PHYSICS OF PLASMAS VOLUME 7, NUMBER 11 NOVEMBER 2000

Streaming instabilities in a collisional dusty plasma

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(Received 27 June 2000; accepted 11 August 2000)

A pair of low-frequency electrostatic modes, which are very similar to those experimentally observed by Praburam and Goree [Phys. Plasmas **3**, 1212 (1996)], are found to exist in a dusty plasma with a significant background neutral pressure and background ion streaming. One of these two modes is the dust-acoustic mode and the other one is a new mode which is due to the combined effects of the ion streaming and ion–neutral collisions. It has been shown that in the absence of the ion streaming, the dust-acoustic mode is damped due to the combined effects of the ion–neutral and dust–neutral collisions and the electron–ion recombination onto the dust grain surface. This result disagrees with Kaw and Singh [Phys. Rev. Lett. **79**, 423 (1997)], who reported collisional instability of the dust-acoustic mode in such a dusty plasma. It has also been found that a streaming instability with the growth rate of the order of the dust plasma frequency is triggered when the background ion streaming speed relative to the charged dust particles is comparable or higher than the ion–thermal speed. This point completely agrees with Rosenberg [J. Vac. Soc. Technol. A **14**, 631 (1996)]. [S1070-664X(00)04311-1]

I. INTRODUCTION

A dusty plasma, which is ubiquitous in our universe,[1,2] is defined as a plasma containing micron or submicron-sized dust particles. The dust particles acquire a large electric charge by collecting electrons and ions from the ambient plasma.[1,2] Recently, electrostatic modes and their damping/instabilities associated with the dynamics of these highly charged dust particles have attracted a great deal of interest not only because of their numerous applications in various space and astrophysical problems,[1,2] but also because of their important role in laboratory plasma experiments,[3–6] plasma processing techniques,[7,8] Coulomb plasma crystallization,[8–10] etc.

After the theoretical prediction on the existence of the dust-acoustic (DA) waves[11,12] and the dust–ion-acoustic (DIA) waves[13] by Shukla and his collaborators,[11–13] a number of experimental investigations[3–5] and a large number of theoretical studies have been made to examine waves and associated damping/instabilities in a fully ionized or collisionless dusty plasma where either ions are assumed to behave as a Boltzmann fluid or background neutral pressure is completely neglected. However, it has been revealed by a closer examination of the experimental conditions[14–16] that the modes are often excited when there is a significant background pressure of neutrals. It has also been estimated that under such experimental conditions,[14,15] the ion–neutral and the dust–neutral collisional mean free paths may be comparable or even shorter than the typical wavelengths of the excited modes. Therefore, to study these modes in a dusty plasma with a significant background neutral pressure, the use of the collisionless plasma limit is unjustified.

Rosenberg[16] has considered a dusty plasma with a significant background neutral pressure and the ion streaming, and has investigated the ion–dust streaming instability in a processing plasma. D'Angelo and Merlino[17] have investigated the dust-acoustic instability in a collisional dusty plasma with a significant background neutral pressure and with a constant dc electric field E_0. Ivlev *et al.*[18] have shown the instability of the DIA mode due to the ionization and the instability of the DA mode due to the combined effects of the ionization and the ion drag. Goree *et al.*[19] have modeled a stable equilibrium void (a dust free region inside the dust cloud), which results from a balance between the electrostatic and ion drag forces on a dust particle, taking into account dust–electron and dust–ion collisions inside the dust region. The ion drag force is driven by a flow of ions outward from an ionization source and toward the surrounding dust cloud, which has a negative space charge. They[19] have used this model to predict the conditions for a void's existence, its size, and its sharp boundary with the surrounding plasma.

Recently, Kaw and Singh[20] have also considered a dusty plasma with a significant background neutral pressure and with the electron–ion recombination onto the dust grain surface. They[20] have found a collisional instability in parameter regimes which contradict the approximations they used. It can also be estimated that for dusty plasma parameters,[14,15] even for the plasma parameters used by Kaw and Singh,[20] the effect of dust–neutral collisions, which has been neglected by Kaw and Singh[20] without any justification, is much higher than that of the electron–ion recombination rate onto the dust grain surface (which has been considered by Kaw and Singh[20]). Therefore, in the present work, we have reexamined the low-frequency electrostatic modes in a collisional dusty plasma, taking into account collisions of ions and dust particles with background stationary neutrals, the electron–ion recombination onto the dust-grain surface, and the background ion streaming (the drift of the ions relative to the dust particles). We have found a pair of low-frequency electrostatic modes, which are very similar to those experimentally observed by Praburam and Goree.[15] One of these modes is the usual dust-acoustic mode and the other one is a new mode which is due to the combined effects of the ion streaming and the ion–neutral collisions. It has been shown by means of both analytical and numerical analyses that in the absence of the ion streaming effect, the dust-acoustic mode is damped due to the combined effects of the ion–neutral and dust–neutral collisions and the electron–ion recombination onto the dust grain surface. This result disagrees with Kaw and Singh[20] who reported a collisional instability of the dust-acoustic waves in such a dusty plasma. When we have considered the frequency regime considered by Rosenberg,[16] our results completely agree with her's[16] in that a streaming instability with the growth rate of the order of the dust plasma frequency is driven when the ion streaming speed relative to the dust particles is comparable to or higher than the ion thermal velocity.

