

Oscillations in a Dusty Plasma Medium

Gurudas Ganguli¹, Robert Merlino², and Abhijit Sen³

¹Plasma Physics Division

Naval Research Laboratory, Washington DC 20375, USA

Tel: +1 (202) 767-2401; Fax: +1 (202) 767-0631; E-mail: gang@ppd.nrl.navy.mil

²Department of Physics and Astronomy

The University of Iowa, Iowa City, IA 52242, USA

Tel: +1 (319) 335-1756; Fax: +1 (319) 335-1753; E-mail: robert-merlino@uiowa.edu

³Institute for Plasma Research

Bhat, Gandhinagar 382 428, INDIA

Tel: +91-(79)-326-9023; Fax: +91-(79)-326-9016; E-mail: abhijit@ipr.res.in

ABSTRACT

Novel properties introduced by charged particulates in a plasma medium and how they influence excitation and propagation of waves are discussed. Such a medium, commonly known as dusty plasma, is generated in the near Earth environment by dust and other debris of meteoric origin and exhausts and effluents from space platforms. A novel feature of dusty plasma is that the charge to mass ratio can become a dynamical variable and represent an additional degree of freedom unavailable to a classical plasma. Charged dust particles in a plasma introduce unique potential structures and significantly alter the short and long range forces which can affect the short and long range ordering of the dust grains. More interestingly, large amount of charges on dust grains can enable the average potential energy of the dust component to exceed its average kinetic energy giving rise to a strongly coupled plasma component with liquid-like and solid-like characteristics. These aspects can introduce new types of plasma oscillations or significantly modify the existing ones. Selected theoretical and experimental studies of low frequency electrostatic waves in weakly and strongly coupled plasmas containing negatively charged dust grains are used to illustrate the unique oscillations in a dusty plasma medium. 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.

1. INTRODUCTION

Plasma is generally considered to be an ensemble of ions and electrons. But in fact plasmas often contain large number of fine solid particles, loosely referred to as 'dust'. For example, the Earth's D-Region (roughly 60 to 100 kms) is known to be populated by substantial amounts of dust and other debris of meteoric origin. Low temperatures in this region can lead to condensation of water vapor on these 'smoke' particles from meteorites [Hunten et al., 1980] and can form larger particles which are observed as noctilucent and polar mesospheric clouds [Thomas, 1984]. In addition, there are large numbers of multi-hydrated molecules and ions, which are capable of attaching free electrons. Any of these species could provide electron removing mechanisms which might be responsible for the order of magnitude changes in the conductivity [Manyard et al., 1981], which have been observed in horizontally stratified layers. Also, it has been suggested that the strong radar echoes [Balsley et al., 1983; Hoppe et al., 1990; Cho and Kelley, 1993] and the electron 'bite-outs' [Ulwick et al., 1988; Kelley and Ulwick, 1988], which are often experienced in the D-Region, can be a direct consequence of highly charged aerosol (or dust) particles in this region forming a layer of dusty plasma [Havnes et al., 1990].

Typical metallic elements of meteoric origin introduced in the ionosphere are Fe, Al, and Ni [Castleman, 1973]. The solar sources on the other hand introduce metallic elements of higher atomic weights like La, Tu, Os, Yt, and Ta [Link, 1973]. These atomic species are assumed to arise due to high temperature activity on the sun. Most of the metallic elements introduced in the ionosphere are oxidized easily, forming FeO, AlO, TiO, etc. and is suspected of forming aggregates, which become constituents of the background dust. Dust particles immersed in plasmas and UV radiation tend to collect large amounts of electrostatic charges and respond to electromagnetic forces in addition to all the other forces acting on uncharged grains. The charged dust particles participate in complex interactions with each other and the plasma, leading to completely new types of plasma behavior. Dust particles in plasmas are unusual charge carriers. They are many orders of magnitude heavier than any other plasma component and they can have many orders of magnitude larger (negative or positive) charges, which can fluctuate in time. They can communicate non-electromagnetic effects (gravity, drag, and radiation pressure) to the plasma that can represent new free energy sources. Dusty plasmas represent the most general form of space, laboratory and industrial plasmas.

For a long period, the study of dusty plasmas was mainly of interest to select groups in the astrophysical community. The subject gained popularity in the early eighties with the

Voyager spacecraft observations of peculiar features in the Saturnian ring system (e.g., the radial spokes), that could not be explained by gravitation alone [Goertz, 1989]. This led to the development, and numerous successful applications, of the gravitoelectrodynamic theory of dust dynamics [Mendis et al., 1982], wherein the fine charged dust particles are about equally influenced by planetary gravity and electromagnetic forces in the rotating planetary magnetosphere. These dynamical studies were complemented in the early nineties by the study of collective processes in dusty plasmas. This led to the discovery of new modes of oscillations with wide ranging consequences for the space environment. It also stimulated laboratory studies leading to the observation of several of them, including the very low frequency dust acoustic mode, which can be made strikingly visual to the naked eye by laser light scattering off the dust [Thompson et al., 1999]. The role of charged dust in enhanced electromagnetic wave scattering has also been investigated together with its possible application to the observed enhanced radar backscatter from the high latitude summer mesopause, where noctilucent clouds are present [Tsytovich et. al., 1989; Cho and Kelley, 1993].

Perhaps, the most fascinating new development in dusty plasmas is the phenomenon of crystallization [Morfill et al., 1998]. In these so-called ‘plasma crystals’, micron-sized dust, which are either externally introduced or internally grown in the plasma, acquire large negative charges and form Coulomb lattices as was theoretically anticipated by Ikezi [1986]. Ikezi argued that since a dust grain can hold a large number of electrons, the average potential energy of the dust component can substantially exceed its average kinetic energy. This could result in a sharp deviation in the plasma properties as compared with the familiar Vlasov (or weakly coupled) plasma and lead to the formation of a strongly coupled plasma component for ordinary density and room temperatures. Strongly coupled plasma, which otherwise can exist under extraordinary conditions of extremely high densities and very low temperatures, such as a stellar environment, can display liquid-like or solid-like properties. This entirely new material, where phase transition and crystalline structure is so vividly observed by naked eye, is becoming a valuable tool for studying physical processes in condensed matter, such as melting, annealing and lattice defects. It also provides a strong motivation for investigating the collective properties in a strongly coupled plasma, an area which has remained largely unexplored so far.

