac{zQ_d}{\sigma_i}) + \frac{4a}{5}(\frac{5\Phi^2}{{\sigma_i}^2} + \frac{(zQ_d)^2}{{\sigma_i}^2}) + \frac{16azQ_d}{5\sigma_i}\right]\exp(-\frac{zQ_d}{\sigma_i}) \tag{12}$$

while the primary electron current $\bar{I}_e$ and secondary electron current $\bar{I}_e^s$ are,[3]

$$\bar{I}_e = -\pi {r_0}^2 e\sqrt{\frac{8T_e}{\pi m_e}} n_{e0} \exp{(\Phi)}\,(1 + zQ_d) \tag{13}$$

$$\bar{I}_e^s = 3.7\delta_M \pi {r_0}^2 e\sqrt{\frac{8T_e}{\pi m_e}} n_{e0} \exp(\Phi)(1 + \frac{zQ_d}{\sigma_s}) \exp(zQ_d - \frac{zQ_d}{\sigma_s}) F_{5,B}\left(\frac{E_M}{4T_e}\right) \tag{14}$$

Here m_i, m_e are ion and electron masses respectively and δ_M is the maximum yield of secondary electrons which occurs when the impinging electrons have the maximum kinetic energy E_M. The function $F_{5,B}(x)$ is given by,[3]

$$F_{5,B}(x) = x^2 \int_B^\infty u^5 \exp\left[-(xu^2 + u)\right] du, \text{ where } x = \frac{E_M}{4T_e} \text{ and } B = \sqrt{\frac{\frac{eq_d}{r_0 T_e}}{x}}, \tag{15}$$

The grain charging frequency in this case has been calculated in the form,

$$\nu_d = -\frac{\partial(\bar{I}_i + \bar{I}_e + \bar{I}_e^s)}{\partial Q_d}\Bigg|_{Q_d = z_d e} = \frac{a}{\sqrt{2\pi}} \frac{\omega_{pi}^2}{V_{thi}} [A_d \exp(-\frac{z}{\sigma_i}) + \frac{\alpha_{2s}\sqrt{m_e^i \sigma_i}}{\delta_i}] \tag{16}$$

with $A_d = \frac{1}{1+3a}\left\{1 + \frac{8a}{5} + \frac{4a}{5}(\frac{z^2}{\sigma_i^2}) + \frac{8az}{5\sigma_i}\right\}$ and

$$\alpha_{2s} = 1 - 3.7\delta_M \exp(z - \frac{z}{\sigma_s})\{\frac{1}{\sigma_s} + (1 + \frac{z}{\sigma_s})(1 - \frac{1}{\sigma_s})\} F_{5,B_0}\left(\frac{E_M}{4T_e}\right)$$

Here grain charge number z is not arbitrary. It satisfies the quasineutrality condition (1) which follows $\delta_i < 1 + \delta_s$. The equilibrium current balance equation $\bar{I}_i + \bar{I}_e + \bar{I}_e^s = 0$ gives

$$\delta_i = \sqrt{\frac{m_e^i}{\sigma_i}}(1 + z)\alpha_{1s} \exp(\frac{z}{\sigma_i}) \frac{5(1 + 3a)}{\left[(5 + 24a) + 4a(\frac{z^2}{\sigma_i^2}) + \frac{16az}{\sigma_i}\right]}, \tag{17a}$$

which is a function of both a and z(=$z_{d0}e^2/r_0T_e$) with $\alpha_{1s} = 1 - 3.7\delta_M \exp(z - \frac{z}{\sigma_s}) F_{5,B_0}\left(\frac{E_M}{4T_e}\right)$ $(1 + \frac{z}{\sigma_s})/(1 + z)$ and $m_e^i = \frac{m_i}{m_e}$.

