Laboratory studies of waves and instabilities in dusty plasmas*

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(Received 17 November 1997; accepted 29 December 1997)

Theoretical and experimental studies of low-frequency electrostatic waves in plasmas containing negatively charged dust grains are described. The presence of charged dust is shown to modify the properties of ion-acoustic waves and electrostatic ion-cyclotron waves through the quasineutrality condition even though the dust grains do not participate in the wave dynamics. If the dust dynamics is included in the analysis, new ''dust modes'' appear—dust acoustic and dust cyclotron modes. The results of laboratory experiments dealing with dust ion acoustic (DIA) waves and electrostatic dust ion cyclotron (EDIC) waves are shown. These modes are more easily excited in a plasma containing negatively charged dust. Finally, observations of dust acoustic (DA) waves are presented and measurements of the dispersion relation are compared with one obtained from fluid theory. © *1998 American Institute of Physics.* [S1070-664X(98)90505-5]

I. INTRODUCTION

The presence of dust grains can significantly affect the behavior of a plasma in which they are immersed. Both electrons and ions will be collected by the dust grains, but since the electrons move about more swiftly than the ions, the grains tend to acquire a negative charge. Secondary and photoelectron emission from grains in radiative or energetic plasma environments may also contribute to grain charging and can lead to positively charged grains. As a result, the balance of charge is altered by the presence of the dust, so that the condition for charge neutrality in a plasma with negatively charged grains becomes

$$n_i = n_e + Z_d n_d , \tag{1}$$

where n_α ($\alpha = e,i,d$) is the number density of electrons, ions, and dust grains, and $Z_d = q_d / e$ is the ratio of the charge, q_d, on a dust grain to the electron charge, e. The term ''dusty plasma'' usually refers to the situation in which there is a significant number of dust grains in the plasma ($Z_d n_d \approx n_e$) as opposed to the case of a few isolated grains.

The motivation for studying dusty plasmas is due to the realization of their occurrence in both the laboratory and space. Examples include: cometary environments, planetary rings, the interstellar medium, and the lower ionosphere. Dust has been found to be a detrimental component of rf plasmas used in the microelectronic processing industry, and it may also be present in the limiter regions of fusion plasmas due to the sputtering of carbon by energetic particles. It is interesting to note that the recent flurry of activity in dusty plasma research has been driven largely by discoveries of the role of dust in quite different settings: The rings of Saturn[1] and plasma processing devices![2]

The initial experimental work in dusty plasmas dealt largely with measurements of the charge on individual dust grains.[3] The experimental results compared well with the standard model of the charging of dust grains due to the collection of electrons and ions. In this model, a grain is treated as a conducting sphere of radius a which is charged to a surface potential V_s relative to the plasma. The charge q_d can then be computed from the grain capacitance C_g using the relation $q_d = C_g V_s = 4\pi\epsilon_0 a V_s$. The equilibrium surface potential is determined by the requirement that the net current to the (floating) dust grain must be equal to zero. In a hydrogen plasma, with $T_e = T_i = T$, this condition reduces to $V_s = -2.5kT/e$. As an illustration, for $kT = 1$ eV, a dust grain of radius $a = 1\ \mu$m (with mass, $m_d \approx 10^{12} m_{\text{proton}}$) would acquire a negative charge corresponding to about 1800 electrons.

Measurements of the charge on dust grains in situations where the dust density is high enough so that the intergrain spacing is comparable to the plasma Debye length have also been performed.[4] In this case, the charge on the dust grains is reduced compared to that of an isolated grain in the plasma.

More recently, research in dusty plasmas has expanded into a wider range of problems including studies of collective processes, i.e., waves and instabilities. The presence of charged dust can have a strong influence on the characteristics of the usual plasma wave modes, even at frequencies where the dust grains do not participate in the wave motion. In these cases, the dust grains simply provide an immobile charge-neutralizing background [see Eq. (1)]. When one considers frequencies well below the typical characteristic frequencies of an electron/ion plasma, new dust modes appear in the dispersion relations derived from either the kinetic or fluid equations for the three species system consisting of ions, electrons, and charged dust grains. Some of these new modes are very similar to those found in negative ion plasmas, but with some important differences unique to dusty plasmas. For example, dusty plasmas in nature tend to be composed of grains with a range of sizes (and shapes!). This means, of course, that one must deal with a range of grain masses and charges. In addition, the charge on any grain may not be a constant. In the presence of electrostatic oscillations,

*Paper dMopT-2 Bull. Am. Phys. Soc **42**, 1842 (1997).
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the electron and ion currents to a grain are also oscillatory, resulting in a time-dependent grain charge. One of the very interesting developments that has been observed is the tendency of the dust grains, under certain conditions, to form into regular structures called Coulomb crystals.[5–9] These structures are examples of strongly coupled systems which are presenting new challenges to those attempting to model dusty plasmas.[10]

This paper summarizes theoretical and experimental dusty plasma research carried out mainly by our group. (More comprehensive reviews are listed in Ref. 11.) The theoretical work is presented in Sec. II and the experimental work in Secs. III and IV. The summary, conclusions, and final comments are given in Sec. V.