The motivation for studying dusty plasmas is due to the realization of their occurrence in both the laboratory and space environments. As alluded to earlier, 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 confined in tokamak devices 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 [Goertz, 1989] and plasma processing devices [Selwyn, 1993]. The purpose of this article is not to review all possible waves in a dusty plasma medium but to highlight the novelties of this medium and to elucidate how wave generation and propagation in this medium is altered from our classical notion. For a detailed review of waves in dusty plasmas we refer the reader to Verheest [1996]. In Section 2 we first treat waves in weakly coupled dusty plasma. We first discuss the case where the dust charge is time stationary and then consider the effects of dust charge fluctuations on the evolution of waves. In Section 3 we discuss waves in a strongly coupled dusty plasma. Finally, in Section 4 we provide a discussion of some outstanding issues that need to be resolved in the future

2. WAVES IN A WEAKLY COUPLED DUSTY PLASMA

In a plasma the ratio of the potential energy to the kinetic energy of the particles is given by $\Gamma = q^2 \exp(-b/\lambda_D)/bT$, where $b = (3/4\pi n)^{1/3}$ is the interparticle distance, T is the temperature, λ_D is the Debye length, q is the charge, and n is the particle density. It is found that if $\Gamma > \Gamma_c$, where Γ_c is a critical value, then there is a phase transition to a solid state and a Coulomb lattice is formed. Typically, for a Coulomb system, $\Gamma_c \sim 170$ [Slattery et al., 1980] but it has a different value if plasma shielding effects are considered. Under normal circumstances for ordinary ion/electron plasmas, Γ is much smaller than Γ_c . Hence, the gaseous state normally prevails and we are most familiar with this plasma regime. The $\Gamma \ll \Gamma_c$ condition defines the weak coupling regime. However, in a dusty plasma, a dust grain can acquire a large amount of charge, i.e., $q_d = Ze$ where Z can be very large ($\sim 10^3 - 10^5$). Under such circumstances it is possible for Γ to exceed Γ_c for ordinary dust density and temperature values. This ($\Gamma \gg \Gamma_c$) condition defines the strong coupling regime where a solid-like behavior, such as Coloumb crystals, is manifested. For intermediate values of Γ a liquid-like state exists. In the following we discuss waves in a weakly coupled dusty plasma, first with stationary grain charge in Sec. 2.1 and subsequently examine the effects of grain charge fluctuations on the evolution of waves in Sec. 2.2.

2.1 Stationary Grain Charge

In this section we assume that the dust grain charge does not vary during wave evolution. The presence of charged dust grains acts as a third species but can significantly affect the behavior of a plasma in which they are immersed because of their unusual value of charge to mass ratio. 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

$$n_i = n_e + Z n_d \quad (1)$$

where n_α ($\alpha = e, i, d$) is the number density of electrons, ions and dust grains, and $Z = q_d/e$ is the ratio of the charge, q_d , on a dust grain to the electron charge, e .

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.

2.1.1. 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 can be obtained using a multifluid analysis [D'Angelo, 1990]. By low frequencies we mean frequencies on the order of or less than Ω_{ci} , ω_{pi} , the ion gyrofrequency and ion plasma frequency. We consider a three component plasma that is uniform and immersed in a uniform magnetic field, \mathbf{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 $v_{t\alpha} = (\kappa T_\alpha/m_\alpha)^{1/2}$, gyrofrequency $\Omega_{c\alpha} = eZ_\alpha B/cm_\alpha$, and gyroradius $\rho_\alpha = v_{t\alpha}/\Omega_{c\alpha}$. 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:

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

$$n_\alpha m_\alpha \frac{\partial \mathbf{v}_\alpha}{\partial t} + n_\alpha m_\alpha (\mathbf{v}_\alpha \cdot \nabla) \mathbf{v}_\alpha + \kappa T_\alpha \nabla n_\alpha + q_\alpha n_\alpha \nabla \phi - q_\alpha n_\alpha \mathbf{v}_\alpha \times \mathbf{B} = 0 \quad (3)$$

For the low frequency waves being considered the electron inertia can be neglected, and we can also take the electron motion entirely along \mathbf{B} . This amounts to assuming that the electrons are in Boltzmann equilibrium, i.e., $\kappa T_e \nabla n_e = e n_e \nabla \phi$. In addition to the continuity and momentum equations, the charge neutrality condition (Eq. 1) is also used both in the equilibrium and in the perturbed state. A standard linear perturbation analysis is performed around the uniform, non-drifting equilibrium plasma, with $E_0 = -(\nabla \phi_0) = 0$. Assuming that the first order quantities vary as $\exp[i(k_x x + k_z z - \omega t)]$ the following dispersion relation is obtained:

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

where

$$G = \left(\frac{\xi_i^2}{\xi_i^2 - 1} \right) k_x^2 \rho_i^2 + k_z^2 \rho_i^2 \quad (4a)$$

and

$$H = \left(\frac{\xi_i^2}{\xi_i^2 - (\xi_i / \xi_d)^2} \right) k_x^2 \rho_i^2 + k_z^2 \rho_i^2 \quad (4b)$$

$\xi_i = \omega / \Omega_{ci}$, $\xi_d = \omega / \Omega_{cd}$, $\mu_{i/d} = m_i / m_d$, $\tau_{d/i} = T_d / T_i$, and $\tau_{i/e} = T_i / T_e$. The parameter $\epsilon = n_{d0} / n_{i0}$, so that from (1) $n_{e0} = (1 - \epsilon Z_d) n_{i0}$. The subscript '0' implies equilibrium (zero order) quantities. 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 4 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 (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 \mathbf{B} (acoustic modes) or nearly perpendicular to \mathbf{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 ($\omega \gg k_z v_{td}$)

