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Effect of Positive Dust on Non-linear Properties of Electron-acoustic Waves

Sanjit Kumar Paul

Department of Basic Sciences and Humanities,

University of Asia Pacific,Green Road,

Farm Gate Dhaka-1215, Bangladesh.

Abstract

The nonlinear propagation of the dust-electron-acoustic waves in a dusty plasma consisting of cold and hot electrons, stationary and streaming ions, and charge fluctuating stationary dust has been investigated by employing the reductive perturbation method. It has been shown that the dust charge fluctuation is a source of dissipation, and is responsible for the formation of the dust-electron-acoustic shock waves in such a dusty plasma. The basic features of such dust-electron-acoustic shock waves have been identified. It has been proposed to design a new laboratory experiment which will be able to identify the basic features of the dust-electron-acoustic shock waves predicted in this theoretical investigation.

About thirty years ago, Watanabe and Taniuti [1] have first shown the existence of the electron-acoustic (EA) mode in a plasma of two-temperature (cold and hot) electrons, which are common in both laboratory [2, 3] and space [4–10] plasmas. The EA mode [11, 12] is basically an electro-acoustic wave in which the inertia is provided by the cold electrons, and the restoring force comes from the pressure of the hot electrons. The ions play the role of a neutralizing background, i.e. the ion dynamics does not influence the EA waves, since the EA wave frequency is much larger than the ion plasma frequency. The spectrum of the linear EA waves, unlike that of the well known Langmuir waves, extends only up to the cold electron plasma frequency $\omega_{pc} = \left(4\pi n_{c0} e^2 \backslash m_e\right)^{1/2}$ where n_{c0} is the unperturbed cold electron number density, e is the magnitude of electron charge, and m_e is the electron mass. This upper wave frequency limit ($\omega \simeq \omega_{pc}$) corresponds to a short-wavelength EA wave, and depends on the unperturbed cold electron number density n_{c0}. On the other hand, the dispersion relation of the linear EA waves in the long-wavelength limit [in comparison with the hot electron Debye radius $\lambda_{Dh} = \left(T_h/4\pi n_{h0} e^2\right)^{1/2}$ where T_h is the hot electron temperature in units of the Boltzmann constant, and n_{h0} is the unperturbed hot electron number density] is [11, 12] $\omega \simeq kC_e$, where k is the wave number, and C_e = $\left(n_{c0} T_h/n_{h0} m_e\right)^{1/2}$ is the electron-acoustic speed.

The propagation of the EA mode has received a great deal of renewed interest not only because the two electron temperature plasma is very common in both the space and laboratory plasmas, but also because of the vital role of the EA mode in interpreting electrostatic disturbances in space [4–10] and laboratory [2, 3] plasmas. The conditions for the existence of the linear EA waves and their dispersion properties have been investigated by many au-thors [11–13], and are now well-understood. The nonlinear propagation of the EA waves (as EA solitary waves) in an unmagnetized plasma has also been considered by several authors [5, 8, 14, 15]. Dubouloz et al. [5] introduced an one-dimensional, unmagnetized, collisionless plasma composed of cold and hot electrons with motionless ions to study the EA solitary waves. Mace et al. [14] investigated the EA solitary waves in an unmagnetized plasma model in which the ions and the cold electron fluid are of finite temperature. They showed the existence of negative potential solitary structures associated with the compression of the cold electron density. Berthomier et al. [8] considered another unmagnetized plasma model composed of an electron beam component, in addition to the cold and hot electron components, to study the EA solitary waves, and showed the existence of positive potential solitary structures associated with a rarefaction of the cold electron density. Mamun and Shukla [15] have considered a plasma model consisting of a cold electron fluid, hot electrons obeying a non-isothermal (trapped/vortex-like) distribution, and stationary ions, and have investigated the properties of both the small and arbitrary amplitude EA solitary waves moving along the geo-magnetic field lines of force.

On the other hand, it is now well established that the presence of charged dust [16–18] does not only significantly modify the basic features of nonlinear ion-acoustic waves, but also introduces some new features, which are very important from both the theoretical and experimental points of view [19–23]. Recently, the nonlinear propagation of the ion-acoustic waves [24–30] in a plasma with charged dust, where the ion mass provides inertia, the electron thermal pressure gives rise to the restoring force, and the charged dust maintain the background charge neutrality condition, has been investigated. Since the effect of the dust charge fluctuation on any kind of low-frequency electrostatic waves (e.g. modified ion-acoustic waves, modified electron-acoustic waves, etc.), whose frequency is comparable to the dust charging frequency, is very important from both the theoretical and experimental points of view [16, 17, 23], in the present work we investigate the nonlinear propagation of a low phase speed (in comparison with the hot electron thermal speed) electrostatic perturbation mode in a dusty plasma containing cold and hot electrons, stationary and streaming ions, and charge fluctuating stationary dust. It is found here that the dust charge fluctuation is the source of dissipation, and is responsible for the formation of the dust-electron-acoustic shock waves in such a dusty plasma.

