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Large amplitude shock wave in a strongly coupled dusty plasma due to delayed charging

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The effect of delayed charging on nonlinear characteristics of a large amplitude longitudinal dust acoustic wave in the "kinetic regime" of a strongly coupled dusty plasma described by the generalized hydrodynamic equation has been investigated. Numerical investigations reveal that delayed charging induced anomalous dissipation causes the generation of a large amplitude shock wave in a strongly coupled dusty plasma only for Mach numbers lying between a minimum and a maximum value. It is found that the shock can cause the state transition from a strongly coupled to a weakly coupled state. In the case of high dust flow velocity the shock height is higher than the case of low flow velocity in comparison with the ion thermal velocity. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2167583]

I. INTRODUCTION

In thermodynamical equilibrium, a dusty plasma system is characterized by the two parameters: (i) the shielding parameter $k=\Delta/\lambda_p$ and (ii) the Coulomb coupling parameter $\Gamma_s=q_d^2/4\pi\epsilon_0\Delta T_d$, where Δ, λ_p, q_d, and T_d are the inter dust distance, plasma Debye length, dust charge, and dust temperature, respectively. In the case of a one-component plasma (OCP), $k=0$. The system is classified as "strongly coupled" or "weakly coupled" for $\Gamma(=\Gamma_s e^{-k})>1$ or $\Gamma\ll 1$. For $\Gamma\gg 1$, the system is in a solid state and has form ordered structures provided $\Gamma>\Gamma_c$ (critical value), which supports a variety of dust lattice wave (DLW) modes.[1–3] On the other hand, when $1\ll\Gamma<\Gamma_c$, the system is in a quasicrystal state and supports both longitudinal[4–6] and transverse modes.[6–8]

One of the most interesting characteristics of a truly dusty plasma is that the charge q_d on a dust grain fluctuates with time and it is an extra dynamical variable that controls the grain motion but is itself to be determined from the OML grain charging equation $(\omega_{pd}/\nu_{\rm ch})dq_d/d(\omega_{pd}t)=I(\phi,q_d)/\nu_{\rm ch}$, where $I(\phi,q_d)$ is the total current flowing to the grain surface, ω_{pd} is the dust oscillation frequency, and $\nu_{\rm ch}(\sim\partial I/\partial q_d)$ is the dust charging frequency. The fluctuations of dust charge occur in two ways: (i) stochastically with time and (ii) continuously with time. In the case of statistical charge fluctuation for non-negligible values of $\Omega/\nu_{\rm ch}$ (Ω is the DLW frequency), the DLW becomes energywise unstable in a dusty plasma crystal state $(\Gamma>\Gamma_c)$,[9] whereas in the case of continuous charge fluctuation delayed charging ($\omega_{pd}/\nu_{\rm ch}\ll 1$, but $\neq 0$, which is known as the *nonadiabatic* dust charge variation[10]) causes a dissipation because of the phase difference between the dust charge variation and the wave in a dusty plasma, and this dissipation leads to an instability of transverse shear wave in an inhomogeneous strongly coupled dusty plasma.[2] In the dusty plasma crystal state $(\Gamma>\Gamma_c)$, the nonlinear properties such as soliton,[11] wave-wave interaction,[12] and shock,[13] etc., of the DLW have been studied considering fixed charged dust grains.

To study the nonlinear dynamics of the longitudinal dust acoustic wave (LDAW) in a strongly coupled dusty plasma, we use the generalized hydrodynamic (GH) model[6,14] for the dust component. This model provides the physical picture of both the weakly coupled state $(\Gamma\ll 1)$ and the strongly coupled liquid state $(1\ll\Gamma<\Gamma_c)$ and also even in the region $\Gamma>\Gamma_c$ as long as the plasma retains its fluid character. In the GH equation the most interesting regime is the "strong coupling limit" or the so-called "kinetic limit" $\omega_{pd}\tau_m>1$ (here the strain relaxation time τ_m is greater than the dust acoustic time ω_{pd}^{-1}) where strong correlation effects lead to novel elastic restoring forces and the dusty plasma is in a quasicrystal state $(1\ll\Gamma<\Gamma_c)$. Recently, the effect of delayed charging on a small amplitude nonlinear LDAW has been investigated in a collisional strongly coupled dusty plasma under the assumption that the dust flow velocity is much smaller than the ion thermal velocity.[15] However, in this paper we investigate the large amplitude nonlinear propagation characteristics of LDAW in the kinetic regime of a strongly coupled dusty plasma incorporating the delayed charging effect and considering both the cases of much smaller and larger dust flow velocity than the ion thermal velocity.