Thus to satisfy the quasineutrality condition (1), the grain charge number z(=$z_{d0}e^2/r_0T_e$) must satisfy the condition,

$$\sqrt{\frac{m_e^i}{\sigma_i}}(1 + z)\alpha_{1s} \exp(\frac{z}{\sigma_i}) \frac{5(1 + 3a)}{\left[(5 + 24a) + 4a(\frac{z^2}{\sigma_i^2}) + \frac{16az}{\sigma_i}\right]} < 1 + \delta_s \tag{17b}$$

III. REDUCTIVE PERTURBATION ANALYSIS: ADIABATIC AND NONADIABATIC DUST CHARGE VARIATION

For the study of small amplitude structures in dusty plasma in presence of nonthermal ions and secondary electrons with positive equilibrium dust charge, we employ the reductive perturbation technique, using the stretched coordinates $\xi = \varepsilon^{1/2}(X - \lambda T)$ and $\tau = \varepsilon^{3/2}T$ where ε is a small parameter and λ is the wave velocity normalized by c_d. The variables N_d, V_d, Φ and Q_d are then expanded as,

$$\begin{aligned} N_d &= 1 + \varepsilon N_{d1} + \varepsilon^2 N_{d2} + ... \\ V_d &= \varepsilon V_{d1} + \varepsilon^2 V_{d2} + ... \\ \Phi &= \varepsilon \Phi_1 + \varepsilon^2 \Phi_2 + ... \\ Q_d &= 1 + \varepsilon Q_{d1} + \varepsilon^2 Q_{d2} + \varepsilon^3 Q_{d3} + ... \end{aligned} \tag{18}$$

Substituting these expansions into equations (3)-(9) with (12)-(16) and collecting the terms of different powers of ε we obtain,

$$\lambda N_{d1} = V_{d1},\ V_{d1} = \frac{\Phi_1}{\lambda\alpha_d},\ \mathrm{N}_{d1} = \frac{\Phi_1}{\lambda^2\alpha_d}, \Phi_1 = \alpha_a(\mathrm{N}_{d1} + \mathrm{Q}_{d1}) \tag{19}$$

with $\alpha_a = \frac{1-\delta_i+\delta_s}{\frac{\delta_i}{\sigma_i}(\frac{1-a}{1+3a})+\frac{\delta_s}{\sigma_s}+1}$
in the lowest order of ε.

To the next higher order in ε, we have the following set of equations,

$$\frac{\partial N_{d1}}{\partial\tau} - \lambda\frac{\partial N_{d2}}{\partial\xi} + \frac{\partial}{\partial\xi}(N_{d1}V_{d1}) + \frac{\partial V_{d2}}{\partial\xi} = 0 \tag{20}$$

$$\frac{\partial V_{d1}}{\partial\tau} - \lambda\frac{\partial V_{d2}}{\partial\xi} + V_{d1}\frac{\partial V_{d1}}{\partial\xi} = -\frac{1}{\alpha_d}(\frac{\partial\Phi_2}{\partial\xi} + Q_{d1}\frac{\partial\Phi_1}{\partial\xi}) \tag{21}$$

$$\frac{\partial^2\Phi_1}{\partial\xi^2} = A\Phi_2 - \alpha_d N_{d2} - \alpha_d Q_{d2} - B\Phi_1^2 \tag{22}$$

where $\mathrm{A} = \frac{\frac{\delta_i}{\sigma_i}(\frac{1-a}{1+3a})+\frac{\delta_s}{\sigma_s}+1}{\frac{\delta_i}{\sigma_i}+\frac{\delta_s}{\sigma_s}+1}$ and $\mathrm{B} = \left[\frac{1}{\lambda^2}(\frac{1}{\alpha_a} - \frac{1}{\alpha_d\lambda^2}) + \frac{1}{2}\frac{(\frac{\delta_i}{\sigma_i^2} - \frac{\delta_s}{\sigma_s^2} - 1)}{(\frac{\delta_i}{\sigma_i}+\frac{\delta_s}{\sigma_s}+1)}\right]$

The above set of equations are common to both adiabatic and nonadiabatic dust charge variation. The grain charging equation (8) will be separate for these two cases.

In case of adiabatic dust charge variation $\frac{\omega_{pd}}{\nu_d} \approx 0$, the dust charging frequency ν_d is very high compared to dust plasma frequency whereas for nonadiabatic dust charge variation $\frac{\omega_{pd}}{\nu_d}$ is small but finite i.e. dust grains are charged in comparatively slow time scale so that dust charging frequency ν_d is not very high.