II. LOW-FREQUENCY ELECTROSTATIC WAVES IN A DUSTY PLASMA THEORY

A. Dispersion relation

The linear dispersion relation for low-frequency electrostatic waves in a magnetized dusty plasma was obtained using a multifluid analysis.[12] By low frequencies we mean frequencies on the order of or less than f_{ci}, f_{pi}, the ion gyrofrequency and ion plasma frequency. This approach will determine which modes are possible but does not generally provide information regarding wave growth or damping. We consider a three component plasma that is uniform and immersed in a uniform magnetic field, **B**, oriented along the z axis of a Cartesian coordinate system. Each species has a mass m_α, charge q_α, charge state $Z_\alpha = q_\alpha/e$, density n_α, temperature T_α, thermal velocity $C_\alpha = (kT_\alpha/m_\alpha)^{1/2}$, gyrofrequency $\omega_{c\alpha} = eZ_\alpha B/m_\alpha$, and gyroradius $\rho_\alpha = C_\alpha/\omega_{c\alpha}$, where $\alpha = (e,i,d)$ for electrons, ions, and dust. All dust grains are assumed to have the same mass and the same negative charge. The three plasma components are described by their continuity and momentum equations

$$\frac{\partial n_\alpha}{\partial t} + \nabla\cdot(n_\alpha \mathbf{v}_\alpha) = 0, \tag{2}$$

$$n_\alpha m_\alpha \frac{\partial \mathbf{v}_\alpha}{\partial t} + n_\alpha m_\alpha(\mathbf{v}_\alpha\cdot\nabla)\mathbf{v}_\alpha + kT_\alpha\nabla n_\alpha + q_\alpha n_\alpha \nabla\varphi - q_\alpha n_\alpha \mathbf{v}_\alpha \times \mathbf{B} = 0. \tag{3}$$

For the low-frequency waves being considered the electron inertia can be neglected, and we can also take the electron motion entirely along **B**. This amounts to assuming that the electrons are in Boltzmann equilibrium, i.e., $kT_e\nabla n_e = en_e\nabla\varphi$. In addition to the continuity and momentum equations, the charge neutrality condition [Eq. (1)] is also used both in the equilibrium and perturbed state. A standard linear perturbation analysis is performed around the uniform, nondrifting equilibrium plasma, with $E_0 = -(\nabla\varphi)_0 = 0$, and electron, ion, and dust densities denoted by n_{e0}, n_{i0}, and n_{d0}. Assuming that the first-order quantities vary as $\exp[i(K_x x + K_z z - \omega t)]$ the following dispersion relation is obtained:

$$\frac{G}{\xi_i^2 - G} + \epsilon Z_d^2 \mu_{i/d}\frac{H}{\xi_i^2 - \tau_{d/i}\mu_{i/d} H} - \tau_{i/e}(1-\epsilon Z_d) = 0 \tag{4}$$

where

$$G = \left(\frac{\xi_i^2}{\xi_i^2 - 1}\right) K_x^2\rho_i^2 + K_z^2\rho_i^2 \tag{4a}$$

and

$$H = \left(\frac{\xi_i^2}{\xi_i^2 - (\xi_i/\xi_d)^2}\right) K_x^2\rho_i^2 + K_z^2\rho_i^2, \tag{4b}$$

$\xi_i = \omega/\omega_{ci}$, $\xi_d = \omega/\omega_{cd}$, $\mu_{i/d} = m_i/m_d$, $\tau_{d/i} = T_d/T_i$, and $\tau_{i/e} = T_i/T_e$. The parameter $\epsilon = n_{d0}/n_{i0}$, so that from Eq. (1) $n_{e0} = (1-\epsilon Z_d)n_{i0}$. The quantity ϵZ_d represents the fraction of negative charge per unit volume on the dust. In a plasma without dust, $\epsilon = 0$, the dispersion relation (4) yields the usual two roots corresponding to ion-acoustic and electrostatic ion cyclotron waves. For $\epsilon \neq 0$, the dispersion relation has four positive solutions in ω/ω_{ci} corresponding to: Ion-cyclotron (EIC), ion-acoustic (IA), dust acoustic (DA), and dust cyclotron (EDC) modes. Numerical solutions of Eq. (4) can be obtained for arbitrary values of K_x/K_z, but it is more instructive to obtain the ''pure'' roots, i.e., those corresponding to propagation either along **B** (acoustic modes) or nearly perpendicular to **B** (cyclotron modes).

1. Acoustic modes ($K_x = 0$)

We first obtain the dispersion relations for the acoustic modes, valid in the long wavelength limits $K\lambda_{De} \ll 1$ and $K\lambda_{Dd} \ll 1$, where $\lambda_{De(d)}$ is the electron (dust) Debye length.