The paper is organized in the following manner. The formulation of the problem and basic equations are described in Sec. II. The nonlinear evolution equations have been derived in Sec. III. The numerical solution of these nonlinear equations and their graphical as well as physical explanations are given in Sec. IV. Finally a summary of the results is presented in Sec. V.

II. FORMULATION OF THE PROBLEM AND BASIC EQUATIONS

A. Dusty plasma parameters

To ensure ease of following the text, the symbols for different physical parameters and normalizations of the physical variables are listed below:

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The number density and temperature of electron, ion, and dust grains are, respectively, n_e, n_i, n_d, and T_e, T_i, T_d. The charge on the dust grain is $q_d=-q$ so that the equilibrium dust charge is $q_d^{\rm eq}=-q^{\rm eq}=-z_{d0}e$. The dust radius is r_0. Also we introduce the following four dusty plasma parameters:

$$\sigma_i=\frac{T_i}{T_e},\quad \sigma_d=\frac{z_{d0}T_e}{T_d},\quad z=\frac{z_{d0}e^2}{4\pi\epsilon_0 r_0 T_e},\quad \delta=\frac{n_{i0}}{n_{e0}}, \tag{1}$$

where $4\pi\epsilon_0 r_0 T_e$ is the capacitance of spherical dust grain of radius r_0 and $n_{i0}(n_{e0})$ is the equilibrium ion (electron) number density.

The space and time coordinates (x,t), the dust grain number density, dust flow velocity, dust charge (n_d,v_d,q_d), and electrostatic potential $\phi(x,t)$ are normalized by the following substitutions:

$$X=\frac{x}{\lambda_{d0}},\quad T=\omega_{pd}t,\quad N=\frac{n_d}{n_{d0}},$$
$$V=\frac{v_d}{V_{td}},\quad \Phi=\frac{e\phi}{T_e},\quad Q_d=\frac{q_d}{z_{d0}e}=-\frac{q}{z_{d0}e}=-Q, \tag{2}$$

where $\omega_{pd}(=\sqrt{z_{d0}^2e^2n_{d0}/\epsilon_0 m_d})$ is the dust plasma frequency, $\lambda_{d0}(=\sqrt{\epsilon_0 T_d/n_{d0}z_{d0}^2e^2})$ is the dust Debye length, and $V_{td}(=\sqrt{T_d/m_d})$ is the dust thermal velocity. In the normalization, the last one shows that the normalized value of dust charge is $Q_d=-Q$ and hence Q implies the normalized magnitude of dust charge.

B. Basic assumptions and equations

The basic assumptions that will help us to formulate the physical problem and allow us to proceed through this problem and also to find the explicit final results are the following:

(i) At far upstream, i.e., at $x\to-\infty$, there is a dust flow velocity V_0, where the plasma is assumed to be in its equilibrium state defined by $\phi=0(\Phi=0)$; $n_e=n_{e0}$, $n_i=n_{i0}$, $n_d=n_{d0}(N=1)$, $q_d=q_d^{\rm eq}=-z_{d0}e(Q_d=-1\Rightarrow Q=1)$ and $v_d=v_0(V=V_0)$ so that the plasma is quasineutral:

$$n_{e0}+z_{d0}n_{d0}=n_{i0}. \tag{3}$$

(ii) Due to their higher temperature and lower electronic charge, electrons and ions are weakly correlated and constitute a light fluid in comparison to the dust grains and can be modeled by Boltzmann distributions:

$$n_e=n_{e0}e^{\Phi},\quad n_i=n_{i0}e^{-\Phi/\sigma_i}. \tag{4}$$

On the other hand, due to low temperature and high electronic charge, the dust grains are strongly correlated.