For adiabatic dust charge variation normalized grain charging equation (8) reduces to,

$$\bar{I}_i + \bar{I}_e + \bar{I}_e^s = 0 \tag{23}$$

Substituting the expressions of $\bar{I}_i, \bar{I}_e\ and\ \bar{I}_e^s$ from (12)-(14) then equating from both sides the terms containing ε and ε^2, we get,

$$\mathrm{Q}_{d1} = \beta_d\Phi_1, \quad \mathrm{Q}_{d2} = \beta_d\Phi_2 + \gamma_d\Phi_1^2, \tag{24}$$

The expressions of β_d and γ_d are given in Appendix.
Here the normalized phase velocity of the dust acoustic waves

$$\lambda = \frac{1}{\sqrt{A - \alpha_d\beta_d}} \tag{25}$$

provided $\alpha_d\beta_d \neq A$. The expressions of α_d, β_d and γ_d depend upon the nonthermal parameter a.

Eliminating all the second-order terms from equations (20)-(24) we get the K-dV equation

$$\frac{\partial\Phi_1}{\partial\tau} + \alpha\Phi_1\frac{\partial\Phi_1}{\partial\xi} + \beta\frac{\partial^3\Phi_1}{\partial\xi^3} = 0 \tag{26}$$

where,

$$\alpha = \beta\left[\frac{3\mathrm{A}}{\lambda^2\alpha_\mathrm{d}} + 2\alpha_\mathrm{d}\gamma_\mathrm{d} + \frac{(\frac{\delta_\mathrm{i}}{\sigma_\mathrm{i}^2} - \frac{\delta_\mathrm{s}}{\sigma_\mathrm{s}^2} - 1)}{(\frac{\delta_\mathrm{i}}{\sigma_\mathrm{i}} + \frac{\delta_\mathrm{s}}{\sigma_\mathrm{s}} + 1)}\right], \beta = \frac{\lambda^3}{2} = \frac{1}{2}(A - \alpha_d\beta_d)^{-3/2} \tag{27}$$

The KdV equation (26) possesses soliton solution,

$$\Phi_1 = \Phi_{1m}\sec h^2\left[\frac{(\xi - M\tau)}{w}\right] \tag{28}$$

with amplitude $\Phi_{1m} = \frac{3M}{\alpha}$ and width $w = 2\sqrt{\frac{\beta}{M}}$ respectively. M is the Mach number. It is clear that both $\Phi_{1\mathrm{m}}$ and w depend on both secondary electron yield δ_M and ion nonthermal parameter a through the coefficients α and β. Thus changes in both δ_M and a change the amplitude and width of the soliton which will be shown numerically in section IV.

As in case of nonadiabatic dust charge variation $\frac{\omega_{pd}}{\nu_d}$ is small but finite we can assume $\frac{\omega_{pd}}{\nu_d} = \nu\sqrt{\varepsilon}$ where ε is small and ν is of the order of unity. The dust charge perturbation in that case is governed by,

$$Q_{d1} = \beta_d\Phi_1;\ Q_{d2} = \beta_d\Phi_2 + \gamma_d\Phi_1^2 + \frac{\lambda\nu\beta_d}{\sigma_i\beta_a}(\delta_i A_d \exp(-\frac{z}{\sigma_i}) + \alpha_{2s}\sqrt{\mu_i\sigma_i})\frac{\partial\Phi_1}{\partial\xi} \tag{29}$$

which has been obtained from equation (8) and (12)-(14) with the perturbation (18) and the above nonadiabaticity condition.

Eliminating all the second-order terms of equation (20), (21) and (22) we get the standard KdV-Burger equation,

$$\frac{\partial\Phi_1}{\partial\tau} + \alpha\Phi_1\frac{\partial\Phi_1}{\partial\xi} + \beta\frac{\partial^3\Phi_1}{\partial\xi^3} = \mu\frac{\partial^2\Phi_1}{\partial\xi^2} \tag{30}$$

where

$$\mu = -\frac{\lambda^4\nu\beta_d}{2\sigma\beta_a}\left[\delta_i A_d \exp(-\frac{z}{\sigma_i}) + \alpha_{2s}\sqrt{\mu_i\sigma_i}\right] \tag{31}$$

is the coefficient of dissipation and α, β are same as in (27).
Here all the coefficients α, β and μ are functions of both the secondary electron yield δ_M and the ion nonthermal parameter a. The KdV-Burger equation (30) possesses dust acoustic shock solution which is oscillatory if it is dispersion dominated and monotonic if it is dissipation dominated which depends upon the nonthermal parameter a and the secondary electron yield δ_M. This dependence will numerically shown in section IV.