The manuscript is organized as follows. The basic governing equations for our dusty plasma model are given in Sec. II. We have given the linearized equations, derived the dispersion relation, and investigated the dispersion properties of the low-frequency modes and associated damping/instabilities in Sec. III. A brief discussion is presented in Sec. IV.

II. GOVERNING EQUATIONS

We consider a weakly ionized, unmagnetized, uniform dusty plasma consisting of electrons, ions, negatively charged dust particles, and stationary neutrals. The dust particles are assumed to be extremely massive point charges with sizes much smaller than the dusty plasma Debye radius and the collisional mean free path. We also assume that the dusty plasma under consideration is macroscopically neutral, i.e., the quasineutrality condition holds. The electrons are assumed to behave as a Boltzmann fluid, whereas the ions are non-Maxwellian because of their streaming and collisional effects. The basic equations governing the weakly ionized unmagnetized dusty plasma in the presence of a significant background neutral pressure are given by

$$\frac{\partial N_i}{\partial t}+\nabla\cdot(N_i\mathbf{U}_i)=-\nu_R\frac{N_d}{N_{d0}}N_i+Q, \tag{1}$$

$$\frac{\partial \mathbf{U_i}}{\partial t}+\mathbf{U}_i\cdot\nabla\mathbf{U}_i=-\frac{e}{m_i}\nabla\Phi-\frac{T_i}{m_iN_i}\nabla N_i-\nu_{in}\mathbf{U}_i, \tag{2}$$

$$\frac{\partial N_d}{\partial t}+\nabla\cdot(N_d\mathbf{U_d})=0, \tag{3}$$

$$\frac{\partial \mathbf{U_d}}{\partial t}+\mathbf{U}_d\cdot\nabla\mathbf{U_d}=\frac{Z_de}{m_d}\nabla\Phi-\mathbf{g}-\frac{T_d}{m_dN_d}\nabla N_d-\nu_{dn}\mathbf{U_d}, \tag{4}$$

and

$$N_i=N_{e0}\exp\left(\frac{e\Phi}{T_e}\right)+Z_dN_d, \tag{5}$$

N_i (N_d) is the ion (dust) number density, N_{e0} (N_{d0}) is the equilibrium electron (dust) number density, Z_d is the number of electronic charges residing onto the dust grain surface, $\mathbf{U_i}$ ($\mathbf{U_d}$) is the ion (dust) fluid velocity, m_i (m_d) is the ion (dust) mass, T_i (T_e) is the ion (electron) temperature in units of the Boltzmann constant k_B, T_d is the dust fluid temperature in units of the Boltzmann constant k_B, Φ is the electrostatic wave potential, $\mathbf{g}$ is the acceleration due to gravity, and e is the electronic charge. ν_{in} (ν_{dn}) is the collision frequency of ions (dust) with background stationary neutrals, and $\nu_R=\beta N_{d0}\pi r_d^2 c_s$, where r_d is the radius of the dust grain, $c_s=(T_e/m_i)^{1/2}$ is the ion-acoustic speed, and β is a numerical factor of order unity.[1] The term $Q(=\sigma N_n\varphi$, where σ is the ionization cross section, N_n is the stationary (incompressible) neutral gas density, and φ is the flux of ionizing electrons) accounts for the creation of new ions through ionization of the neutral atoms by fast (ionizing) electrons.[21–23] It is assumed, as in Ref. 21–23, that the density of fast (ionizing) electrons is much smaller than the density of thermal electrons N_e. The ion continuity equation, i.e., Eq. (1) contains a sink term, which arises due to the electron–ion recombination onto the dust grain surface,[20] and a source term which arises due to the creation of new ions through ionization of the neutral atoms by fast electrons.[21–23]

To compare our present model equations with those considered by D'Angelo and Merlino,[17] it may be noted here that we have assumed the electrons to behave as a Boltzmann fluid, but considered the effects of the electron–ion recombination onto the dust grain surface,[20] whereas D'Angelo and Merlino[17] have not taken into account the effects of the electron–ion recombination onto the dust grain surface, but have assumed non-Maxwellian electrons because of their collisions with stationary neutral atoms.