a. DIA—dust ion acoustic mode ($\omega \gg K_z C_d$). This is the usual ion acoustic wave with modifications introduced by the presence of the negatively charged dust.[12,13] In this case we can consider the dust to be a static background ($m_d \to \infty$), yielding the dispersion relation

$$\frac{\omega}{K_z} = \left[\frac{kT_i}{m_i} + \frac{kT_e}{m_i(1-\epsilon Z_d)}\right]^{1/2} = C_{S,d}, \tag{5}$$

where $C_{S,d}$ is the dust-modified ion acoustic speed. Note that the wave phase velocity, ω/K_z, of the DIA wave increases with increasing relative dust concentration, ϵ. One can see this by writing the linearized momentum equation for the ions in the form $m_i n_{i0}\partial v_{i1}/\partial t = -[kT_i + kT_e/(1-\epsilon Z_d)] \times (\partial n_{i1}\partial x)$, where the Boltzmann relation has been used to express the wave electric field, E_1, in terms of $\partial n_{e1}/\partial t$. The term $m_i n_{i0}\partial v_{i1}/\partial t$ is the force per unit volume on a typical ion fluid element in the presence of the wave perturbation, and the right hand side of the equation is the acoustic ''restoring'' force per unit volume on the fluid element, which increases with increasing ϵ. An increase in the restoring force then gives rise to an increase in the wave phase velocity. Physically, as more and more electrons become attached to the immobile dust grains, there are fewer available to provide neutralization for the ion space charge perturbations. As Chow and Rosenberg[14] point out, one can think of the term $kT_e/(1-\epsilon Z_d)$ as an ''effective'' electron temperature.

b. DA—dust acoustic mode ($\omega \ll K_z C_i$). This is a very low-frequency acoustic mode in which the dust grains participate directly in the wave dynamics.[15] For this mode both the electron and ion inertia can be neglected. The dispersion relation is

$$\frac{\omega}{K_z}=\left[\frac{kT_d}{m_d}+\epsilon Z_d^2\,\frac{kT_i}{m_d}\,\frac{1}{1+(T_i/T_e)(1-\epsilon Z_d)}\right]^{1/2}=C_{\mathrm{DA}}, \tag{6}$$

where C_{DA} is the dust acoustic velocity. For this mode the inertia is provided by the dust grains while the restoring force is provided by the electron and ion pressures as can be seen from the linearized momentum equation for the dust (with $T_d=0$) $m_d n_{d0}(\partial v_{d1}/\partial t)=-[kT_e(\partial n_{e1}/\partial x)+kT_i(\partial n_{i1}/\partial x)]$.

2. Cyclotron modes ($K_z \ll K_x$)

These are modes that propagate nearly perpendicular to the **B** field, but with a finite K_z so that the assumption that the electrons remain in Boltzmann equilibrium along **B** remains valid.

a. EDIC—electrostatic dust ion cyclotron mode ($\omega\sim\omega_{ci}$) This is the dust-modified EIC mode. For $\omega\sim\omega_{ci}$, the dust grains can be taken as immobile and the dispersion relation reduces to

$$\omega^2=\omega_{ci}^2+K_x^2\left[\frac{kT_i}{m_i}+\frac{kT_e}{m_i(1-\epsilon Z_d)}\right]. \tag{7}$$

In Eq. (7) we note that the frequency increases with increasing ϵ.

b. EDC—electrostatic dust-cyclotron mode ($\omega\ll\omega_{ci}$) For this mode, the dynamics of the magnetized dust grains must be taken into account, while the ions can be taken to be in Boltzmann equilibrium along **B** in response to the very small, but finite E_z. The dispersion relation is

$$\omega^2=\omega_{cd}^2+K_x^2\left[\frac{kT_d}{m_d}+\epsilon Z_d^2\,\frac{kTi}{m_d}\,\frac{1}{1+(T_i/T_e)(1-\epsilon Z_d)}\right]. \tag{8}$$

Summary: The four dispersion relations can be expressed compactly in the form

$$\text{DIA}\quad \omega^2=K_z^2C_{S,d}^2, \tag{9a}$$

$$\text{DA}\quad \omega^2=K_z^2C_{\mathrm{DA}}^2, \tag{9b}$$

$$\text{EDIC}\quad \omega^2=\omega_{ci}^2+K_x^2C_{S,d}^2, \tag{9c}$$

$$\text{EDC}\quad \omega^2=\omega_{cd}^2+K_x^2C_{\mathrm{DA}}^2, \tag{9d}$$

where $C_{S,d}$ and C_{DA} are defined in Eqs. (5) and (6). The modes described by Eqs. (9a) and (9c) are modes in which the dust dynamics does not play a role although the effect of the dust can be very important in the excitation of the waves. The DA [Eq. (9b)] and EDC [Eq. (9d)] modes are the new low-frequency dust modes.

B. Wave excitation and damping

The fluid analysis just presented yields a dispersion relation with a purely real ω. To examine the conditions for wave excitation a Vlasov analysis is required, except when dealing with resistive, current-driven instabilities. Rosenberg[16] investigated the conditions for the excitation of DIA and DA waves by ion and/or electron drifts in an unmagnetized dusty plasma using a standard Vlasov analysis. In both cases the real part of the dispersion relation agreed with the one obtained using fluid theory.

For the DIA wave, the presence of negatively charged dust reduces the strength of the (collisionless) Landau damping. Thus even in plasmas with $T_e=T_i$ (where Landau damping gives rise to spatial attenuation of the wave over a distance less than one wavelength), the waves can, in the presence of negatively charged dust, propagate over several wavelengths. This result could, of course, be anticipated from the fluid analysis (Sec. II 1 a) which showed that the DIA phase velocity increased with increasing dust density, thus reducing the importance of Landau damping due to wave particle interactions at $\omega/K\approx C_i$. The Vlasov analysis for the DA mode gave similar results. It was shown that DA waves could be driven unstable by weak ion and electron drifts greater than the DA phase speed. This analytical result was confirmed by Winske *et al.*,[17] who performed a one-dimensional (1D) particle simulation of a dusty plasma including electron and ion drifts.