IV. NUMERICAL RESULTS

In our numerical calculation for positively charged dust grains we have considered MgO material for which δ_M takes values 3-25, $E_M(eV) \approx 400 - 1500$, $\kappa T_e \approx 2eV$, $\kappa T_s \approx 3eV$.[3] Since δ_M is the ratio of the emitted electrons to the incident electrons, for positively charged dust grains higher values of δ_M is justified. We have taken here two values 22 and 24. Also $\delta_s = \frac{n_{s0}}{n_{e0}} = 0.8$ and M = 1.2 have considered. Satisfying condition (17b) range of z has been calculated $0 < z \leq 0.24$. All the figures have been drawn within this range of z.

Figures 1 has been plotted for the soliton solution (28) against χ for ion non thermal parameter a=0.1 and δ_M = 22, 24. This figure show the existence of compressive dust acoustic soliton whose amplitude increases and width decreases with increasing δ_M i.e., with increasing secondary electron emission. The soliton solution (28) against χ has been plotted in figure 2 for three different values

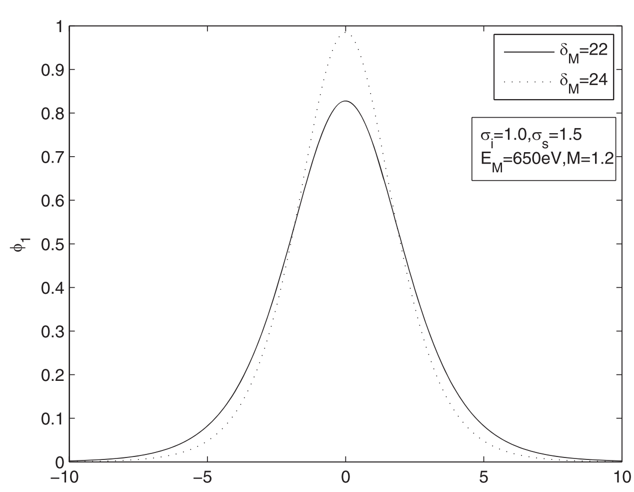

FIG. 1. Plot of the compressive Dust Acoustic Soliton for different δ_M at $a = 0.1$in case of adiabatic dust charge variation.

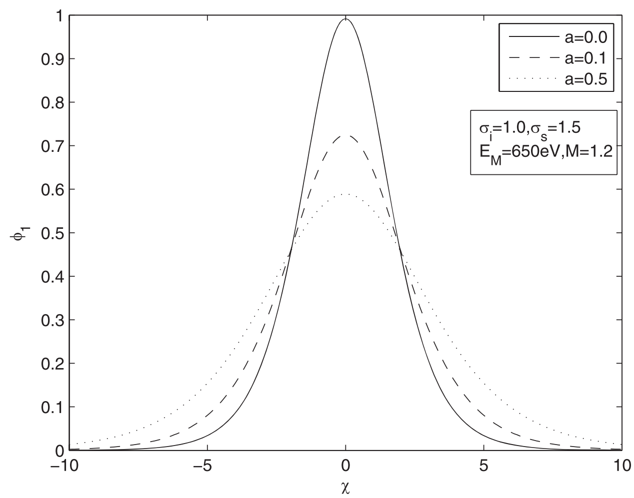

FIG. 2. Plot of the compressive Dust Acoustic Soliton for different a at $\delta_M = 24$ in case of adiabatic dust charge variation.

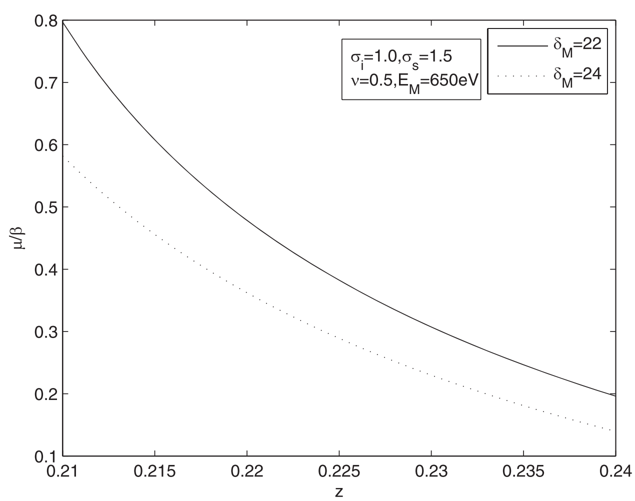

FIG. 3. Plot of the ratio μ / β versus z for different δ_M at $a = 0.1$ and $\nu = 0.5$ in case of nonadiabatic dust charge variation.