We consider a one-dimensional, collisionless, and unmagnetized dusty plasma system. It contains four-components which are cold and hot electrons, streaming ions, and charge fluctuating positively charged stationary dust. We assume that i) the hot electrons follow the Bolzmann distribution, ii) the total charge is conserved at equilibrium $n_{c0}+n_{h0} = n_{i0}-z_{d0}n_{d0}$, n_{s0} is the constant number density of the plasma species s (s equals i for ions,c for cold electrons, h for hot electrons and d for dust), and z_{d0} is the number of dust charge at equilibrium, and iii) the streaming ions maintain only the equilibrium current flowing on the dust grain surface. We consider the propagation of a low phase speed (in comparison with the hot electron thermal speed) electrostatic perturbation mode whose nonlinear dynamics is described by

$$\frac{\partial n_c}{\partial t} + \frac{\partial}{\partial x}(n_c u_c) = 0, \quad (1)$$

$$\frac{\partial u_c}{\partial t} + u_c \frac{\partial u_c}{\partial x} = \frac{e}{m_e}\frac{\partial \varphi}{\partial x}, \quad (2)$$

$$\frac{\partial^2 \varphi}{\partial x^2} = 4\pi e(n_c + n_h - n_{i0} - n_{d0} z_d), \quad (3)$$

where n_c is the cold electron number density, u_c is the cold electron fluid speed, φ is the electrostatic wave potential, n_h is the number density of the hot electrons which are assumed to follow the Boltzmann distribution:

$$n_h = n_{h0} \exp\left(\frac{e\varphi}{T_h}\right) \quad (4)$$

.

q_d is the dust charge, which is not constant, but varies according to

$$e\frac{\partial z_d}{\partial t} = I_p + I_h, \quad (5)$$

in which I_p (I_h) is the photoemission (electron absorption current) current flowing on the dust grain surface. We assume that the electron I_h is mainly due to the hot electrons, and the photoemission current I_p is due to the streaming ions streaming with a constant speed u_b. Therefore, for the negatively charged dust $q_d < 0$, I_e and I_i are given by [16, 17]

$$I_p = P\, e \exp(-\alpha z_d), \tag{6}$$

$$I_h = -Qe(1 + \alpha z_d) \exp\left(-\frac{e\varphi}{T_h}\right), \tag{7}$$

where $\alpha = e^2/r_d T_h$, $P = \pi r_d^2 J_p Q_{ab} Y_p$, and $Q = \pi r_d^2 n_{h0}(8T_h/\pi m_e)^{1/2}$, where r_d is the radius of the dust which are assumed to be spherical. We note that u_b maintains only the equilibrium current flowing on the dust grain surface, and that at equilibrium we have for $|\, 2eq_{d0}/r_d m_i u^2_b \,| \ll 1$ which is valid for any dusty plasma situation [16, 17].

To derive a dynamical equation for the nonlinear propagation of the electrostatic waves in a dusty plasma under consideration, and employ the reductive perturbation technique [31]. We introduce the stretched coordinates [32]

$$\xi = \in (x - V_0 t) \quad (8)$$

$$\tau = \in^2 t \quad (9)$$

where $\in$ is a smallness parameter ($0 < \in < 1$) measuring the weakness of the dispersion, and V_0 is the Mach number (the phase speed normalized by C_e), and expand N_c, U_c, Φ and Z_d about their equilibrium values in power series of $\in$, viz.

$$n_c = n_{c0} + \in n_c^{(1)} + \in^2 n_c^{(2)} + ------ \tag{10}$$

$$u_c = \in u_c^{(1)} + \in^2 u_c^{(2)} \tag{11}$$

$$\varphi = \in \varphi^{(1)} + \in^2 \varphi^{(2)} + ------- \quad (12)$$

$$z_d = z_{d0} + \in z_d^{(1)} + \in^2 z_d^{(2)} + ---------------------------------- \quad (13)$$