The effect of charged dust on the collisionless electrostatic ion cyclotron instability (EDIC) was investigated by Chow and Rosenberg[14,18] using Vlasov theory. The critical electron drift velocity in the presence of either positively or negatively charged dust was determined. For the case of negatively charged dust, they found that the critical drift decreased as the relative concentration of the dust increased, showing that the mode is more easily destabilized in a plasma containing negatively charged dust. This result again could be surmised from the fluid analysis which showed that the EDIC mode frequency increased with relative dust concentration, reducing the (collisionless) cyclotron damping which is most important for frequencies close to ω_{ci}. Although, to the best of our knowledge, the Vlasov theory of the EDC mode has not been reported, we might be able to draw some conclusions concerning the EDC instability from the work of Chow and Rosenberg[19] on the heavy negative ion EIC mode excited by electron drifts along the magnetic field. The mode frequency again increases with increasing ε, whereas the critical electron drift decreases with increasing ε. The maximum growth rate was found to shift to larger perpendicular wavelengths with increasing ε.

In many of the laboratory dusty plasma environments that have been investigated, the plasmas are only weakly ionized so that the effects of collisions between charged particles, including the dust, and the neutral gas atoms must be considered. These plasmas also often contain quasistatic electric fields which may excite current-driven (resistive) instabilities.[20–22] Using kinetic theory and taking into account collisions with the neutrals, Rosenberg[20] investigated an ion-dust streaming instability that might occur at the plasma-sheath interface of a processing plasma. A similar situation was considered by D'Angelo and Merlino[21] who analyzed a dust acoustic instability in a four component fluid plasma consisting of electrons, ions, negatively charged dust, and neutrals, with an imposed zero-order electric field. Relatively small electric fields, which might generally be found

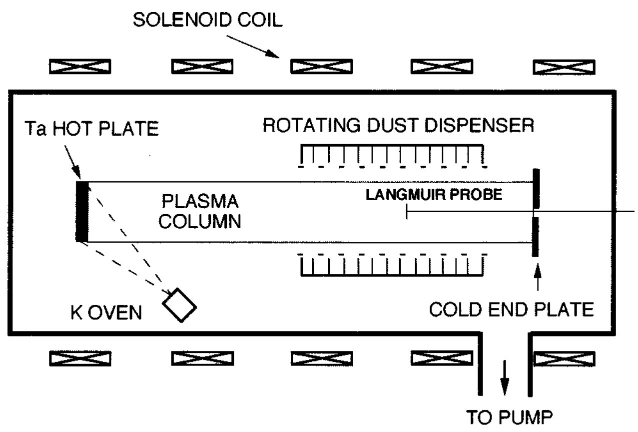

FIG. 1. Schematic diagram of the dusty plasma device (DPD).

in typical laboratory plasmas, were required to excite the DA instability. Similar results were found by Merlino,[22] who studied the excitation of the DIA mode in a collisional dusty plasma. For one particular set of parameters, it was found that the critical electron drift speed was decreased by a factor of ≈ 3 for a plasma in which 90% of the negative charge was on dust grains compared to a plasma with no dust.

Finally, we briefly discuss two of the novel wave damping mechanisms that may arise in a dusty plasma. The first is the so-called ''Tromsø damping'' [23] for dust acoustic waves. This mechanism is related to the fact that the charge on a dust grain may vary in response to oscillations in the electrostatic potential of the wave. A finite phase shift between the potential and the grain charge oscillations leads to wave damping, particularly for wave periods comparable to the characteristic grain charging time. As pointed out by D'Angelo,[24] Tromsø damping may also be an important damping mechanism for the DIA mode. Another damping mechanism for the DIA mode which is related to the fact that the dust grains continuously absorb electrons and ions from the plasma, is the ''creation damping'' of D'Angelo.[24] This effect is due to the continuous injection of ''new'' ions to replace those which are lost to the dust grains. These newly created ions cause a drain on the wave, since some of the wave energy must be expended in bringing them into concert with the wave motion. This damping mechanism is expected to be the dominant one for some typical laboratory dusty plasmas.

Finally, we mention that in addition to the four modes described above, work on the Kelvin–Helmholtz instability,[25] the Rayleigh Taylor instability,[26] and the ionization instability[27] has also been performed by our group.

III. THE EFFECT OF NEGATIVELY CHARGED DUST ON ELECTROSTATIC ION CYCLOTRON WAVES AND ION ACOUSTIC WAVES. EXPERIMENTS

A. The dusty plasma device (DPD)

The dusty plasma device is an apparatus for introducing dust grains into a plasma. It consists of a single-ended Q machine and a rotating dust dispenser as shown schematically in Fig. 1. The plasma is formed, in the usual manner, by surface ionization of potassium atoms from an atomic beam oven on a hot ($\sim$2200 K) 6 cm diam tantalum plate which also emits thermionic electrons. The electrons and K^+ ions are confined to a cylindrical column about one meter in length by a longitudinal magnetic field with a strength up to 0.35 T. Typically, the electron and ion temperatures are $T_e \approx T_i \approx 0.2$ eV, with plasma densities in the range of $10^8 - 10^{10}$ cm^{-3}. As in typical single-ended Q machines, the plasma drifts from the hot plate with a speed between one and two times the ion acoustic speed.