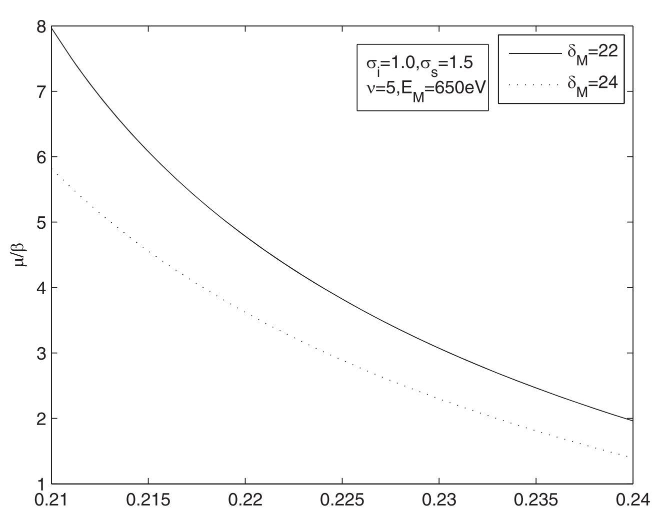

FIG. 4. Plot of the ratio μ / β versus z for different δ_M at $a = 0.1$ and $\nu = 5$ in case of nonadiabatic dust charge variation.

of ion nonthermal parameter $a = 0, 0.1, 0.5$ at fixed $\delta_M = 24$. This figure shows that amplitude of the compressive dust acoustic soliton reduces and its width increases with increasing ion non thermality. These figures 1, 2 have been plotted for adiabatic dust charge variation.

The above observations imply that increase in the strength of the secondary electron emission increases amplitude and decreases width of dust acoustic soliton whereas increase in ion nonthermality decreases amplitude and increases width of the dust acoustic soliton. Thus if both secondary electron emission and ion nonthermality are increased amplitude and width of the soliton may remain unchanged at certain value of δ_M and a.

Figure 3 and 4 have been plotted for the dissipation-dispersion ratio μ / b against grain charge number z at $\delta_M = 22{,}24$ and $a = 0.1$. In figure 3, $\nu = 0.5$ (weak nonadiabaticity) and in figure 4, $\nu = 5$ (strong nonadiabaticity) have been considered.

These two figures show that for weak nonadiabaticity (figure 3) the dissipation-dispersion ratio μ / b is less than 1, so it produces oscillatory shock whereas for strong nonadiabaticity (figure 4) it is greater than 1 and hence produces monotonic shock. Moreover the the dissipation-dispersion ratio μ / b reduces with increasing secondary electron yield δ_M in case of both weak ($\nu = 0.5$) and strong ($\nu = 5$) nonadiabaticity. Thus for fixed nonzero ion nonthermality dust acoustic shock wave loses

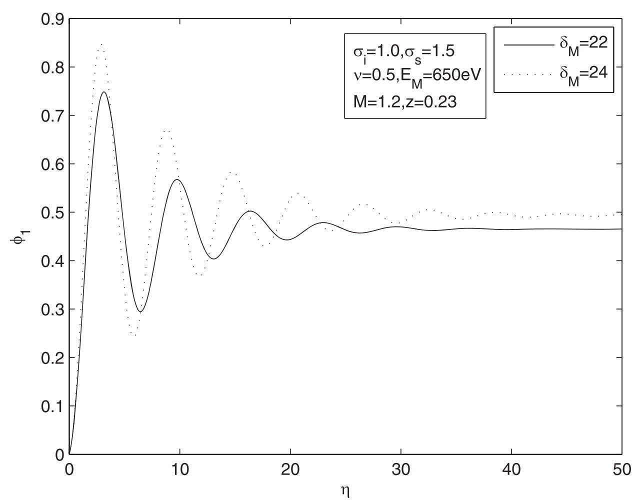

FIG. 5. Oscillatory shock wave for different δ_M at $a = 0.1$ and $\nu = 0.5$ in case of non adiabatic dust charge variation.