(iii) The effect of delayed charging only in the kinetic regime $(\omega_{pd}\tau_m>1)$ is taken into account. Hence, in this case, the normalized GH equation[6,15] becomes

$$D_T(ND_TV-N\sigma_dQ\partial_X\Phi+\gamma_d\mu_d\partial_XN)=l\partial_X^2V,$$
$$D_T=\partial_T+V\partial_X, \tag{5}$$

where γ_d is the adiabatic index and

$$l=\eta_d/\omega_{pd}\tau_m=1-\gamma_d\mu_d+\frac{4}{15}u(\Gamma), \tag{6}$$

with η_d as the longitudinal viscosity coefficient normalized by $\lambda_{d0}^2/\Delta_d^2$ ($\Delta_d=\Delta e^{-k/2}$ is the effective interaction distance of dust grains), $\mu_d=1+(1/3)u(\Gamma)+(\Gamma/9)\partial_\Gamma u(\Gamma)$ is the compressibility, $u(\Gamma)=E_c/(n_{d0}T_d)$ is a measure of the excess internal energy of the system, and E_c is the correlation energy. For weakly coupled plasmas $(\Gamma\ll1)$ $u(\Gamma)\approx-(\sqrt{3}/2)\Gamma^{3/2}$, whereas in the range of $1\leqslant\Gamma\leqslant200$, $u(\Gamma)\approx-0.89\Gamma+0.95\Gamma^{1/4}+0.19\Gamma^{-1/4}-0.81$.[16]

(iv) The dust density scale length of dust cloud is comparable to the plasma Debye length and hence the dust density N at the potential Φ is fixed up by the following Poisson equation:

$$\partial_X^2\Phi=[e^{\Phi}-\delta e^{-\Phi/\sigma_i}+(\delta-1)QN]/\sigma_d(\delta-1). \tag{7}$$

(v) The dust grains are negatively charged due to plasma electron current (I_e) and ion current (I_i) and the charges on the dust grains varies continuously with time. Therefore the charge $(Q_d=-Q)$ on the dust surface is determined by the following normalized dust charging equation:

$$(\omega_{pd}/\nu_{\rm ch})(\partial_TQ+V\partial_XQ)=-(I_e+I_i)/z_{d0}e\nu_{\rm ch}. \tag{8}$$

In general, the dust-to-plasma relative velocity $V\ll V_{te}(=\sqrt{2T_e/m_e})$, the electron thermal velocity, but it might become comparable to or even exceed the ion thermal velocity $V_{ti}(=\sqrt{2T_i/m_i})$ so that the ion flux becomes anisotropic. A Maxwellian distribution in the plasma frame translates into a drifting Maxwellian distribution in a frame fixed to the dust grain. In this case of a negatively charged dust grain, the normalized expressions of the electron current (I_e) and ion current (I_i) for dust grain of radius r_0 are, respectively,[17]

$$I_e=-\pi r_0^2e\sqrt{8T_e/\pi m_e}n_{e0}e^{(\Phi-zQ)} \tag{9}$$

and

$$I_i=\pi r_0^2e\sqrt{\frac{8T_i}{\pi m_i}}n_{i0}e^{-\Phi/\sigma_i}\left(\gamma(\alpha V)+\frac{zQ}{\sigma_i}\psi(\alpha V)\right),$$
$$\alpha=\sqrt{\frac{T_dm_i}{2T_im_d}},$$
$$\gamma(\alpha V)=\frac{\sqrt{\pi}}{4}\frac{(1+2\alpha^2V^2)}{\alpha V}\mathrm{erf}(\alpha V)+\frac{1}{2}e^{-\alpha^2V^2}, \tag{10}$$
$$\psi(\alpha V)=\frac{\sqrt{\pi}}{2}\alpha^{-1}V^{-1}\mathrm{erf}(\alpha V),$$

where $\mathrm{erf}(x)=2/\sqrt{\pi}\int_0^xe^{-y^2}dy$ is the error function. The dust charging frequency $\nu_{\rm ch}$ is given by

$$\nu_{\rm ch}=\frac{r_0}{\sqrt{\pi}}\frac{\omega_{pi}^2}{V_{ti}}\frac{z\psi_0+\gamma_0\sigma_i}{z\beta_d},\quad \beta_d=\frac{z\psi_0+\gamma_0\sigma_i}{z[(1+z)\psi_0+\gamma_0\sigma_i]}, \tag{11}$$

where ω_{pi} is the ion plasma frequency and $\psi_0=(\psi)_0$, $\gamma_0=(\gamma)_0$ are the values of ψ and γ at equilibrium.