To describe zero-order state of this weakly ionized unmagnetized dusty plasma system, we first express our dependent variables in terms of their equilibrium and perturbed parts as $N_i=N_{i0}+n_i$, $N_d=N_{d0}+n_d$, $\mathbf{U}_i=\mathbf{u}_0+\mathbf{u}_i$ ($\mathbf{u}_0$ is the ion streaming velocity), $\mathbf{U}_d=0+\mathbf{u}_d$, and $\Phi=\phi_0+\phi$ (we assume that at equilibrium there exists a zero-order electric field $E_0=-\nabla\phi_0$). Therefore, substituting these into our basic equations (1)–(5), we obtain the zero-order equations, describing the equilibrium (zero-order) uniform dusty plasma state, as

$$Q=\nu_RN_{i0}, \tag{6}$$

$$\nu_{in}\mathbf{u}_0=\frac{e}{m_i}\mathbf{E}_0, \tag{7}$$

$$\mathbf{g}=-\frac{Z_de}{m_d}\mathbf{E}_0, \tag{8}$$

and

$$N_{i0}=N_{e0}\exp\left(\frac{e\phi_0}{T_e}\right)+Z_dN_{d0}. \tag{9}$$

It is obvious from (6) that at equilibrium the rate of the creation of new ions through ionization of neutral atoms is balanced by the rate of the electron–ion recombination onto the dust grain surface. Equation (7) describes how ion drag force is balanced by the electrostatic force at equilibrium. We can infer from (8) that the balance between the equilib-

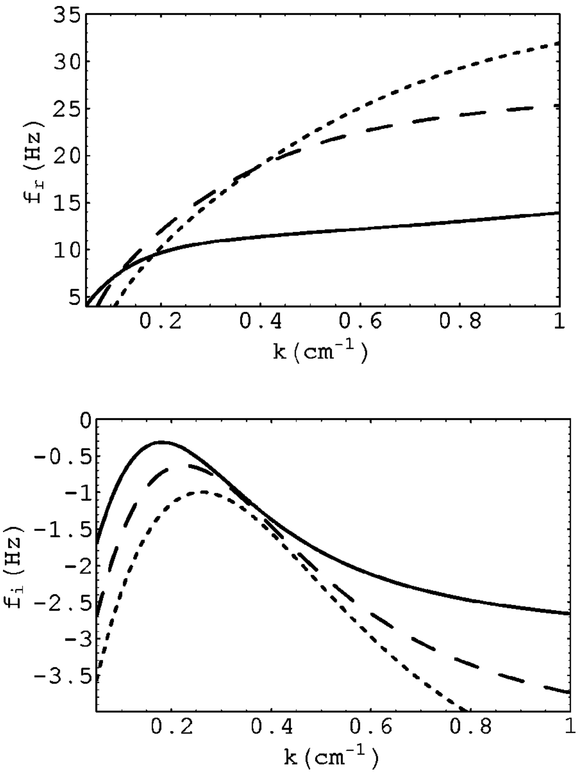

FIG. 1. Upper plot: The effect of N_n on ω_r of the dust-acoustic mode for $u_0\cos\theta=0$, $N_n=1.0\times10^{16}$ cm^{-3} (the solid curve), $N_n=5.0\times10^{16}$ cm^{-3} (the dash curve), and $N_n=1.0\times10^{17}$ cm^{-3} (the dotted curve). Lower plot: The effect of N_n on ω_i of the dust-acoustic mode for $u_0\cos\theta=0$, $N_n=2.0\times10^{16}$ cm^{-3} (the solid curve), $N_n=3.0\times10^{16}$ cm^{-3} (the dash curve), and $N_n=4.0\times10^{16}$ cm^{-3} (the dotted curve). The other parameters in both cases are given in the text.