We develop equations in various powers of ọ. To the lowest order of ọ we have (14)

$$n_c^{(1)} = -\frac{e n_{c0} \varphi^{(1)}}{m_c V_0^2}, \tag{15}$$

$$u_c^{(1)} = -\frac{e\varphi^{(1)}}{m_c V_0}, \tag{16}$$

$$z_d^{(1)} = -R\varphi^{(1)}, \tag{17}$$

where $\mu_c = n_{c0}/n_{d0}$, $\mu_h = n_{h0}/n_{d0}$, and $R = Qe(1 + \alpha z_{d0})/\alpha(P + Q)T_h$. Equation (17) represents the linear dispersion relation for the EA waves significantly modified by the presence of the charge fluctuating dust. This implies that for no dust (f = 0) the phase speed of the EA waves is equal to C_e. This completely agrees with Yu and Shukla [11] as well as with Gary and Tokar [12]. However, in a plasma with negatively charged dust f ≃ 31 for the laboratory plasma [21–23, 33] conditions ($n_{h0} \simeq 10^{13}$ m^{-3}, $T_h \simeq 10$ eV , $r_d \simeq 5$ μm and $n_d \simeq 1$ m^{-3}) and f = 312 for the space plasma [5, 6, 16, 17] conditions ($n_{h0} \simeq 2.5 \times 10^6$ m^{-3}, $T_h \simeq 250$ eV , $r_d \simeq 0.5$ μm and $n_d \simeq 10^{-6}$ m^{-3}). Therefore, it is obvious from (17) that the presence of the charge fluctuating dust significantly reduces the phase speed of the EA waves, and introduces a new low phase speed (in comparison with the electron-acoustic speed) electrostatic mode (we referee it to as dust-electron-acoustic mode) associated with the dust charge fluctuation since f ≫ 1 for both the space [5, 6, 16, 17] and laboratory [5, 6, 16, 17] dusty plasma conditions. The phase speed of this dust-electron-acoustic mode $C_e/\sqrt{f} = \sqrt{n_{c0} e^2/n_d r_d m_e}$.

iTherefore, for f ≫ 1, which is valid for both the space and laboratory dusty plasma conditions, the phase speed of this dust-electron-acoustic mode is directly proportional to $\sqrt{e^2/r_d m_e}$ and is inversely proportional to $\sqrt{n_d/n_{c0}}$

To the next higher order of $\in$, one obtains

$$\frac{\partial n_c^{(1)}}{\partial \tau} - V_0 \frac{\partial n_c^{(2)}}{\partial \xi} + n_{c0} \frac{\partial u_c^{(2)}}{\partial \xi} + \frac{\partial}{\partial \xi}\left[n_c^{(1)} u_c^{(1)}\right] = 0 ----------- (18)$$

$$\frac{\partial u_c^{(1)}}{\partial \tau} - V_0 \frac{\partial u_c^{(2)}}{\partial \xi} + u_c^{(1)} \frac{\partial u_c^{(2)}}{\partial \xi} = \frac{e}{m_c} \frac{\partial \varphi^{(2)}}{\partial \xi} 0 ----------- (19)$$

$$V_0 \frac{\partial z_d^{(1)}}{\partial \xi} = Q(1 + \alpha z_{d0}) \frac{e}{T_h}\left[\varphi^{(2)} + \frac{e\{\varphi^{(1)}\}^2}{2T_h}\right] + Q\alpha\left[z_d^{(1)} \frac{e\varphi^{(1)}}{T_h}\right] - P\left[\frac{\alpha^2 \{z_d^{(1)}\}^2}{2} - \alpha z_d^{(2)}\right] ---- (20)$$

$$n_c^{(2)} + n_{h0}\left[\frac{e\varphi^{(2)}}{T_h} + \frac{e^2\{\varphi^{(1)}\}^2}{2T_h^2}\right] - n_{d0} z_d^{(2)} = 0 -------------- (21)$$

Now, using (14) - (21), one can eliminate $n_c^{(2)}$, $u_c^{(2)}$, $Z_d^{(2)}$ and $\varphi^{(2)}$, and can finally obtain

$$\frac{\partial\varphi^{(1)}}{\partial\tau} + A\varphi^{(1)}\frac{\partial\varphi^{(1)}}{\partial\xi} = C\frac{\partial^2\varphi^{(1)}}{\partial\xi^2} \text{----------------} (22)$$

where the nonlinear coefficient A, and the dissipation coefficient C are given by

$$A = \frac{\alpha C}{V_0}\left[\alpha PR - \frac{e}{T_h}\left\{3Q + P - \frac{e\mu_h}{RT_h}(p+Q)\right\}\right] - \frac{3e}{2m_c V_0},$$

$$C = \frac{V_0{}^4 R m_c}{2e\mu_c\alpha(p+Q)}$$

Equation (22) is the well-known Burger equation (with negative nonlinear coefficient) describing the nonlinear propagation of the EA waves in the dusty plasma under consider-ation. It is obvious from (22) and (24) that the dissipative term, i.e. the right-hand side of (22) is due to the presence of the charge fluctuating dust.