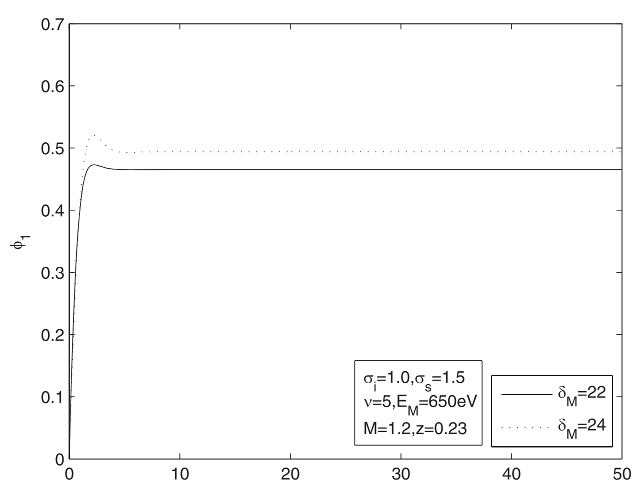

FIG. 6. Monotonic shock wave for different δ_M at $a = 0.1$ and $\nu = 5$ in case of non adiabatic dust charge variation.

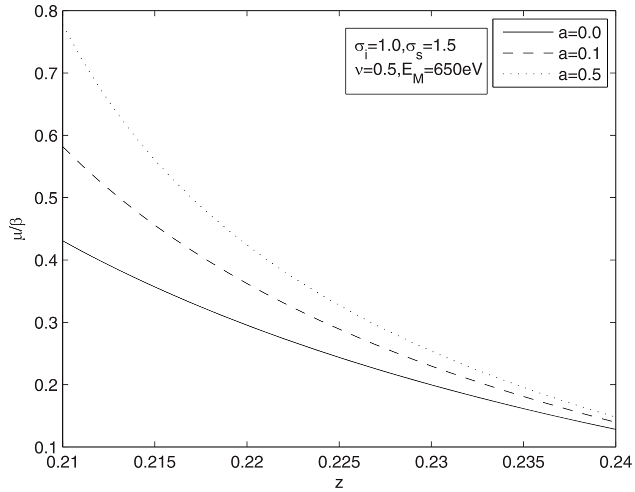

FIG. 7. Plot of the ratio μ / β versus z for different a at $\delta_M = 24$ and $\nu = 0.5$ in case of nonadiabatic dust charge variation.

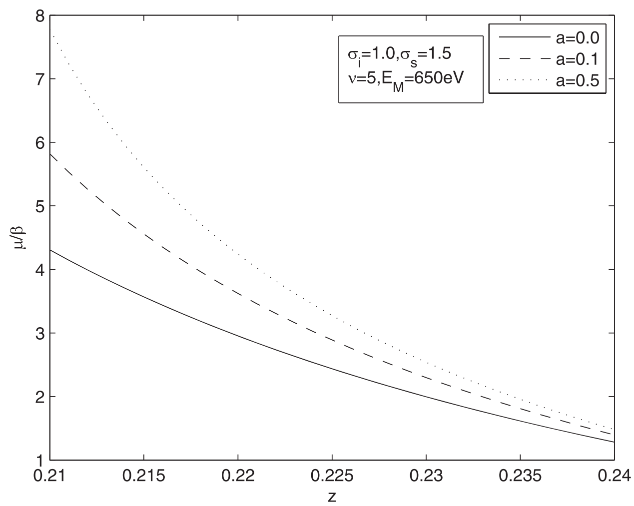

FIG. 8. Plot of the ratio μ / β versus z for different a at $\delta_M = 24$ and $\nu = 5.0$ in case of nonadiabatic dust charge variation.