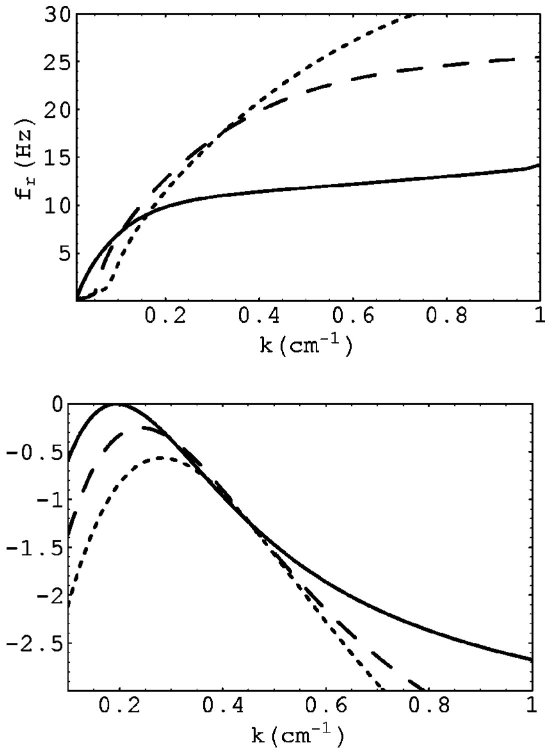

FIG. 2. Upper plot: The effect of N_n on ω_r of the dust-acoustic mode for $u_0\cos\theta=0.001v_{ti}$, $N_n=1.0\times10^{16}$ cm^{-3} (the solid curve), $N_n=5.0\times10^{16}$ cm^{-3} (the dash curve), and $N_n=1.0\times10^{17}$ cm^{-3} (the dotted curve). Lower plot: The effect of N_n on ω_i of the dust-acoustic mode for $u_0\cos\theta=0.001v_{ti}$, $N_n=2.0\times10^{16}$ cm^{-3} (the solid curve), $N_n=3.0\times10^{16}$ cm^{-3} (the dash curve), and $N_n=4.0\times10^{16}$ cm^{-3} (the dotted curve). The other parameters in both the cases are given in the text.

rium electric and gravity forces is responsible for the levitation of the dust grains. Equation (9), which for $e\phi_0/T_e \ll 1$ becomes $N_{i0}=N_{e0}+Z_dN_{d0}$, represents the quasineutrality condition at equilibrium.

III. DISPERSION PROPERTIES

To study the properties of electrostatic waves in a weakly ionized, uniform, unmagnetized dusty plasma system under consideration, we shall carry out a normal mode analysis, and linearize our basic equations (1)–(5) as

$$\left(\frac{\partial}{\partial t}+\mathbf{u}_0.\boldsymbol{\nabla}+\nu_R\right)n_i+N_{i0}\boldsymbol{\nabla}\cdot\mathbf{u_i}=-\nu_R\frac{N_{i0}}{N_{d0}}n_d, \tag{10}$$

$$\mathbf{u_i}=-\frac{e}{m_i\nu_{in}}\boldsymbol{\nabla}\left(\phi+\frac{T_i}{e}\frac{n_i}{N_{i0}}\right), \tag{11}$$

$$\frac{\partial n_d}{\partial t}+N_{d0}\boldsymbol{\nabla}\cdot\mathbf{u_d}=0, \tag{12}$$

$$\left(\frac{\partial}{\partial t}+\nu_{dn}\right)\mathbf{u_d}=\frac{Z_de}{m_d}\boldsymbol{\nabla}\phi, \tag{13}$$

and

$$n_i=n_{e0}\left(\frac{e\phi}{T_e}\right)+Z_dn_d. \tag{14}$$

To express the ion momentum balance equation, i.e., Eq. (11), we have used the assumption $\nu_{in}\gg|\partial/\partial t+u_0\cdot\nabla|$. To write the dust momentum balance equation, i.e., Eq. (13), we assumed that the wave phase speed is much higher than the dust-thermal speed. It is obvious that our linearized basic equations differ from those of Kaw of Singh[20] only due to the two extra terms, namely, the term ν_Rn_i in (10), which is dropped out by Kaw and Singh,[20] and the term $\nu_{dn}u_d$ in (13), which is not taken into account by Kaw and Singh[20] because of their omission of dust–neutral collisions. It should be mentioned here that for dusty plasma parameters,[14,15] even for the parameters used by Kaw and Singh,[20] the effect of dust–neutral collisions (neglected by Kaw and Singh[20]) is much higher than that of the electron–ion recombination onto the dust grain surface (considered by Kaw and Singh[20]).

Now, performing the Fourier transformation, i.e., taking $\partial/\partial t\rightarrow -i\omega$ and $\boldsymbol{\nabla}\rightarrow i\mathbf{k}$, and using (10)–(14), we can obtain a general dispersion relation

$$\left[1-\frac{k^2c_{d\star}^2}{\omega(\omega+i\nu_{dn})}\right]\left[1-i\frac{\nu_{in}(\omega-ku_0\cos\theta+i\nu_R)}{k^2v_{ti}^2}\right]+\tau_\star-\frac{\alpha\nu_{in}\nu_R}{\omega(\omega+i\nu_{dn})}=0, \tag{15}$$

where $c_{d\star}^2=c_d^2Z_dN_{d0}/N_{e0}$, $c_d=(Z_dT_e/m_d)^{1/2}$ is the dust-acoustic speed, $v_{ti}=(T_i/m_i)^{1/2}$ is the ion–thermal velocity, $\alpha=(c_d^2/v_{ti}^2)N_{i0}/N_{e0}$, $\tau_\star=\tau N_{i0}/N_{e0}$, $\tau=T_e/T_i$, and θ is