This is the usual ion acoustic wave with modifications introduced by the presence of the negatively charged dust [D'Angelo, 1990; Shukla and Silin, 1992]. In this case we can consider the dust to be a static background ($m_d \rightarrow \infty$), yielding the dispersion relation

$$\frac{\omega}{k_z} = \left[\frac{\kappa T_i}{m_i} + \frac{\kappa T_e}{m_i(1 - \epsilon Z_d)} \right]^{\frac{1}{2}} = C_{S,d} \quad (5)$$

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 $m_i n_{i0} \partial \mathbf{v}_{i1} / \partial t = -[\kappa T_i + \kappa T_e / (1 - \epsilon Z)] (\partial n_{i1} / \partial x)$, where the Boltzmann relation has been used to express the wave electric field, E_1 , in terms of $\partial n_{e1} / \partial t$. The subscript '1' implies fluctuating (first order) quantities. The term $m_i n_{i0} \partial \mathbf{v}_{i1} / \partial t$ 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 . 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. An increase in the "restoring" force then gives rise to an increase in the wave frequency, which increases the wave phase speed removing the wave from Landau resonance. Chow and Rosenberg [1995] interpret the term $\kappa T_e / (1 - \epsilon Z_d)$ as an "effective" electron temperature.

b. DA - dust acoustic mode ($\omega \ll k_z v_{ti}$)

This is a very low frequency acoustic mode in which the dust grains participate directly in the wave dynamics [Rao et al., 1990]. For this mode both the electron and ion inertia can be neglected and the dust provides the mode inertia. The restoring force is provided by the electron and ion pressures as can be seen from the linearized dust momentum equation with $T_d=0$; $m_d n_{d0} (\partial v_{d1} / \partial t) = -[\kappa T_e (\partial n_{e1} / \partial x) + \kappa T_i (\partial n_{i1} / \partial x)]$. The dispersion relation is

$$\frac{\omega}{k_z} = \left[\frac{\kappa T_d}{m_d} + \epsilon Z_d^2 \frac{\kappa T_i}{m_d} \frac{1}{1 + (T_i / T_e)(1 - \epsilon Z_d)} \right]^{\frac{1}{2}} = C_{DA} \quad (6)$$

where C_{DA} is the dust acoustic velocity.

2. Cyclotron modes ($k_z \ll k_x$)

These are modes that propagate nearly perpendicular to the \mathbf{B} field, but with a finite k_z so that the assumption that the electrons remain in Boltzmann equilibrium along \mathbf{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

$$\omega^2 = \Omega_{ci}^2 + k_x^2 \left[\frac{\kappa T_i}{m_i} + \frac{\kappa T_e}{m_i(1 - \epsilon Z_d)} \right] \quad (7)$$

In (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 \mathbf{B} in response to the very small, but finite E_z . The dispersion relation is

$$\omega^2 = \Omega_{cd}^2 + k_x^2 \left[\frac{\kappa T_d}{m_d} + \epsilon Z_d^2 \frac{\kappa T_i}{m_d} \frac{1}{1 + (T_i / T_e)(1 - \epsilon Z_d)} \right] \quad (8)$$

Summary : The 4 dispersion relations can be expressed compactly in the form

$$\mathbf{DIA} \quad \omega^2 = k_z^2 C_{S,d}^2 \quad (9a)$$

$$\mathbf{DA} \quad \omega^2 = k_z^2 C_{DA}^2 \quad (9b)$$

$$\mathbf{EDIC} \quad \omega^2 = \Omega_{ci}^2 + k_x^2 C_{S,d}^2 \quad (9c)$$

$$\mathbf{EDC} \quad \omega^2 = \Omega_{cd}^2 + k_x^2 C_{DA}^2 \quad (9d)$$

where $C_{S,d}$ and C_{DA} are defined in (5) and (6). The modes described by (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 (9b) and EDC (9d) modes are the new low frequency "dust modes".

B. Wave excitation and damping

The fluid analysis just presented describes the normal modes of the system. To examine the conditions for wave excitation a Vlasov analysis is required, except when dealing with

resistive or non-resonant instabilities. Rosenberg [1993] 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.

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 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 $\omega/k \approx v_{di}$. 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. [1995], in a 1-D 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 [1995; 1996a]. 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 [1996b] 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 [Rosenberg, 1996; D'Angelo and Merlino, 1996, Merlino, 1997]. Using kinetic theory and taking into account collisions with the neutrals, Rosenberg [1996] 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 [1996] 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 in typical laboratory plasmas, were required to excite the DA instability. Similar results were found by Merlino [1997], 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" [Melandso et al., 1993] 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. Effects of charging dynamics on waves are treated in more detail in the next section. As pointed out by D'Angelo [1994], 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 [1994]. This effect is due to the continuous injection of "new" ions to replace those that 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.

2.1.2. 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 (~ 2200 K) 6 cm diameter tantalum plate which also emits thermionic electrons. The electrons and K^+ ions are confined to a cylindrical column about 1 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 [Xu et al., 1992]. 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 (~ 0.1 s) to affect the behavior of electrostatic plasma modes, although not long enough to study processes involving dust dynamics.

As pointed out earlier, the quantity $\epsilon Z_d = 1 - n_e/n_i$ 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)

The electrostatic ion-cyclotron instability is produced by drawing an electron current along the axis of the plasma column to a 5 mm diameter 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 wavevector that is nearly perpendicular to the magnetic field. To study the effect of the dust on the instability [Barkan et al., 1995a], the wave amplitude, $A_{Nd} \equiv (\delta n/n)_{Nd}$, (with no dust present) was measured, and without introducing any other changes in the plasma conditions, the dust dispenser was turned on and the wave amplitude $A_d \equiv (\delta n/n)_d$ (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*, it was possible, *by simply turning the dust on*, to excite the EDIC waves. This result was in line with the prediction of Chow and Rosenberg [1995,1996a], namely, that the presence of negatively charged dust reduces the critical electron drift for excitation of the EDIC mode.