(vi) In absence of any particle loss mechanism the plasma model considered here is closed by the following dust fluid continuity equation:

$$\partial_T N + \partial_X (NV) = 0. \quad (12)$$

III. NONLINEAR EVOLUTION EQUATIONS

To find the nonlinear evolution equations, we introduce the following transformation in the wave frame moving with velocity λ (normalized by V_{td}):

$$\chi = X - \lambda T. \quad (13)$$

The upstream boundary conditions are

$$N = 1, \quad V = V_0, \quad Q = 1, \quad \Phi = 0. \quad (14)$$

Now transforming to the wave frame χ [Eq. (13)] and using boundary conditions (14), the continuity equation (12) yields

$$N(V - \lambda) = V_0 - \lambda = U. \quad (15)$$

Next, using the integral of the equation of continuity in the GH equation (5) to get rid of V, we have the following equation for N:

$$(U^2 - \gamma_d \mu_d N^2 - lN) d_\chi^2 N = -\sigma_d Q N^3 d_\chi^2 \Phi + 2[(U^2 - lN)/N](d_\chi N)^2 - \sigma_d N^2 (Q d_\chi N + N d_\chi Q) d_\chi \Phi. \quad (16)$$

Poisson's equation for electrostatic potential Φ is

$$d_\chi^2 \Phi = [e^{\Phi} - \delta e^{-\Phi/\sigma_i} + (\delta - 1) QN]/\sigma_d(\delta - 1), \quad (17)$$

where the dust charging equation in the wave frame is

$$d_\chi Q = \frac{N}{\mu U}\left(e^{\Phi - z(-1+Q)} - \frac{\sigma_i}{z\psi_0 + \gamma_0 \sigma_i} \times \left[\gamma(N) + \frac{z}{\sigma_i}\psi(N) Q \right] e^{-\Phi/\sigma_i} \right), \quad (18)$$

where $\mu = \omega_{pd}/\nu_{\text{ch}}/\beta_d$ and

$$\gamma(N) = \frac{1 + 2\alpha^2\left(\lambda + \frac{U}{N}\right)^2}{2\alpha\left(\lambda + \frac{U}{N}\right)} \int_0^{\alpha(\lambda + U/N)} e^{-x^2} dx + \frac{1}{2} e^{-\alpha^2(\lambda + U/N)^2},$$

$$\psi(N) = \frac{1}{\alpha\left(\lambda + \frac{U}{N}\right)} \int_0^{\alpha(\lambda + U/N)} e^{-x^2} dx. \quad (19)$$

IV. NUMERICAL SOLUTION AND DISCUSSIONS

To investigate the numerical solutions of the Eqs. (16)–(18), we use the following representative plasma parameters of gas discharge laboratory plasma:[8] $T_e \sim 9$ eV, $T_i = T_d \sim 0.03$ eV, $n_{i0} \sim 10^{16}$ m^{-3}, $n_{e0} \sim 5 \times 10^{15}$ m^{-3}, $m_i \sim 6.69 \times 10^{-26}$ kg, $m_d \sim 5.4 \times 10^{-14}$ kg, $\gamma_d \sim 1.5$, and $r_0 \sim 1$ μm so that the average plasma Debye length $\lambda_p \sim 13$ μm. For $\alpha V_0 (\ll 1) = 0.01$, $\psi_0 = \gamma_0 \sim 1$, which implies the magnitude of dust surface potential $z \sim 1.6$, the dust charge $z_d \sim 10^4$, and dust density $n_{d0} \sim 5 \times 10^{11}$ m^{-3}. Thus the interparticle distance $\Delta \sim 78$ μm and shielding parameter $k = \Delta/\lambda_p \sim 6$. Hence the coupling parameter $\Gamma \sim 152$, dust plasma frequency $\omega_{pd} \sim 2 \times 10^3$ s^{-1}, and the dust charging frequency $\nu_{\text{ch}} \sim 1.55 \times 10^6$ s^{-1} so that $\omega_{pd}\tau_m \sim 2.2 (>1)$, $\omega_{pd}/\nu_{\text{ch}} \sim 1.29 \times 10^{-3}$, and $\mu \sim 3.4 \times 10^{-3}$.