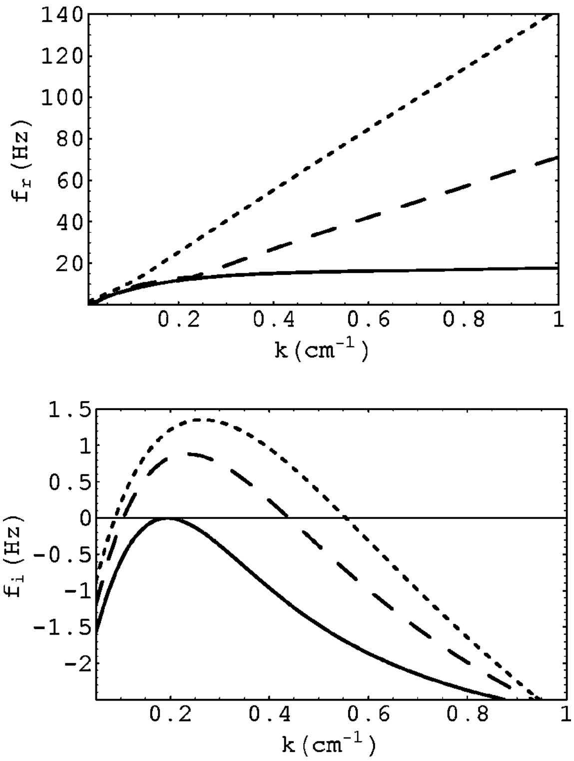

FIG. 3. Upper plot: The effect of u_0 or cos θ on ω_r of the dust-acoustic mode for $N_n = 2.0\times 10^{16}$ cm^{-3}, $u_0\cos\theta = 0.001 v_{ti}$ (the solid curve), $u_0\cos\theta = 0.05 v_{ti}$ (the dash curve), and $u_0\cos\theta = 0.01 v_{ti}$ (the dotted curve). Lower plot: The effect of u_0 or cos θ on ω_i of the dust-acoustic mode for $N_n = 2.0\times 10^{16}$ cm^{-3}, $u_0\cos\theta = 0.001 v_{ti}$ (the solid curve), $u_0\cos\theta = 0.005 v_{ti}$ (the dash curve), and $u_0\cos\theta = 0.01 v_{ti}$(the dotted curve). The other parameters in both the cases are given in the text.

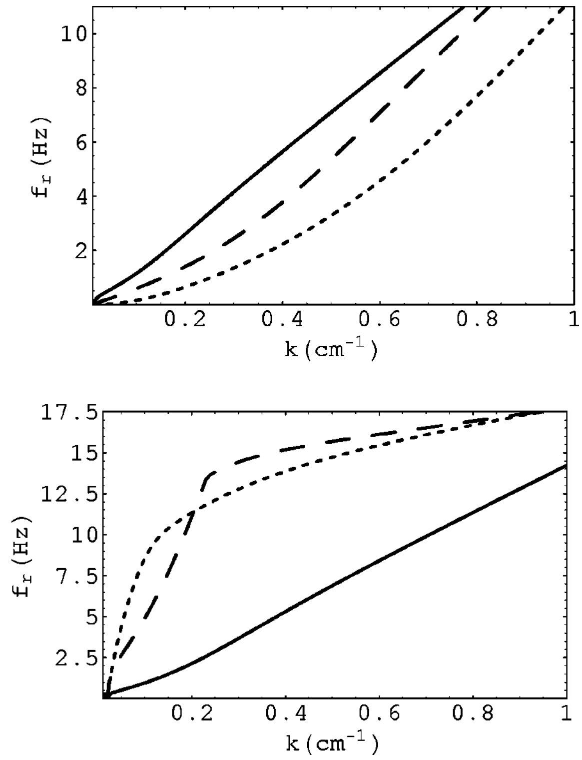

FIG. 4. Upper plot: The effect of N_n on ω_r of our new mode for $u_0\cos\theta = 0.001 v_{ti}$, $N_n = 2.0\times 10^{16}$ cm^{-3} (the solid curve), $N_n = 3.0\times 10^{16}$ cm^{-3} (the dash curve), and $N_n = 4.0\times 10^{16}$ cm^{-3} (the dotted curve). Upper plot: The effect of u_0 or cos θ on ω_r of the new mode for $N_n = 2.0\times 10^{16}$ cm^{-3}, $u_0\cos\theta = 0.001 v_{ti}$ (the solid curve), $u_0\cos\theta = 0.005 v_{ti}$ (the dash curve), and $u_0\cos\theta = 0.01 v_{ti}$ (the dotted curve). The other parameters in both cases are given in the text.