To produce a dusty plasma kaolin (aluminum silicate) powder was dispersed into a portion of the plasma column. Electron microscope analysis of samples of the kaolin dust indicated that the grains were irregular in shape with sizes ranging from a fraction of a micron to tens of microns. The average grain size was on the order of a few microns. The grains were dispersed into the plasma using the rotating dust dispenser also shown in Fig. 1. The dispenser consists of a 30 cm long cylinder surrounding a portion of the plasma column.[28] This cylinder is divided into a number of slots which contain the kaolin powder. A stationary mesh with an inner diameter slightly smaller than that of the rotating cylinder also surrounds the plasma column. When the cylinder is rotated the dust grains are continuously deposited on the outer surface of the stationary mesh. Bristles attached to the rotating slots scrape the outer surface of the mesh causing it to vibrate and gently allow the dust grains to sift through it and fall into the plasma. The fallen dust is then returned to the cylinder through the bottom of the mesh and recirculated through the plasma. The amount of dust dispersed into the plasma increases as the rotation rate of the cylinder is increased. The grains attain their equilibrium charge while falling through a very thin layer at the top of the plasma column. The negatively charged dust grains remain in the plasma for a sufficient length of time ($\sim$0.1 s) to affect the behavior of electrostatic plasma modes, although not long enough to study processes involving dust dynamics.

As pointed out in Sec. II A, the quantity $\varepsilon Z_d = 1 - n_e/n_i$ is the fraction of negative charge per unit volume in the plasma on the dust grains. The ratio n_e/n_i can be determined from Langmuir probe measurements of the reduction in the electron saturation current that occurs when the dust is present as compared to the case with no dust.

B. Current-driven electrostatic dust ion-cyclotron waves (EDIC)[29]

The electrostatic ion-cyclotron instability is produced by drawing an electron current along the axis of the plasma column to a 5 mm diam disk located near the end of the dust dispenser furthest from the hot plate. A disk bias $\sim$0.5–1 V above the space potential produces an electron drift sufficient to excite electrostatic waves with a frequency slightly above the ion gyrofrequency, which propagate radially outward from the current channel with a wave vector that is nearly perpendicular to the magnetic field. To study the effect of the dust on the instability, the wave amplitude, $(\delta n/n)_{nd} \equiv A_{nd}$ (with no dust present) was measured, and without introducing any other changes in the plasma conditions, the dust

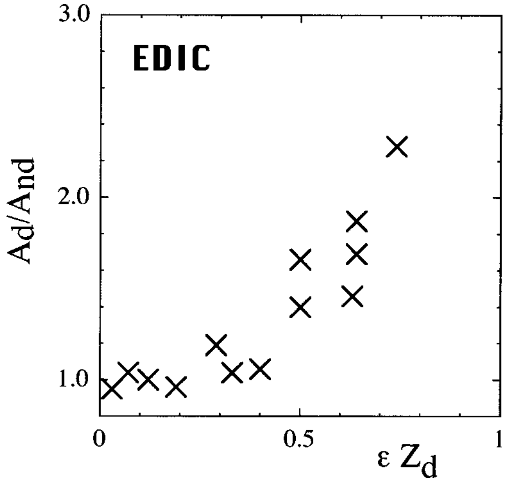

FIG. 2. The electrostatic dust ion cyclotron (EDIC) wave amplitude with dust divided by the amplitude without dust as a function of εZ_d.

dispenser was turned on and the wave amplitude $(\delta n/n)_d \equiv A_d$ (with dust) was measured. The ratio A_d/A_{nd} could then be used as an indication of the effect of the dust. This procedure was repeated for various dust dispenser rotation rates. For each value of the rotation rate the quantity εZ_d was determined from measurements made with a Langmuir probe located in the dusty plasma. The results of these measurements are shown in Fig. 2. It appears that as more and more electrons become attached to the dust grains (larger εZ_d's) it becomes increasingly easier to excite EDIC waves in the sense that for a given value of the electron drift speed along the magnetic field, the wave amplitude is higher when the dust is present. By lowering the disk bias to the point that the electron drift was insufficient to excite the waves, *with the dust off*, we were then able, *by simply turning the dust on*, to excite the EDIC waves. This result was in line with the prediction of Chow and Rosenberg,[14,18] that the presence of negatively charged dust reduces the critical electron drift for excitation of the EDIC mode.