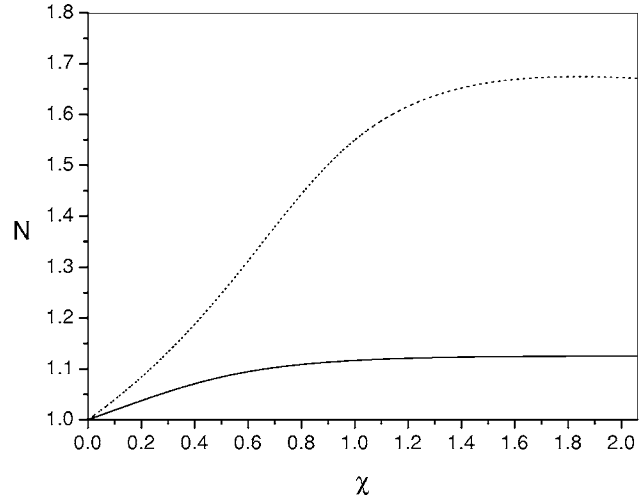

FIG. 1. Variation of dust number density N with χ in a strongly coupled dusty plasma. The different curves are as follows: the solid curve for $\alpha V_0 = 0.01$, $\Gamma \sim 152$ and the dotted curve for $\alpha V_0 = 5$, $\Gamma = 108$.

On the other hand, for the same plasma parameters and for $\alpha V_0 (\gg 1) = 5$, $\psi_0 \sim 0.2$, $\gamma_0 \sim 4.5$, which implies $z \sim 2.7$, $z_d \sim 2 \times 10^4$, $n_{d0} \sim 2.5 \times 10^{11}$ m^{-3}, $\Delta \sim 99$ μm, and $k \sim 7.5$. Also $\Gamma \sim 108$, $\omega_{pd} \sim 2.32 \times 10^3$ s^{-1}, and $\nu_{\text{ch}} \sim 5 \times 10^5$ s^{-1} so that $\omega_{pd}\tau_m \sim 1.8 (>1)$, $\omega_{pd}/\nu_{\text{ch}} \sim 4.7 \times 10^{-3}$, and $\mu \sim 2 \times 10^{-2}$.

For the purpose of the numerical integration of the set of equations (16)–(18), it is permissible to choose $\chi = 0$ as the upstream point since there is no explicit dependence of χ on the right-hand side of the above set of equations. On the basis of the above-mentioned plasma parameters starting from a small perturbation of the upstream boundary conditions (14) and upon numerical integration of the set of equations (16)–(18) by the Runge-Kutta-Felhberg method of order five, it is seen that perturbation develops into a shock wave provided the plasma flow velocity V_0 at far upstream exceeds the wave velocity λ, i.e., $U > 0$ (here $U = 400$). The prototype of the dust shock wave is shown in Fig. 1. The transition from the far upstream value to the far downstream value may occur with monotonic behavior. The dust density N is found to increase monotonically to a steady value at downstream, exhibiting a monotonic shock wave (Fig. 1), while the dust charge magnitude Q is found to decrease monotonically to 0 at downstream (Fig. 2). Also Eq. (15) reveals that if the unperturbed dust fluid velocity V_0 at upstream exceeds the wave velocity λ, the dust density N increases from its upstream value with a concomitant decrease of the dust fluid velocity V, which is a consequence of the conservation of the dust fluid mass flow. Actually due to delayed charging, i.e., the nonzero value of $\omega_{pd}/\nu_{\text{ch}}$, there is an extra contribution from the dust charge Q through the charging equation (8). This causes an oscillatory/monotonic