the angle between $\mathbf{u}_0$ and $\mathbf{k}$. Equation (15) is the dispersion relation for low-frequency electrostatic waves propagating in an unmagnetized dusty plasma in the presence of the significant background neutrals, the background ion streaming, and the electron–ion recombination onto the dust grain surface. To study the role of ion–neutral and dust–neutral collisions, the ion streaming, the electron–ion recombination rate onto the dust grain surface, etc., on the instability/damping of the low-frequency electrostatic modes under consideration, we have to numerically analyze (15). However, before going to numerical analysis of (15), we make analytical instability analysis to reexamine whether the instability analysis presented by Kaw and Singh[20] is of physical interest. The difference between our dispersion relation (15) and that of Kaw and Singh[20] is that our dispersion relation contains a few more important extra terms, namely, the term containing ν_R in the square brackets and the terms containing ν_{dn} inside the first brackets. Thus, by using the approximations, namely, $\nu_R \ll k^2 v_{ti}^2/\nu_{in}$, $\nu_d \ll |\omega|$, and $\theta \simeq 0$, which are valid for the analysis of Kaw and Singh,[20] we obtain the exact form of the general dispersion relation (16) derived by Kaw and Singh[20]

$$\left(1-\frac{k^2 c_{d\star}^2}{\omega^2}\right)\left[1-i\,\frac{\nu_{in}(\omega-ku_0)}{k^2 v_{ti}^2}\right]+\left[\tau_\star-\frac{\alpha\nu_{in}\nu_R}{\omega^2}\right]=0. \tag{16}$$

To examine whether the waves characterized by (16) are unstable or damped, we use a further approximation $\nu_{in}|\omega - ku_0| \ll k^2 v_{ti}^2$, and substitute $\omega = \omega_r + i\omega_i$, where $\omega_i \ll \omega_r$, into (16). That is, we can express the real and imaginary parts of ω as

$$\omega_r^2 = \frac{k^2 c_{d\star}^2 + \alpha\nu_{in}\nu_R}{1+\tau_\star} \tag{17}$$

and

$$\omega_i = \frac{\omega_r\nu_{in}(\omega_r - ku_0)}{2(1+\tau_\star)k^2 v_{ti}^2}\left(\frac{\alpha\nu_{in}\nu_R}{\omega_r^2}-\tau_\star\right). \tag{18}$$

Our present expression for imaginary part of ω, viz. Eq. (18) differs from that [Eq. (8b)] found by Kaw and Singh.[20] However, if we use the approximation $\alpha\nu_{in}\nu_R \ll k^2 c_{d\star}^2$, i.e., $\nu_{in}\nu_R \ll k^2 v_{ti}^2 Z_d N_{d0}/N_{i0}$, we can express (18) as

$$\omega_i = \frac{\nu_{in}}{2(1+\tau_\star)^2}\left[\frac{\alpha\nu_{in}\nu_R(1+\tau_\star)}{k^2 v_{ti}^2}-\tau_\star\frac{c_{d\star}^2}{v_{ti}^2}\right]\left(1-\frac{ku_0}{\omega_r}\right). \tag{19}$$

We now compare our Eq. (19) with (8b) of Kaw and Singh,[20] and analyze the instability criterion for $\omega_r > ku_0$ in both cases. Equation (19) differs from equation (8b) of Kaw and Singh[20] due to only one important term inside the square brackets, namely, $(1+\tau_\star)$, which plays a destabilizing role. The instability criterion obtained from (8b) of Kaw and