C. Ion acoustic waves (DIA)

Ion acoustic waves were launched into the dusty plasma by means of a grid that was located approximately 3 cm in front of the dust dispenser (hot plate side) and oriented perpendicular to the magnetic field [Barkan et al., 1996]. 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 wavenumber.) 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 ($\epsilon Z_d = 0$). 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 lines in Fig. 3 (a) are curves obtained from fluid theory for the case of no plasma drift along the magnetic field (upper curve) and for a drift of twice the acoustic speed (lower curve). 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 .

2.1.3. 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 [Barkan et al., 1995b]. The negatively charged dust grains were trapped in the positive potential region of the anode glow and DAWs were spontaneously excited, probably due to an ion-dust streaming instability [Rosenberg, 1993].

Further experiments on the DAW were made in the device shown schematically in Fig. 4a [Thompson, et al., 1997]. 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 illuminated the cloud 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} .

When 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, as shown in Fig. 4(b).

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 to 30 Hz. At each frequency a video recording of the waves was made and the wavelength was measured. The resulting wavenumber (k) vs. angular frequency (ω) plot is shown in Fig. 5. Over this frequency range below $\omega_{pd} [= (4\pi n_d e^2 Z^2 / m_d)^{1/2}]$, the dust plasma frequency] the waves are non-dispersive and have a phase velocity ≈ 12 cm/s. The data in Fig. 5 were compared to a theoretical dispersion relation for DA waves taking into account collisions between the dust grains and neutral gas molecules [Rosenberg, 1996; D'Angelo and Merlino, 1996; Wang and Bhattacharjee, 1997], $\omega(\omega + i\nu_{dn}) = k^2 C_{DA}^2$, where ν_{dn} is the dust-neutral collision frequency, and C_{DA} is the dust acoustic speed defined in Eq. 5. Here $T_e = 2.5$ eV and $T_i = 0.05$ eV. ν_{dn} was computed from an expression obtained by Baines *et al.* [1965]. $\nu_{dn} \approx 4m_n N a^2 v_n / m_d$, 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, $N = 3 \times 10^{21} \text{ m}^{-3}$, $a = 0.35 \mu$, and $m_d = 3.6 \times 10^{-16}$ kg, we find $\nu_{dn} \approx 60 \text{ s}^{-1}$. The solid curve in Fig. 5 was then obtained by taking ω to be real and k to be complex, and solving for the wavenumber k_r vs ω ,

$$k_r = \frac{1}{\sqrt{2}C_{DA}} \sqrt{\omega(\omega + \sqrt{\omega^2 + \nu_{dn}^2})} \quad (10)$$

with $C_{DA} = 12$ 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 [1996], when account is taken of the equilibrium longitudinal electric field, E_0 , in the plasma. This theory predicts DAW instability for values of $E_0 > 1$ V/cm, quite close to the fields, $E_0 \approx 2 - 5$ V/cm, measured with an emissive probe.

2.2 *Effects of Dust Charge Fluctuations*

In Section 2.1 we described the wave properties in a dusty plasma in which the effects of dust charge fluctuation were ignored. Consequently, as far as the waves are concerned, the dust represented a third species in essentially a multi-species plasma. However, in many important cases, such as meteor ablation in the D-region [Havnes, 2001], discharge of effluents and exhausts from space platform [Horyani et al., 1988, Bernhardt et al., 1995], etc., the time scales of dust charging and the waves may be comparable. Physically, these situations represent an expansion of a dust cloud through a plasma medium. In such cases the dust charging dynamics is likely to influence the wave properties, and vice-versa. This led to the development of a self-consistent formalism to account for the dust charging physics on wave excitation and propagation in a dusty plasma [Jana et al., 1993; Varma et al., 1993].

It is important to realize that, in general, both charge and mass of the dust grain could be time dependent and hence the Lorentz force on the dust grain is time dependent even when the electric and magnetic fields are stationary. For simplicity of discussion, in the following we assume that the mass of the dust grain is time independent. Thus the equation of motion for a dust grain is given by,

$$\frac{dv}{dt} = \frac{q_d(t)}{m} (E + v \times B) \quad (11)$$

To obtain the instantaneous value of dust charge $q_d(t)$ we have to solve the dust charging equation given by,

$$\frac{dq_d}{dt} = \sum_j I_j \quad (12)$$

where I_j are currents arriving on the surface of the dust grain. I_j could be of various origins. For example, it could be due to thermal fluxes of electrons and ions, secondary electron emissions, photoelectrons, backscattered electrons, etc. [Horanyi et al., 1988]. The steady state value of the charge is obtained from the $dq_d(t)/dt = 0$ condition.

For illustrating the important new physics that is introduced by dust charging dynamics, we consider a simple case where the charging currents are due only to electron and ion fluxes arriving on the dust grain. We express the electron and ion currents as,

$$I_e = -\pi a^2 e \left(\frac{8\kappa T_e}{\pi m_e} \right)^{1/2} n_e \exp \left[\frac{e\phi_f}{\kappa T_e} \right], \quad (13)$$

$$I_i = \pi a^2 e \left(\frac{8\kappa T_i}{\pi m_i} \right)^{1/2} n_i \left[1 - \frac{e\phi_f}{\kappa T_i} \right], \quad (14)$$

where a is the grain radius, ϕ_f is the floating potential on the dust grain with respect to the local plasma. Expressions (13) and (14) were derived on the basis of orbit motion limited (OML) theory [Laframboise and Parker, 1973; Allen, 1992] which assumes a (i) steady state, (ii) collisionless electrons and ions, (iii) all ions come in from $r = \infty$ where potential $\phi=0$, and therefore have positive energy, (iv) the electron and ion distributions are Maxwellians and $r = \infty$, and (v) the trajectory of any ion or electron can be traced back to $r = \infty$ without encountering grain surfaces or potential barriers. More recently, the validity of the OML theory has been extensively scrutinized [Allen et al., 2000]. It has been found that as long as the grain size is much smaller than the Debye length and for typical values of T_i and T_e , OML theory remains valid [Lampe, 2001; Lampe et al., 2001a]. For ionospheric applications these conditions are generally well satisfied.