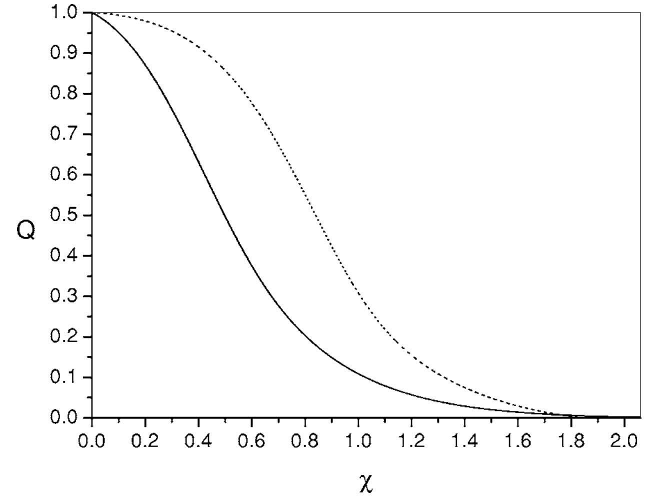

FIG. 2. Variation of magnitude of dust charge Q with χ in a strongly coupled dusty plasma in the presence of delayed charging. The curves are the same as in Fig. 1.

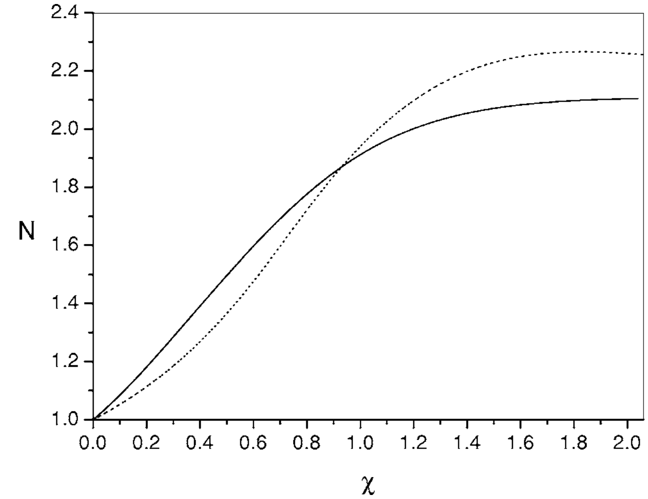

FIG. 3. Variation of dust number density N with χ for Mach number $M=M_{\max}$. The curves are the same as in Fig. 1.

decay (Fig. 2) of the dust charge magnitude and consequently plays the role of dissipative mechanism on the dust fluid by decreasing the driving force ($\propto Q$), causing dust motion, and this dissipation, besides the dispersive effect, tries to balance with the wave breaking nonlinear force and under suitable conditions gives rise to a generation of oscillatory/monotonic shock waves provided $V_0 > \lambda$ (Fig. 1). Also both the curves in Fig. 1 shows that the shock height of the dotted curve ($\alpha V_0 \Rightarrow v_0/\sqrt{2T_i/m_i} \sim 5$) is larger than that of solid curve ($\alpha V_0 \sim 0.01$). Hence, in case of high dust flow velocity ($\alpha V_0 \gg 1$), the shock height is higher than the low flow velocity ($\alpha V_0 \ll 1$) in comparison with the ion thermal velocity.

Also an investigation based on the numerical integration of Eqs. (16)–(18) keeping V_0 fixed but varying U reveals a certain feature of the shock propagation. It is observed that the shock wave is generated only for $U=V_0-\lambda$ lying between two extreme values

$$0 < U_{\min} \leqslant U \leqslant U_{\max} \Rightarrow \lambda_{\min} \leqslant \lambda \leqslant \lambda_{\max}, \qquad (20)$$

$$\lambda_{\min(\max)} = V_0 - U_{\max(\min)}.$$

The above relation corresponds to the bounds of Mach number $M=V_p/c_s$, where $V_p(=V_{td}\lambda)$ (as λ is normalized by V_{td}) is the wave velocity and $c_s(=\sqrt{z_{d0}T_e/m_d})$ is the dust acoustic speed. Thus the corresponding bounds of the Mach number M is defined by

$$M_{\max} = \frac{V_{td}}{c_s}\lambda_{\max} = \frac{V_{td}}{c_s}(V_0 - U_{\min}),$$

$$M_{\min} = \frac{V_{td}}{c_s}\lambda_{\min} = \frac{V_{td}}{c_s}(V_0 - U_{\max}). \qquad (21)$$