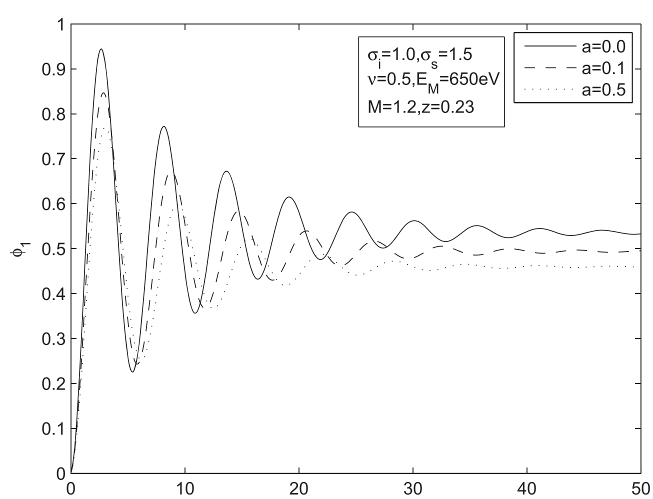

FIG. 9. Oscillatory shock wave for different a at $\delta_M = 24$ and $\nu = 0.5$ in case of non adiabatic dust charge variation.

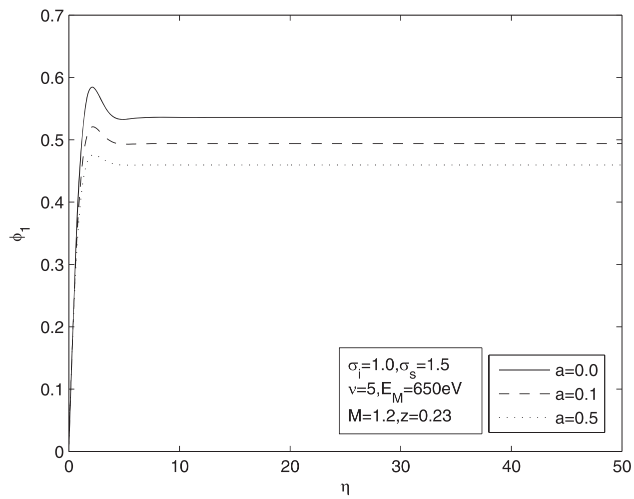

FIG. 10. Monotonic shock wave for different a at δ_M = 24 and ν = 0.5 in case of non adiabatic dust charge variation.

monotonicity and gains oscillation if secondary electron emission becomes higher. Figures 5 and 6 confirm this finding.

On the other hand figures 7 and 8 show that for both weak (ν = 0.5) and strong nonadiabaticity (ν = 5) the dissipation-dispersion ratio μ / b increase with increasing ion nonthermality at fixed secondary electron yield δ_M = 24. Thus increasing ion nonthermality helps to gain monotonicity and loose oscillation of dust acoustic shock. Figures 9 and 10 confirm this observation.

Since increase in secondary electron emission causes gain and increase in ion nonthermality causes loss of oscillation of dust acoustic shock wave, oscillation may remain unaffected if both secondary electron yield and ion nonthermality are increased.

V. CONCLUSION

In this paper we have studied the effect of ion nonthermality on nonlinear dust acoustic wave propagation in a complex plasma in presence of secondary electron emission when equilibrium dust charge is positive, both adiabatic and nonadiabatic dust charge variation taking into account. It has been shown that characteristics of dust acoustic soliton for adiabatic dust charge variation and dust acoustic shock for nonadiabatic dust charge variation depend on the strength of the ion nonthermality as well as the secondary electron yield. Numerical results show that for adiabatic dust charge variation higher secondary electron emission increases amplitude and decreases width of the dust acoustic soliton whereas the amplitude decreases and width increases at higher ion nonthermality. Thus amplitude and width of dust acoustic soliton may remain unchanged if both the strength of the secondary electron emission and the ion nonthermality are raised. Moreover in case of nonadiabatic dust charge variation dust acoustic shock wave loses monotonicity and gains oscillation at higher secondary electron emission whereas it gains monotonicity and loose oscillation at higher ion nonthermality. Thus dust acoustic shock wave remains unaffected if both secondary electron emission and ion nonthermality are increased.