To consider effects of dust charging on collective effects, the fluctuating (linearized) currents can be expressed as [Jana et al., 1993],

$$I_{1e} = I_{e0} \left(\frac{n_{1e}}{n_{0e}} + \frac{e\phi_{1f}}{\kappa T_e} \right), \quad (15)$$

$$I_{1i} = I_{i0} \left(\frac{n_{1i}}{n_{0i}} - \frac{e\phi_{1f}}{w_0} \right), \quad (16)$$

where $w_0 = (\kappa T_i - e\phi_{f0})$ and $I_{i0} = -I_{e0}$ because of equilibrium constraints. Using (15) and (16) in (12) it can be shown that,

$$\frac{dq_{1d}}{dt} + \eta q_{1d} = |I_{e0}| \left(\frac{n_{1i}}{n_{0i}} - \frac{n_{1e}}{n_{0e}} \right). \quad (17)$$

Here η , is the dust charge relaxation rate, which is given by,

$$\eta = \frac{e|I_{e0}|}{C} \left(\frac{1}{\kappa T_e} + \frac{1}{\kappa T_i - e\phi_{f0}} \right), \quad (18)$$

where ϕ_{f0} is the equilibrium floating potential and C is the capacitance of the dust grain (assumed to be spherical). Physically, η represents the natural decay rate of the dust charge fluctuations. These fluctuations arise when the electron/ion current on to the grain surface compensates the deviation of grain potential from the equilibrium floating potential (see Figs. 6 and 7).

It is clear from Eq. (17) that a fluctuation in the current will lead to a fluctuation in the dust charge via plasma density fluctuations. Eq. (17) is an additional dynamical equation that has to be considered along with the standard equations for deriving the wave dispersion relation. This has an important bearing on the collective behavior since the linearized Poisson equation will now include an additional term proportional to the first order dust charge fluctuation

$$-\nabla^2 \phi_1 = 4\pi \left(\sum_{\alpha} n_{1\alpha} e_{\alpha} + n_{0d} q_{1d} \right) \quad (19)$$

where $e_d = q_{0d}$ and q_{1d} , $n_{1\alpha}$, ϕ_1 , represent fluctuations in dust charge, plasma density, and electrostatic potential respectively.

In the simplest form the local dispersion relation incorporating the effects of dust charge fluctuations is given by [Jana et al., 1993],

$$1 + \chi_e(\omega, k) \left(1 + \frac{i\beta}{\omega + i\eta} \right) + \chi_i(\omega, k) \left(1 + \frac{i\beta}{\omega + i\eta} \frac{n_{e0}}{n_{i0}} \right) + \chi_d(\omega, k) = 0 \quad (20)$$

Here χ_i and χ_e are ion and electron susceptibilities. The new physics introduced by the dust charge fluctuations is represented by the two new parameters η and β . While η describes the charge relaxation, the second parameter, $\beta = (|I_{e0}|/e)(n_{d0}/n_{e0})$, represents a dissipation rate which is similar to collisional dissipation. It can lead to damping or generation of waves depending on the circumstances.

We briefly discuss an application of these ideas to the problem of expansion of a dust cloud through a plasma environment since it generically represents a number of important situations in space plasmas. Scales et al [2001] have developed a hybrid numerical simulation model which incorporates a simple dust charging physics and considers the dust charge as a dynamical variable. Both electron and ion components are represented as fluids while the dust component is treated with the particle-in-Cell (PIC) method. Eq. (12) is solved at every time step to obtain the instantaneous value of the grain charge and only electron and ion flux currents, as described in Eqs. (13) and (14), are used. Poisson equation is solved to calculate the instantaneous electrostatic potential.

Besides providing the characteristics of an expanding dust cloud, the simulation was also used to validate the fundamental processes of dust charge relaxation and dissipation. Considering the simple case of lower hybrid oscillations for which $\chi_e = \omega_{pe}^2/\Omega_e^2$ and $\chi_i = \omega_{pi}^2/\omega^2$, and $\chi_d = 0$, i.e., dust grains are infinitely massive and hence they are immobile, it can be shown that there are two fundamental modes [Scales et al., 2001]. They are $\omega = -i\eta$ and $\omega \approx \omega_{lh} - i(\beta/2)(n_{0e}/n_{0i})$, where ω_{lh} is the lower hybrid frequency. Simulation was initiated with a sinusoidal dust charge and its time evolution was monitored. Figure 6 shows the decay of a spatial sinusoidal perturbation in the dust charge at the rate of η . This confirms the dust charge relaxation physics. Subsequently, a lower hybrid wave was launched and its amplitude was followed in time. Figure 7 shows the ion density perturbation and dust charge perturbation in two simulations. The first has no dust charging (i.e., $\beta = 0$) and it can be seen that there is no damping of the wave. In the second case, which is subject to dust charging ($\beta = 0.01\omega_{lh}$), the wave decays at a rate proportional to β . Also, note that the damping of the wave increases with dust charge fluctuation amplitude as expected. Similar effects of dust charging on ion acoustic waves have been discussed by Chae [2000].

Expansion of a dust cloud across a magnetic field was investigated by releasing neutral dust in the middle of the simulation box and allowing the dust cloud to thermally expand. As the dust cloud expand, they receive both electron and ion fluxes on their surface and since the electrons are faster the grains get negatively charged. This leads to the creation of a narrow layer less than an ion gyro radius wide in which electrons are sharply reduced in density and there is a

corresponding enhancement in the density of the charged dust component. The quasi-neutrality in this layer is maintained by positive ions, electrons and negatively charged massive dust grains. However, the density gradients of the dust and the electron components have opposite signs. Consequently, while the electron density decreases the charged dust density increases in the radial direction within the layer. This results in an intense transverse ambipolar electric field localized over a short scale size on the order of an ion gyroradius [Ganguli et al., 1993; Scales et al., 1998]. Because the transverse electric field is localized over such a short scale size the ions do not experience the electric field in its entirety over one complete gyro orbit and hence their $E \times B$ drift is not fully developed. The dust grains are so massive that for all practical purposes they behave essentially as an unmagnetized species. However, the electrons experience a strongly sheared $E \times B$ drift. This condition is ideal for exciting the electron-ion-hybrid (EIH) instability around the lower hybrid frequency and with wavelengths short compared to the ion gyroradius [Ganguli et. al., 1988; Romero et al., 1992; Scales et al., 1995].