For $\alpha V_0=0.01$ ($V_0=1.3\times 10^4$), $U_{\min}\approx 190$ and $U_{\max}\approx 5\times 10^3$, which corresponds to $M_{\max}=7.4$ and $M_{\min}=6.4$. Also for $\alpha V_0=5$ ($V_0=6\times 10^6$), $U_{\min}\approx 350$ and $U_{\max}\approx 9\times 10^3$, which corresponds to $M_{\max}=2449.35$ and $M_{\min}=2445.81$. These values of $U_{\min}$ and $U_{\max}$ are determined by varying U and integrating Eqs. (16)–(18) numerically until $|N|\to\infty$. The corresponding variations of dust density are shown in Figs. 3 and 4. Figure 3 shows that as $M\to M_{\max}$ the dust density becomes sufficiently large (about 180%–220% of the initial density).

On the other hand, in absence of delayed charging effect ($\omega_{pd}/\nu_{\text{ch}}\sim 0$), the dust charging equation (6) reduces to $I_e+I_i\approx 0$ and the charge on the dust grain is given by the following equation:

$$Q = 1 + \left(\frac{1+\sigma_i}{z\sigma_i}\right)\Phi - \frac{1}{z}\ln\left[\frac{\sigma_i}{z\psi_0+\gamma_0\sigma_i}\left(\gamma(N) + \frac{z}{\sigma_i}\psi(N)Q\right)\right]. \qquad (22)$$

In this case the dust charge varies but the response is instantaneous and hence there is no dissipation. Thus in the absence of delayed charging effect no shock wave is generated as shown in Fig. 5.

The observed shock causes a state transition of dusty plasma. As the shock propagates into the medium, at the shock front we have the following: (i) the compression of

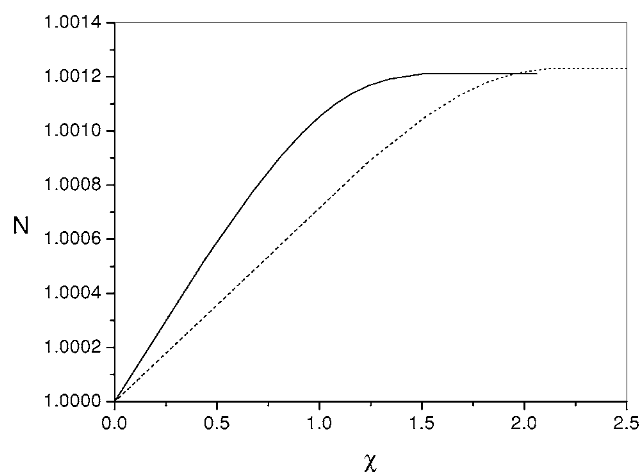

FIG. 4. Variation of dust number density N with χ for Mach number $M=M_{\min}$. The curves are the same as in Fig. 1.

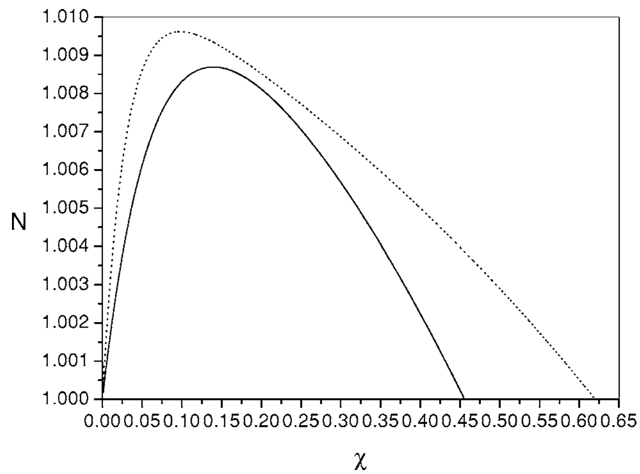

FIG. 5. Variation of dust number density N with χ in the absence of delayed charging effect. The curves are the same as in Fig. 1.