C. Ion acoustic waves (DIA)

1. Grid-launched ion acoustic waves[30]

Ion acoustic waves were launched into the dusty plasma by means of a grid that was located ~ 3 cm in front of the dust dispenser (hot plate side) and oriented perpendicular to the magnetic field. The grid was biased at several volts negative with respect to the space potential and a sinusoidal ($f \sim 20-80$ kHz) tone burst of about 4–5 V peak-to-peak amplitude was applied to it. This produced a density perturbation near the grid that traveled down the plasma column as an ion-acoustic wave. Using an axially movable Langmuir probe the phase velocity ($v = \omega/K_r$), wavelength ($\lambda = 2\pi/K_r$), and spatial attenuation length ($\delta = 2\pi/K_i$) could be measured as a function of the dust parameter εZ_d (K_r and K_i are the real and imaginary parts of the wave number). The variation of the phase speed and the spatial damping parameter K_i/K_r with εZ_d is shown in Fig. 3; both quantities being normalized to their respective values in the absence of dust ($\varepsilon Z_d = 0$). As the fraction of negative charge per unit volume on the dust *increases* the wave phase velocity *increases* and the wave damping *decreases*. The solid and dashed lines in Fig. 3(a) are curves obtained from fluid theory for the case of no plasma drift along the magnetic field (solid) and for a drift of twice the acoustic speed (dashed). The solid curve in Fig. 3(b) was obtained from the solution of the Vlasov equation. The reduction in the wave damping is a consequence of the reduction in Landau damping that accompanies the increase in phase velocity with increasing εZ_d.

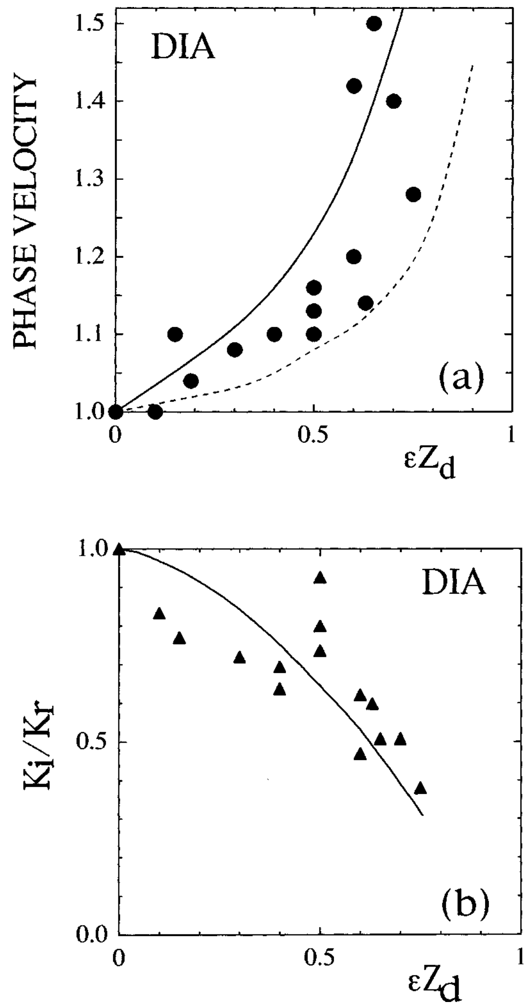

FIG. 3. Properties of grid-launched dust ion acoustic (DIA) waves. (a) Measured phase velocity as a function of εZ_d (solid dots). Solid and dotted curves are from fluid theory. (b) Measured ratio of the spatial damping rate to wave number, K_i/K_r as a function of εZ_d (solid triangles). Solid curve is from Vlasov theory. Both the phase velocity and K_i/K_r values are normalized by their respective values for $\varepsilon Z_d = 0$.

2. Current-driven ion acoustic waves[31]

In an ordinary electron-ion plasma with $T_e \approx T_i$, ion Landau damping is very strong making it extremely difficult to excite an ion-acoustic instability. However, as demonstrated in the previous experiment, the presence of a sufficient amount of negatively charged dust reduces the Landau damping, and correspondingly the spatial damping of the waves. We would expect then that a similar effect should occur for ion acoustic waves excited in the plasma by an electron drift relative to the ions. To investigate this, the cold

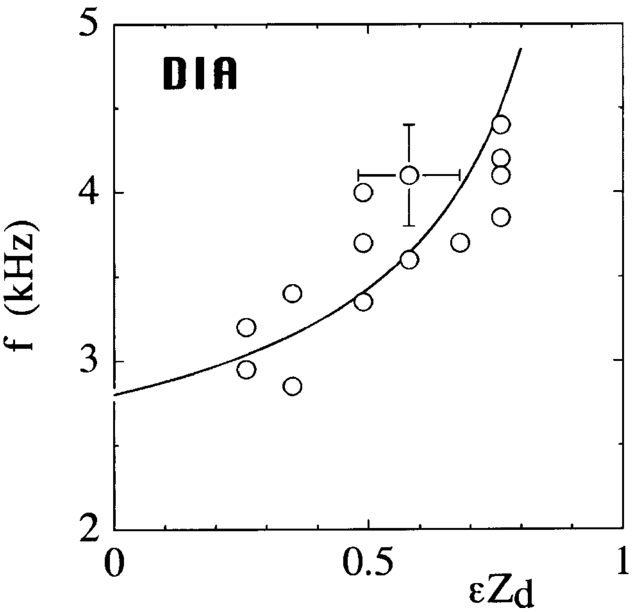

FIG. 4. Measured frequency of current-driven dust ion acoustic (DIA) waves as a function of εZ_d (open circles). Solid line from Eq. (5).