Figures 8 and 9 are a transverse (to B) cross-section of the electron and ion densities and dust charge during the development of the EIH instability at three times during a numerical simulation. (Note that the dust charge rather than dust density is shown since for these time scales there is no dust motion except for the expansion.) Figure 8 shows a relatively slow charging rate case and figure 9 shows a relatively high charging rate case. The value of $\tilde{\beta} = \beta / \omega_{ih}$ is calculated to be 0.15 in figure 8 and 0.7 in figure 9. These values may be used to assess the effects of dust charging on the EIH instability. In both cases, the dust expands towards the right. It can be seen that as the dust expands into the background plasma, a distinct layer of enhanced negative charge develops on the front of the dust cloud. Also, there is a slow reduction of negative charge in the core of the cloud as the electron density is reduced (which ultimately reduces the electron density to sustain a dominant electron flux to the grains). In the higher charging rate case in figure 9, a very sharp enhancement in the dust charge is produced at the boundary between the dust cloud and plasma. This enhancement can be localized to less than an ion gyro radius. Note that the structuring, particularly in the electron density, at late times ($\omega_{ih}t = 5.6$ and 12.6) in both cases is due to the development of the EIH instability which propagates in the y direction. Figure 10 shows that highly sheared electron EXB flow is associated with the sharp boundaries in the electron density in figures 8 and 9. It can be seen that in the higher charging rate case, the velocity shear (dv/dx) is larger. This sheared velocity in the dust cloud ultimately drives the EIH instability.

Fig. 11 is a snapshot in the morphological evolution of a typical charged dust layer [Scales et al., 2001]. The EIH instability is spontaneously generated in the layer and nonlinearly leads to coherent (vortex) structures with typical scale sizes less than an ion gyroradius.

Interestingly, Havnes et al., [2001] discuss radar backscatter from D Region from irregularities of a similar scale size but the origin of such short scale size ($\lambda \sim 0.3\text{m}$) irregularities is not yet established. Similar small-scale irregularities are a mystery in the meteoric contrails where a sharp dust layer is also likely [Kelley et al., 1998]. While the dust expansion mechanism discussed above is an interesting possibility in these near Earth phenomena, a more detailed comparison of theory with observations is necessary for a positive confirmation.

3. WAVES IN A STRONGLY COUPLED DUSTY PLASMA

As discussed in Sec. 2, the dust component in a dusty plasma can often be in the strongly coupled regime where the average Coulomb potential energy between the dust particles can exceed their average thermal energy. This can happen in laboratory dusty plasmas even at room temperatures due to the large amount of charge that a single dust grain can acquire. An interesting question that naturally arises is what happens to the collective modes of the system, such as those discussed in sections 2.1 and 2.2, as one enters the strongly coupled regime. In this section we will discuss the effect of strong coupling on the propagation characteristics of some low frequency modes of a dusty plasma.

The physical manifestation of strong coupling is to introduce short-range order in the system due to the presence of strong correlations between the particles. This is what distinguishes a solid, with its well-correlated lattice structure, from a gas where particles behave randomly. The extent of short-range order is controlled by the Coulomb coupling parameter Γ in a dusty plasma. For $\Gamma \ll 1$, the coupling is weak and the ideal plasma approximation holds. In such a case the wave is unaffected by the particle correlations except through weak collisional effects. In the limit when Γ exceeds Γ_c the short range order becomes so large that the system freezes to a solid - an ordered crystal structure and one can then excite lattice vibrations of the dust component in the plasma. We will briefly discuss such collective excitations in a dust crystal towards the end of this section. For laboratory dusty plasmas as well as for dusty plasmas that are commonly found in space, an interesting regime is the one in which $1 < \Gamma \ll \Gamma_c$, where the coupling parameter is less than the crystallization phase but strong enough to invalidate the weak coupling assumption of the Vlasov picture. In this intermediate regime the dust component still retains its fluid character but develops some short range order in the system which keeps decaying and reforming in time. The short-range order gives rise to solid-like properties in the system e.g. elastic effects, which coexist with the usual fluid characteristics like viscosity. A phenomenological model incorporating these concepts is the so-called generalized hydrodynamics (GH) model [Postogna and Tosi, 1980; Berkovsky, 1992], which has been successfully employed in the past to investigate dense plasmas and liquid metals. We will

employ this model to study the dynamics of the strongly coupled dust component while retaining the ordinary hydrodynamics equations for the electron and ion fluids. Such an approach ensures continuity with the multi-fluid approach adopted in the previous sections.

We now replace the linearized momentum equation for the dust component, (for an unmagnetized plasma with $B=0$), with the following equation given by the GH model,

$$(1 + \tau_m \frac{\partial}{\partial t}) \left[m_d n_{0d} \frac{\partial}{\partial t} v_{d1} + \nabla P_1(r, t) - Z_d e n_{0d} E_1(r, t) \right] = \eta \nabla \cdot \nabla v_{d1} + (\zeta + \frac{\eta}{3}) \nabla (\nabla \cdot v_{d1}) \quad (21)$$

where τ_m is a relaxation time (memory time scale for the decay of the short scale order) and η and ζ are shear and bulk viscosity coefficients respectively. The physical origin of this equation can be traced to the Navier-Stokes equation (to which it reduces for $\tau_m = 0$), where the Fourier transform of the viscous forces have been generalized from $[\eta \mathbf{k}^2 + (\eta/3 + \zeta) \mathbf{k}(\mathbf{k} \cdot)]$ to $[\eta \mathbf{k}^2 + (\eta/3 + \zeta) \mathbf{k}(\mathbf{k} \cdot)] / (1 - i\omega\tau_m)$. In real space and time this amounts to investing the viscosity operator with a nonlocal character leading to memory effects and short-range order. At high frequencies for example (i.e. for $\omega\tau_m \gg 1$) the dense fluid does not have time to flow and tends to behave like a solid with elastic properties. At low frequencies viscous flow is restored. The generalized momentum equation (21) provides a good physical simulation of this viscoelastic behavior of strongly coupled fluids. The various transport coefficients η , ζ and the relaxation time τ_m itself, are functions of the Coulomb parameter Γ . The exact functional dependence on Γ is model dependent and can be deduced either from various first principle statistical schemes or from fitting to direct molecular simulation results. The viscoelastic relaxation time is given by,