APPENDIX

The expressions of β_d and γ_d are calculated in the following form.

$$\beta_d = \frac{\beta_b}{z\beta_a};$$

$$\beta_a = \beta_{a1} + \beta_{a2}; \ \beta_b = \beta_{b1} + \beta_{b2};$$

$$\beta_{a1} = \frac{\delta_i}{1+3a}\left[\frac{16a}{5\sigma_i}\exp(-\frac{z}{\sigma_i}) - \frac{1}{\sigma_i}\left\{(1+\frac{24a}{5}) + \frac{4a}{5}(\frac{z^2}{\sigma_i^2}) + \frac{16az}{5\sigma_i}\right\}\right];$$

$$\beta_{a2} = -\sqrt{\frac{m_e^i}{\sigma_i}} + 3.7\delta_M F_{5,B}\sqrt{\frac{m_e^i}{\sigma_i}}\left[\frac{1}{\sigma_s}\exp(z-\frac{z}{\sigma_s}) + (1+\frac{z}{\sigma_s})\{(1-\frac{1}{\sigma_s}) + z(1-\frac{1}{\sigma_s})^2\}\right];$$

$$\beta_{b1} = \frac{\delta_i}{1+3a}\left[-\frac{8a}{3\sigma_i}(2+\frac{z}{\sigma_i})\exp(-\frac{z}{\sigma_i}) + \frac{1}{\sigma_i}\left\{(1+\frac{24a}{5}) + \frac{4a}{5}(\frac{z^2}{\sigma_i^2}) + \frac{16az}{5\sigma_i}\right\}\exp(-\frac{z}{\sigma_i})\right];$$

$$\beta_{b2} = \sqrt{\frac{m_e^i}{\sigma_i}}\left[(1+z) - 3.7\delta_M F_{5,B}(1+\frac{z}{\sigma_s})\exp(z-\frac{z}{\sigma_s})\right];$$

and $\gamma_d = \frac{\gamma_c}{z\beta_a}$,

$$\gamma_c = (\gamma_{c11}+\gamma_{c12}) + (\gamma_{c21}+\gamma_{c22})(z\beta_d) + (\gamma_{c31}+\gamma_{c32})(z\beta_d)^2,$$

$$\gamma_{c11} = -\frac{\delta_i}{1+3a}\left[\frac{4a}{\sigma_i^2}\exp(-\frac{z}{\sigma_i}) + \frac{1}{2\sigma_i^2}\left\{(1+\frac{24a}{5}) + \frac{4a}{5}(\frac{z^2}{\sigma_i^2}) + \frac{16az}{5\sigma_i}\right\}\right.$$
$$\left.\times\exp(-\frac{z}{\sigma_i}) - \frac{8a}{3\sigma_i^2}(2+\frac{z}{\sigma_i})\exp(-\frac{z}{\sigma_i})\right];$$

$$\gamma_{c12} = 0.5\,[\ \sqrt{\frac{m_e^i}{\sigma_i}}\left[(1+z) - 3.7\delta_M F_{5,B}(1+\frac{z}{\sigma_s})\exp(z-\frac{z}{\sigma_s})\right];$$

$$\gamma_{c21} = -\frac{\delta_i}{1+3a}\left[\frac{8a}{3\sigma_i^2}\exp(-\frac{z}{\sigma_i}) - \frac{8a}{3\sigma_i^2}(2+\frac{z}{\sigma_i}) - \frac{16a}{5\sigma_i^2}\exp(-\frac{z}{\sigma_i})\right.$$
$$\left.+\frac{1}{\sigma_i^2}\left\{(1+\frac{24a}{5}) + \frac{4a}{5}(\frac{z^2}{\sigma_i^2}) + \frac{16az}{5\sigma_i}\right\}\right];$$

$$\gamma_{c22}\sqrt{\frac{m_e^i}{\sigma_i}}\left[1 - 3.7\delta_M F_{5,B}\{(1+\frac{z}{\sigma_s})(1-\frac{1}{\sigma_s}) + \frac{1}{\sigma_s}\exp(z-\frac{z}{\sigma_s})\}\right];$$

$$\gamma_{c31} = -\frac{\delta_i}{1+3a}\left[\frac{4a}{5\sigma_i^2}\exp(-\frac{z}{\sigma_i}) + \frac{1}{2\sigma_i^2}\left\{(1+\frac{24a}{5}) + \frac{4a}{5}(\frac{z^2}{\sigma_i^2}) + \frac{16az}{5\sigma_i}\right\} - \frac{16a}{5\sigma_i^2}\right];$$

$$\gamma_{c32} = -3.7\delta_M F_{5,B}\sqrt{\frac{m_e^i}{\sigma_i}}\left[\frac{1}{\sigma_s}(1-\frac{1}{\sigma_s}) + (1-\frac{1}{\sigma_s})^2(\frac{1+3z/\sigma_s}{2})\right];$$

All the notations are defined in the main body of the paper.

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