dust number density that implies the decrease of interdust distance $\Delta \sim (3/4\pi n_{d0} N)^{1/3}$; (ii) a decrease of magnitude of the dust charge on individual dust grains due to the packing effect; (iii) increase of dust pressure; and (iv) energization of dust grains that implies the increase of kinetic temperature of dust grains. The consequence of the above physical phenomena is the decrease of the value of dust coupling parameter $\Gamma = [(z_{d0} e Q)^2 / 4\pi\epsilon_0 \Delta T_d] e^{-\Delta/\lambda_p}$. Thus as shock moves from upstream to downstream side (i.e., χ increases), the value of coupling parameter Γ decreases from $\Gamma \gg 1$ (strongly coupled) to $\Gamma \ll 1$ (weakly coupled), which is shown in Fig. 6. Hence, the shock causes the state transition from strongly coupled to weakly coupled state.

Finally we observe that the delayed charging induced dissipation causes a monotonic shock wave, whereas it causes an oscillatory shock in the case of small amplitude wave (for the above-mentioned plasma parameters), which is observed in our earlier work.[15] We can explain this physical phenomenon in this way. The energy of a dust particle can be estimated as $W \approx q_d \Psi A$, where Ψ and A are the electrostatic field and oscillation amplitude. It is clear that in the presence of delayed charging, i.e., $\nu_{\mathrm{ch}}/\omega_{pd} \neq 0$, the dust charge q_d exponentially decays with time t according to $q_d \approx q_d^{\mathrm{eq}} \times \exp(-\nu_{\mathrm{ch}}/\omega_{pd} t)$ and consequently the energy W also decays with time. Thus, for large amplitude wave, the rate of change of energy, i.e., the dissipation rate of a dust grain, is much greater than that of the small amplitude wave as $A(\text{large}) \gg A(\text{small})$. Hence the dissipation due to delayed charging for large amplitude wave is much greater than that of the small amplitude wave and as a consequence delayed charging causes a monotonic shock for a large amplitude wave and an oscillatory shock for a small amplitude wave.

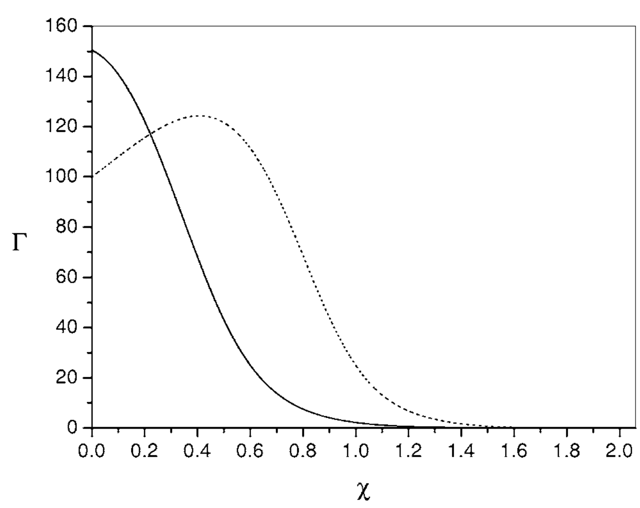

FIG. 6. Variation of coupling parameter Γ with χ. The curves are the same as in Fig. 1.

V. SUMMARY

In this paper we have investigated the physical mechanism of the generation of a large amplitude shock wave and its consequences in the kinetic regime of strongly coupled dusty plasmas using the GH model incorporating the delayed charging effect. The observations of the present investigation can be summarized as follows:

(a) The delayed charging induced dissipation causes a large amplitude shock wave in strongly coupled dusty plasmas provided at far upstream the dust flow velocity V_0 is greater than the wave velocity λ (Fig. 1).

(b) In the absence of the delayed charging effect there is no shock wave (Fig. 5).

(c) The shock height increases or decreases accordingly when the value of the ratio of dust flow velocity to ion thermal velocity is greater or less than unity (Fig. 1).

(d) The shock may cause a phase transition from strongly coupled to weakly coupled by decreasing the value of the coupling parameter Γ (Fig. 6), which is observed in a recent experiment [see Ref. 13 (b)].

(e) The observed shock is monotonic in nature whereas it is oscillatory in the case of a small amplitude wave.[15]

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