$$\omega_{pd} \tau_m = \frac{(\frac{4}{3} \eta + \zeta)}{n_{0d} T_{0d}} \frac{\omega_{pd}}{1 - \gamma_d \mu_d + \frac{4}{15} u} \quad (22)$$

where $\omega_{pd} = [4\pi(Z_d e)^2 n_d / m_d]^{1/2}$ is the dust plasma frequency, T_{0d} is the dust temperature, γ_d is the adiabatic index and $\mu_d = (1/T_{0d})(\partial P / \partial n)_T = 1 + u(\Gamma)$ is the compressibility and $u = E_c / (n_{0d} T_{0d})$. E_c is the correlation energy, which is the standard quantity that is calculated from simulations or statistical schemes and expressed in terms of an analytically fitted formula. The normalized quantity $u(\Gamma)$ is called the excess internal energy of the system. Typically for weakly coupled plasmas ($\Gamma < 1$),

$$u(\Gamma) \approx -\frac{\sqrt{3}}{15} \Gamma^{3/2} \quad (23)$$

Likewise in the range of $1 \leq \Gamma \leq 200$, a widely accepted functional relation is the one provided by [Slattery *et al*, 1980],

$$u(\Gamma) = -0.89\Gamma + 0.95\Gamma^{1/4} + 0.19\Gamma^{-1/4} - 0.81 \quad (24)$$

These relations are based on one component plasma (OCP) calculations. It should be pointed out that the OCP model ignores Debye shielding effects, which are physically significant for dusty plasmas. A more appropriate model for calculating $u(\Gamma)$ and other transport coefficients would be the Yukawa model as has been done in the work of Rosenberg and Kalman [1997]. However it is found that the shielding contributions do not introduce any fundamental changes in the nature of the effects we have discussed so far. Thus we will continue to use the simple OCP estimates for our discussions henceforth. Using the above expressions, it is straightforward now to carry out a linear stability analysis as before and obtain a dispersion relation for low frequency oscillations of a strongly coupled dusty plasma. We begin by examining the low frequency dust acoustic modes.

3.1 Dust Acoustic waves

For longitudinal low frequency waves ($\omega \ll kv_{te}, kv_{ti}$), with the electrons and ions obeying the Boltzmann law, the dispersion relation for the dust acoustic modes with strong correlation effects is now given by [Kaw and Sen, 1998],

$$1 + \frac{1}{k^2 \lambda_p^2} - \frac{1}{\omega(\omega + \nu_{dn}) - \gamma_d \mu_d k^2 \lambda_{Dd}^2 + \omega k^2 \frac{\eta^*}{1 - \omega \tau_m}} = 0 \quad (25)$$

where all temporal quantities have been normalized by the dust plasma frequency ω_{pd} and spatial quantities have been normalized by the inter-particle distance $b = (4\pi n_{0d}/3)^{-1/3}$. Further, $\eta^* = (4\eta/3 + \zeta)/(m_d n_{0d} \omega_{pd} b^2)$ and $\lambda_p^{-2} = b^2 \lambda_p^{-2} = b^2 (\lambda_{De}^{-2} + \lambda_{Di}^{-2})$. In (25) we have also included dust neutral collision effects (through the normalized collision frequency ν_{dn}) which can be important in many experimental and space plasma situations as discussed in Sec. 2.1. For $\omega \tau_m \ll 1$, the dispersion relation (25) simplifies to,

$$\omega(\omega + \nu_{dn}) = k^2 \left(\gamma_d \mu_d \lambda_{Dd}^2 + \frac{\lambda_p^2}{1 + k^2 \lambda_p^2} \right) - \omega \eta^* k^2 \quad (26)$$

and can be readily solved to give,

$$\omega_R = \pm \frac{k\lambda_p}{\sqrt{1+k^2\lambda_p^2}} \left[1 + \frac{k^2\lambda_{Dd}^2\gamma_d\mu_d - ((v_{dn} + 0.5k^2\eta^*)^2)}{k^2\lambda_p^2} (1+k^2\lambda_p^2) \right]^{1/2}$$

$$\omega_I = \frac{v_{dn} + k^2\eta^*}{2} \quad (28)$$

Note that for $\eta^* = \lambda_{Dd} = v_{dn} = 0$, (27) reduces to the standard dust acoustic result of the weak coupling regime, namely, $\omega_R = kC_{DA}$ which is Eq. (9b). Strong correlations contribute to additional dispersive corrections through the μ_d and η^* terms. As shown in Fig. 12, the dispersion curve for the dust acoustic mode changes significantly with increasing values of Γ . Beyond a certain value of Γ (approximately 3.5) the dispersive corrections change sign leading to a turn over in the curve with the group velocity going to zero and then to negative values. In addition to dispersive corrections the mode also suffers additional damping proportional to the η^* contribution as seen from (28). In the weak coupling limit $\Gamma \ll 1$, this term reduces to the usual collisional damping arising from dust dust collisions but in the strong coupling limit it can vary significantly as a function of Γ .

In the opposite limit of $\omega\tau_m \gg 1$ the dispersion relation (25) simplifies to

$$\omega^2 = k^2 \left(\gamma_d\mu_d\lambda_{Dd}^2 + \frac{\eta^*}{\tau_m} + \frac{\lambda_p^2}{1+k^2\lambda_p^2} \right) \quad (29)$$

Substituting for η^* and τ_m this further gives,

$$\omega = \pm k \left[\frac{\lambda_p^2}{1+k^2\lambda_p^2} + \lambda_{Dd}^2 \left(1 + \frac{4}{15} u(\Gamma) \right) \right]^{1/2} \quad (30)$$

In this limit, the dust acoustic mode does not experience any viscous damping. Dissipation can arise only through Landau damping on the electrons and ions, which are of course not included in the GH model. The Γ corrections arise through $u(\Gamma)$ whose estimates can be obtained from the

relations (23) and (24). These corrections once again lead to the turnover effect but the effect is weaker than for the $\omega\tau_m \ll 1$ limit.