endplate (Fig. 1) was biased at a constant voltage of $+20$ V to draw an electron current through the entire cross section of the plasma column. It is well known that in a normal Q machine plasma, this configuration does not lead to a clear excitation of an ion-cyclotron instability, but rather low-frequency (few kHz) potential relaxation (PRI) oscillations are produced.[32] We found, however, that when a sufficient amount of dust was introduced into the plasma column, the PRI oscillations (~ 1.5 kHz) were quenched while somewhat higher frequency (3–5 kHz) oscillations were generated which we identify as the dust-modified ion-acoustic (DIA) waves. (A similar effect was observed in a negative ion plasma.[33]) The frequency of these DIA oscillations depended on the dust parameter εZ that was varied by changing the rotation rate of the dust dispenser, as shown in Fig. 4. The increase in frequency with εZ_d is presumably due to the increase in phase velocity as εZ_d is increased, since the wavelength is fixed, in this case, by the boundary conditions. The solid line in Fig. 4 was obtained from calculations using the dispersion relation given in Eq. (5), using the normalization $f = f_0 = 2.8$ kHz for $\varepsilon Z_d = 0$. The reasonable agreement obtained between the theoretical predictions and the experimental results supports our identification of the source of the oscillations.

IV. OBSERVATIONS OF THE DUST ACOUSTIC WAVE (DAW)

To observe the low-frequency dust acoustic mode it was necessary to develop a method for trapping dust grains within a plasma for long times. The initial observations of the DAW were performed using a modified version of the DPD described earlier in which an anode double layer was formed near the end of the plasma column.[34] The negatively charged dust grains were trapped in the positive potential

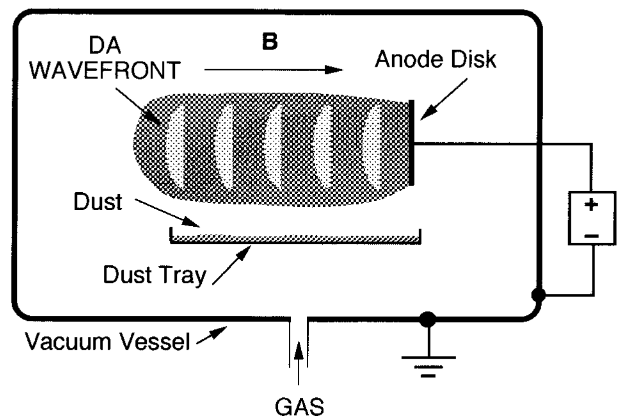

FIG. 5. Schematic diagram of the glow discharge device used to trap negatively charged dust. Several dust acoustic wave fronts are shown.

region of the anode glow and DA waves were spontaneously excited, probably due to an ion-dust streaming instability.[16]

Further experiments on the DAW were made in the device shown schematically in Fig. 5.[35] A glow discharge was formed in nitrogen gas ($p \approx 100$ mTorr) by applying a positive potential (200–300 V, 1–25 mA) to a 3 cm diameter anode disk located in the center of a grounded vacuum chamber. A longitudinal magnetic field of about 100 G provides some radial confinement for the electrons resulting in a cylindrical rod-shaped glow discharge along the magnetic field. Dust grains from a tray located just beneath the anode are attracted into the glow discharge and trapped in this positive potential region. The dust cloud can be observed visually and its behavior recorded on VCR tape by light scattered from a high intensity source which illuminates the clouds from behind. The trapped grains have a relatively narrow size distribution with an average size of about 0.7 micron and a density on the order of 10^5 cm^{-3}.

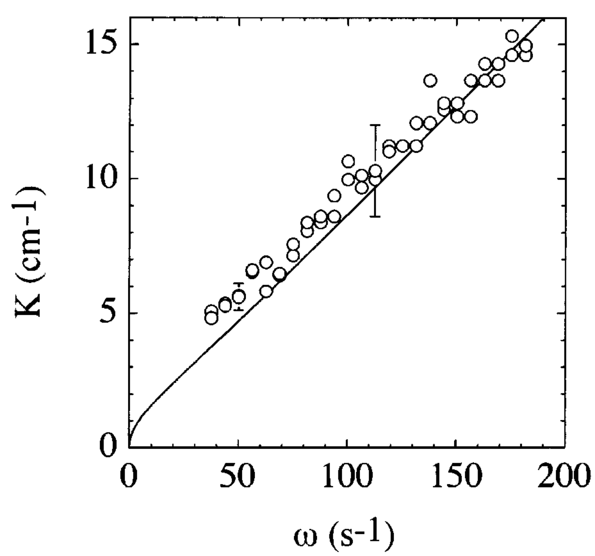

FIG. 6. Measured (open circles) dust acoustic wave dispersion relation (wave number K vs angular frequency ω). The solid curve was computed from the fluid dispersion relation given in Eq. (10).

If the discharge current was sufficiently high (>1 mA) DA waves appeared spontaneously in the dusty plasma, typically at a frequency ≈ 20 Hz, wavelength ≈ 6 mm and propagated at a phase velocity of ≈ 12 cm/s. They were observed as bright bands of enhanced scattered light (from the wave crests) traveling along the axis of the device away from the anode.