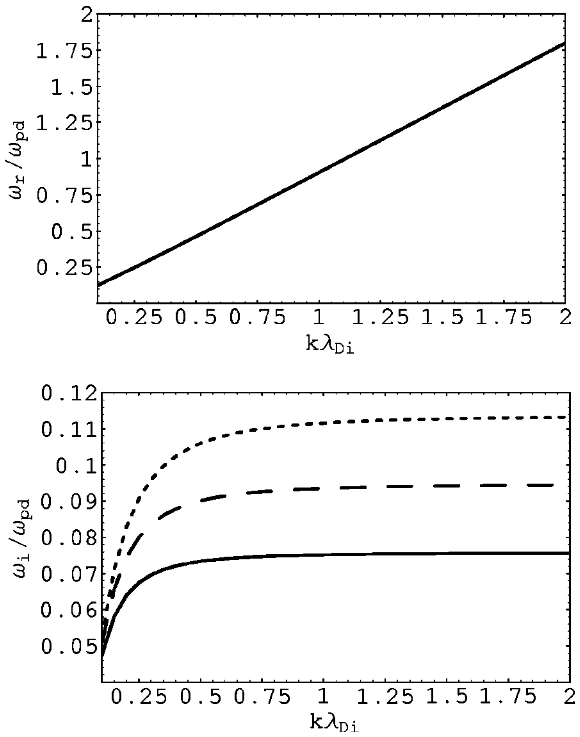

FIG. 5. Upper plot: The effect of N_n on ω_r of the mode in plasma sheath interface regions for $u_0 \cos\theta = v_{ti}$, $N_n = 2.0\times10^{16}$ cm^{-3} (the solid curve), $N_n = 2.5\times10^{16}$ cm^{-3} (the dash curve), and $N_n = 3.0\times10^{16}$ cm^{-3} (the dotted curve). All of these three curves are overlapped. Lower plot: The effect of N_n on ω_i of the mode in plasma sheath interface regions for $u_0 \cos\theta = v_{ti}$, $N_n = 2.0\times10^{16}$ cm^{-3} (the solid curve), $N_n = 2.5\times10^{16}$ cm^{-3} (the dash curve), and $N_n = 3.0\times10^{16}$ cm^{-3} (the dotted curve). The other parameters in both the cases are given in the text.

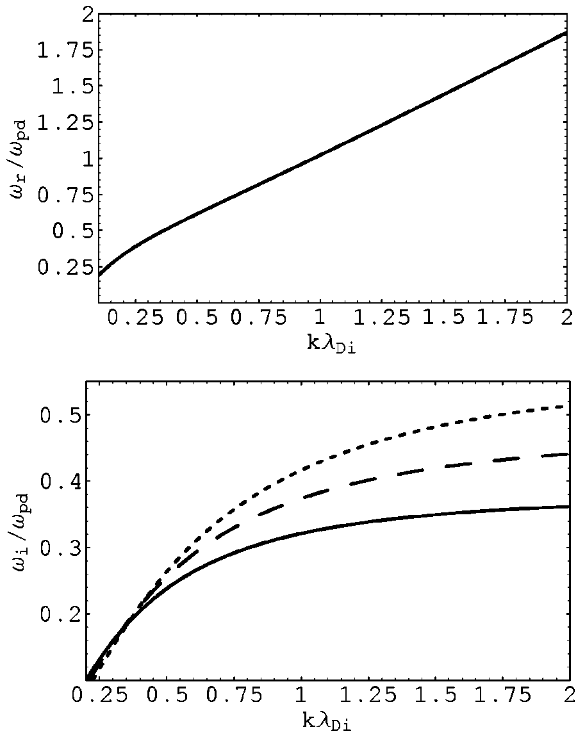

FIG. 6. Upper plot: The effect of N_n on ω_r of the mode in plasma sheath interface regions for $u_0 \cos\theta = 5v_{ti}$, $N_n = 2.0\times10^{16}$ cm^{-3} (the solid curve), $N_n = 2.5\times10^{16}$ cm^{-3} (the dash curve), and $N_n = 3.0\times10^{16}$ cm^{-3} (the dotted curve). All of these three curves are overlapped. Lower plot: The effect of N_n on ω_i of the mode in plasma sheath interface regions for $u_0 \cos\theta = 5v_{ti}$, $N_n = 2.0\times10^{16}$ cm^{-3} (the solid curve), $N_n = 2.5\times10^{16}$ cm^{-3} (the dash curve), and $N_n = 3.0\times10^{16}$ cm^{-3} (the dotted curve). The other parameters in both cases are given in the text.

Singh[20] is $\nu_{in}\nu_R \gg \tau k^2 v_{ti}^2 Z_d N_{d0}/N_{i0}$. Since $\tau \gg 1$, the instability criterion is opposite to the approximation $\nu_{in}\nu_R \ll k^2 v_{ti}^2 Z_d N_{d0}/N_{i0}$ for which our Eq. (19) or Eq. (8b) of Kaw and Singh[20] is valid. This means that the dust-acoustic waves are damped, but not unstable. On the other hand, the instability criterion from our Eq. (19) becomes $\nu_{in}\nu_R(1+\tau_\star) \gg \tau k^2 v_{ti}^2 (Z_d N_{d0}/N_{i0})$. If we assume the experimental conditions of Praburam and Goree,[15] (i.e., $T_i \ll T_e$ and N_{e0} and N_{i0} are of the same order, i.e., $\tau_\star \gg 1$), our instability criterion takes the form $\nu_{in}\nu_R \gg k^2 v_{ti}^2 Z_d N_{d0}/N_{i0}$, which is again just opposite to the approximation $\nu_{in}\nu_R \ll k^2 v_{ti}^2 Z_d N_{d0}/N_{i0}$ for which our Eq. (19) or Eq. (8b) of Kaw and Singh[20] is valid. Therefore, we conclude that the dust-acoustic mode is damped, in contrast to the analytical and numerical results of Kaw and Singh,[20] who reported the collisional instability of the dust-acoustic mode in the presence of the electron–ion recombination onto the dust grain surface.