We are now interested in looking for the stationary shock wave solution of (22) by intro-ducing $\zeta = \xi - U_0\tau'$ and $\tau' = \tau$, where U_0 is the shock wave speed (in the reference frame) normalized by C_e, ζ is normalized by λ_{Dh}, and τ' is normalized by ω_{pc}^{-1}. This leads us to write (22), under the steady state condition ($\partial/\partial\tau' = 0$), as

$$-U_0\frac{\partial\varphi^{(1)}}{\partial\zeta} - A\varphi^{(1)}\frac{\partial\varphi^{(1)}}{\partial\zeta} = C\frac{\partial^2\varphi^{(1)}}{\partial\zeta^2}, \qquad (25)$$

It can be easily shown [34, 35] that (25) describes the shock waves whose speed U_0 (in the reference frame) is related to the extreme values $\varphi^{(1)}(-\infty)$ and $\varphi^{(1)}(\infty)$ by $\varphi^{(1)}(-\infty) - \varphi^{(1)}(\infty) = -2U_0/A$. Thus, under the condition that $\varphi^{(1)}$ is bounded at $\zeta = \pm\infty$, the shock wave solution of (25) is [34, 35]

$$\varphi^{(1)} = -\varphi^{(1)}{}_0[1 - \tanh(\zeta/\Delta)], \qquad (26)$$

where $\varphi^{(1)}{}_0 = U_0/A$ and $\;\; = 2C/U_0$ are, respectively, the height and thickness of the shock waves moving with the speed U_0. It is obvious that the formation of such shock waves is due to the presence of the charge fluctuating static dust, and that the shock structures are associated with the negative potential ($\varphi < 0$) only. It has been already shown that in a plasma with negatively charged static dust $V_0^2 \simeq 1/f = \alpha/\mu_d$, where $f \simeq 31$, $\alpha \simeq 3 \times 10^{-11}$, $\mu_c = 3$ and $\mu_d = 10^{-9}$ for the laboratory plasma [21–23, 33] conditions ($n_{h0} \simeq 10^{13}$ m^{-3}, $n_{c0} \simeq 3 \times 10^{13}$ m^{-3}, $T_h \simeq 10$ eV , $r_d \simeq 5$ μm, $n_d \simeq 1$ m^{-3} and $Z_{d0} = 10^4$), whereas f = 312, $\alpha \simeq 10^{-13}$, $\mu_c = 0.2$ and $\mu_d = 4 \times 10^{-11}$ for the space plasma [5, 6, 16, 17] conditions ($n_{h0} \simeq 2.5 \times 10^6$ m^{-3}, $T_h \simeq 250$ eV , $n_{c0} \simeq 5 \times 10^5$ m^{-3}, $r_d \simeq 0.5$ μm, $n_d \simeq 10^{-6}$ m^{-3} and $Z_{d0} = 10^4$). Since for both the space and laboratory plasmas $\alpha \ll 1$ and $f \gg 1$, one can express $\varphi_0^{(1)}$ and as

$$\varphi_0^{(1)} = \frac{U}{A} , \tag{27}$$

$$= \frac{2C}{U} . \tag{28}$$

It is obvious from (27) that the height (normalized by T_h/e) of the potential structures in the form of the shock waves is directly proportional to the shock speed U_0 and to the the cold electron number density n_{c0}, and it is inversely proportional to the square-root of the dust radius r_d, the dust number density n_d, and the hot electron temperature T_h. On the other hand, (28) implies that the thickness (normalized by λ_{Dh}) of these shock structures is directly proportional to the square-root of the cold electron number density n_{c0}, and it is inversely proportional to the shock speed U_0, to the square of the dust radius r_d, to the dust number density n_d, and to the square-root of the hot electron temperature T_h.

To summarize, the nonlinear propagation of the low phase speed dust-electron-acoustic waves in a dusty plasma containing cold and hot electrons, stationary and streaming ions, and charge fluctuating static dust has been theoretically investigated by the reductive perturbation method. It has been found that the dust charge fluctuation is the source of the dissipation, and is responsible for the formation of the dust-electron-acoustic shock waves in a dusty plasma. It has also been shown that the basic features (Mach number, height and thickness) of such dust-electron-acoustic shock structures are completely different from those of the electron-acoustic shock structures. To conclude, we propose to design a new laboratory experiment with a double plasma (DP) device [33] modified by the dust dispers-ing set up [21] or modified by the rotating dust dispenser [23], which will be able to detect the dust-electron-acoustic shock structures, and to identify their basic features predicted in this theoretical investigation.

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