To investigate the properties of the waves in more detail, a sinusoidal modulation (in addition to the dc bias) was applied to the anode to generate waves with frequencies in the range of 6–30 Hz. At each frequency a video recording of the waves was made and the wavelength was measured. The resulting wave number (K) vs angular frequency (ω) plot is shown in Fig. 6. Over this frequency range below ω_{pd} $[=(4\pi n_d e^2 Z^2/m_d)^{1/2}$, the dust plasma frequency] the waves are nondispersive and have a phase velocity ≈ 12 cm/s. The data in Fig. 6 were compared to a theoretical dispersion relation for DA waves taking into account collisions between the dust grains and neutral gas molecules:[20,21,36] $\omega(\omega+i\beta)=K^2 C_{\mathrm{DA}}^2$, where β is the dust-neutral collision frequency, and C_{DA} is the dust acoustic speed defined in Eq. (6). β was computed from an expression obtained by Baines *et al.*[37] $\beta \approx 4 m_n N a^2 v_n / m_d$, where m_n and v_n are the mass and thermal speed of the neutrals and N is the neutral density. Using $m_n = 5\times 10^{-26}$ kg, $v_n = 283$ m/s, $N=3\times 10^{21}$ m^{-3}, $a=0.35\ \mu$, and $m_d = 3.6\times 10^{-16}$ kg, we find $\beta \approx 60$ s^{-1}. The solid curve in Fig. 6 was then obtained by taking ω to be real and K to be imaginary, and solving for the wavenumber K_r vs ω,

$$K_r = [\omega(\omega+\sqrt{\omega^2+\beta^2})]^{1/2}/(\sqrt{2}C_{\mathrm{DA}}), \tag{10}$$

with $C_{\mathrm{DA}}=12$ cm/s. The effect of the collisions produces an ''offset,'' which explains why the data points do not extrapolate *linearly* through the origin.

Finally we note that spontaneous appearance of the DAW may also be explained by the collisional theory of D'Angelo and Merlino,[21] when account is taken of the equilibrium longitudinal electric field, E_0, in the plasma. This theory predicts DAW instability for E_0's>1 V/cm, quite close to the fields, $E_0 \approx 2-5$ V/cm, measured with an emissive probe.

V. SUMMARY AND CONCLUSIONS

The dispersion relation for low-frequency electrostatic waves in a uniform dusty plasma has been presented. From this general relation the dispersion relations for ion cyclotron, ion acoustic, dust cyclotron, and dust acoustic waves have been derived. In each case, the frequency increases with increasing ε, the ratio of dust density to ion density. This has important consequences for wave excitation, since an increasing frequency is accompanied by a decrease in Landau and cyclotron wave damping.

Laboratory experiments on ion acoustic waves and electrostatic ion cyclotron waves confirm that these modes are more easily excited in a dusty plasma with negatively charged grains. For grid-launched ion acoustic (DIA) waves, the presence of dust allows the waves to propagate over longer distances than with no dust, in which case the Landau damping attenuates the waves in less than one wavelength. Ion acoustic waves could also be excited, in the presence of a sufficient amount of negatively charged dust, by a magnetic-field-aligned current. The theoretical prediction that a substantial amount of negatively charged dust makes the plasma more unstable to the EIC instability was also borne out in the experiments.

The dust acoustic (DA) mode was observed in a dusty plasma in which the charged grains were levitated by an electric field. The measured dispersion relation agreed well with the theoretical relation taking into account the effect of dust-neutral collisions. The dust acoustic waves were most likely driven by ions drifting through the dust grains due to the longitudinal electric field in the discharge. The magnitude of this field inferred from emissive probe measurements was in agreement with that computed from the collisional theory of the current-driven dust acoustic instability.

Finally, we comment on the possibility of performing laboratory experiments in dusty plasmas where the effect of the magnetic field on the dust grains may be important. The difficulty here is in choosing a set of realistic parameters so that the gyroradius of the dust grains, $\rho_d = C_d/\omega_{cd}$, is not too large. Using the expression for the charge on an isolated grain given in Sec. I in terms of the grain potential, V_s, and grain mass, $m_d = \delta(4\pi/3)a^3$, where a is the grain radius and δ is the mass density of the grain material ($\sim 2\times 10^3$ kg/m^3), we obtain

$$\rho_d[m] = 0.33\cdot \frac{\sqrt{a[\mu\mathrm{m}]\cdot T_d[\mathrm{eV}]}}{V_s[\mathrm{V}]\cdot B[\mathrm{T}]}. \tag{11}$$

With: $a=0.01\ \mu$m, $T_d=0.025$ eV, $V_s=1$ V, and $B=0.5$ T, Eq. (11) gives a $\rho_d \approx 1$ cm. For these conditions the dust gyrofrequency, $f_{cd}\approx 10$ Hz. Thus, using relatively small dust grains ($\sim 0.01\ \mu$m), it may be possible to investigate processes involving magnetized dust, e.g., the EDC mode discussed in Sec. II A 2 b.

Recently a current driven electrostatic dust cyclotron instability in a collisional plasma was analyzed by D'Angelo[38] using a four-fluid model. The conditions for excitation of this EDC mode in both laboratory plasmas and in cometary dusty plasma environments were obtained.

ACKNOWLEDGMENTS

Work supported by the National Science Foundation and The Office of Naval Research.

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