To study the role of ion–neutral and dust–neutral collisions, the ion streaming, the electron–ion recombination onto the dust grain surface, etc., on the instability/damping of low-frequency electrostatic modes under consideration, we now numerically analyze (15). For our numerical analysis, we have chosen the plasma parameters of Praburam and Goree,[15] namely, $m_i = 12m_p$ (where m_p is the proton mass), $m_d = 2.4\times10^8 m_p$, $N_{i0} = 5.0\times10^{10}$ cm^{-3}, $N_{d0} = 1\times10^7$ cm^{-3}, $Z_d = 200$, $T_e = 0.4$ eV, $T_i = 0.1$ eV, $T_d = T_n = 300$ K, $r_d = 50$ nm, $\beta = 1$, $\sigma_{in} = 1.0\times10^{-14}$ cm^2, $N_n = 1.0$–5.0×10^{16} cm^{-3}, and $u_0 \cos\theta = 0-5v_{te}$. The numerical results are displayed in Figs. 1–6. Figure 1 shows that in the absence of the ion-drift ($u_0 \cos\theta = 0$), the dust-acoustic mode is damped due to the combined effects of ion–neutral and dust–neutral collisions, and the electron–ion recombination rate onto the dust grain surface. It is also obvious from Fig. 1 that as we increase the neutral number density, the real frequency and the damping rate of the dust acoustic mode increase. Figures 2 and 3 show that as we increase the ion streaming speed (u_0) or cos θ, the real frequency of the dust-acoustic mode increases, the damping rate decreases, and the mode starts to grow when $u_0 \cos\theta$ exceeds a critical value. Figure 4 clearly indicates that the combined effects of the ion–drift and ion–neutral collisions introduce a new low-frequency electrostatic mode in such a collisional dusty plasma. It should be mentioned here that this mode will disappear if we neglect either the effect of the ion-drift or the effect of ion–neutral collisions. Figure 4 also shows how the dispersion properties of our new mode change as we increase the neutral number density (N_n) and the ion-drift speed u_0. Figures 5 and 6 show that the ion–dust streaming instability with the growth rate of the order of the dust plasma frequency may be driven when the drift speed of ions relative to the charged dust particles is comparable or higher than the ion–thermal velocity.

IV. DISCUSSION

We have presented a self-consistent description of low-frequency electrostatic waves and associated damping and instabilities in a collisional dusty plasma with the significant background neutrals and ion streaming. We have first reexamined the work of Kaw and Singh,[20] who neglected some important physical terms without any justification, and then properly investigated the dispersion properties or damping/instabilities of low-frequency electrostatic modes in such a collisional dusty plasma. A pair of low-frequency electrostatic modes, which are very similar to those experimentally observed by Praburam and Goree,[15] are found to exist in such a collisional dusty plasma. One of these is the usual dust-acoustic mode and the other one is a new mode which is due to the combined effects of the ion streaming and ion–neutral collisions. It has been shown here that this mode will disappear if we neglect either the effect of the ion-drift or the effect of ion–neutral collisions. Our analysis reveals that in absence of the ion streaming, the dust-acoustic mode is damped due to the combined effects of the collisions and the electron–ion recombination onto the dust grain surface. This point of our results disagrees with Kaw and Singh,[20] who reported the collisional instability of the dust-acoustic mode in such a dusty plasma. This disagreement is due to the contradictory approximations used by Kaw and Singh[20] as well as due to their omission of dust–neutral collisions (the effect of which is found to be more important than that of the electron–ion recombination onto the dust grain surface) without any justification. We have also found that a streaming instability with the growth rate of the order of the dust plasma frequency may be driven by the drift of ions relative to the charged dust particles, when its value is comparable to or higher than the ion–thermal speed. This point completely agrees with the work of Rosenberg.[16]

ACKNOWLEDGMENTS

A.A.M. gratefully acknowledges the financial support of the Alexander von Humboldt-Stiftung (Bonn, Germany). P.K.S. thanks M. Rosenberg for useful discussions.

This research was partially supported by the International Space Science Institute at Bern (Switzerland) through its international team ''Dust Plasma Interaction in Space'' as well as by Department of Energy Grant No. DE-FG03-97ER54444 and NATO through Grant No. SA(PST.CLG.974733)5066 for carrying out the project, ''Studies of Collective Processes in Dusty Plasmas.''

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