3.2 Transverse Shear Waves

As is well known, a solid lattice can support transverse mechanical waves called shear waves in addition to longitudinal sound waves. Since strong correlations invest a certain 'rigidity' even to the fluid state can one expect transverse oscillations in a strongly coupled dusty plasma? The answer surprisingly is yes and the GH model shows this novel behavior quite easily. Taking the curl of the dust equation of motion (21) and ignoring the negligible electromagnetic contribution arising from the $\nabla \times \mathbf{E}$ term, one immediately gets,

$$\left[(1 - i\omega\tau_m) i\omega m_d n_{0d} - \eta k^2 \right] (\mathbf{k} \times \mathbf{v}_{d1}) = 0 \quad (31)$$

Since $\mathbf{k} \times \mathbf{v}_{d1} \neq 0$ this leads to a dispersion relation for shear waves which can be written in terms of the dimensionless quantities defined in the previous section as,

$$\omega = \frac{-i\eta^* k^2}{1 - i\omega\tau_m} \quad (32)$$

Its solution is given by,

$$\omega_R^2 = \frac{\eta^* k^2}{\tau_m} - \frac{1}{4\tau_m^2} \quad (33)$$

$$\omega_I = -\frac{1}{2\tau_m} \quad (34)$$

We thus get a transverse propagating wave for $k^2 > 1/(4\eta^* \tau_m)$, whose frequency has a linear dependence on \mathbf{k} in the small wavelength regime. Substituting for τ_m in (33) and reverting to dimensional variables, we can also express the real frequency (for large \mathbf{k}) approximately as,

$$\omega^2 = k^2 \lambda_d^2 \omega_{pd}^2 \left[1 - \gamma_d \left(1 + \frac{u(\Gamma)}{3} + \frac{\Gamma}{9} \frac{\partial u}{\partial \Gamma} \right) - \frac{4}{15} u(\Gamma) \right] \quad (35)$$

In the limit of large Γ , $u(\Gamma) \approx -0.9\Gamma$ is large and negative. For $\Gamma \gg |(1 - \gamma_d)/(\gamma_d - 4/15)|$ the RHS of (35) is positive leading to a propagating wave. In fact, in this limit (35) can be written approximately in the form,

$$\omega^2 \approx k^2 \frac{\gamma_d E_c}{m_d n_{0d}} \quad (36)$$

This is analogous to elastic wave propagation in solids with the correlation energy E_c playing the role of the elasticity modulus.

3.3 Dust Lattice Waves

We now briefly discuss wave propagation in a dusty plasma crystal which is a strongly coupled state with $\Gamma > \Gamma_c$. Dust crystals have been observed and studied in many laboratory experiments [Chu and I, 1994, Thomas et al., 1994, Hayashi and Tachibana, 1994]. Typically they are created in the plasma sheath region where the dust particles remain levitated due to a balance between the gravitational force and the electrostatic force of the sheath electric field. Such a state has a high degree of symmetry and order with all the dust particles arranged in a hexagonal pattern in a plane and vertical alignments perpendicular to the plane. The movement of each dust particle is quite restricted and localized so that a fluid theory is no longer valid for their description - in fact they need to be treated as discrete entities. The electrons and ions on the other hand continue to be in the weakly coupled regime and can be considered as charged fluids, which shield the bare Coulomb potential of each dust particle. Thanks to this shielding the individual dust particles in a dusty plasma crystal interact only with a few neighboring particles particularly when the average dust particle separation b is larger than the plasma shielding length λ_p . The collective motion of the lattice sites can then be simply modeled by the excitations of a chain of oscillators (in one dimension) or a network of oscillators (in two dimensions). The one-dimensional model (known as a Bravais lattice model) has been used to study longitudinal oscillations in a dusty plasma [Melandso, 1996]. Keeping only the nearest neighbor interaction, the linear equation of motion for each dust particle can be written as,

$$\frac{d^2 \xi_j}{dt^2} = \frac{\beta(b)}{m_d} (\xi_{j-1} - 2\xi_j + \xi_{j+1}) \quad (37)$$

where ξ_j is the displacement from equilibrium of the j th dust particle, M is the particle mass and

$$\beta(b) = \frac{Q^2}{a^3} \exp(-b/\lambda_p) \left[1 + \frac{b}{\lambda_p} + \frac{b^2}{2\lambda_p^2} \right] \quad (38)$$

Assuming a plane wave solution of the form $\xi_j \propto \exp[i(\omega t - z_{j,0}k)]$, where $z_{j,0}$ is the equilibrium location of the j th dust particle, one gets the following dispersion relation,

$$\omega^2 = 4 \frac{\beta(b)}{m_d} \sin^2\left(\frac{kb}{2}\right) \quad (39)$$

In the long wavelength limit, $kb \ll 1$, the longitudinal dust lattice wave is seen to have a non-dispersive character much like the dust acoustic wave. The phase velocity of the DLW is given by $v_{DLW} = [\beta(b)/m_d]^{1/2}b$. A similar dispersion relation has also been obtained for transverse (in plane) waves, which is valid for horizontal oscillations in a planar crystal [Nunomura et al., 2000]. For out-of-plane (transverse) oscillations the dispersion relation takes the form [Vladimirov et al., 1997] of,

$$\omega^2 = \frac{\gamma}{m_d} - 4 \frac{\beta(b)}{m_d} \sin^2\left(\frac{kb}{2}\right) \quad (40)$$

where the constant γ is a measure of the linear restoring force in the vertical direction and is proportional to the difference between the electrostatic and gravitational force. This transverse wave dispersion relation has the character of an optical mode (for $kb \ll 1$) but with the frequency decreasing as a function of the wave number. As seen from (38) the phase velocities of the various dust crystal modes are a function of the plasma screening parameter $\kappa_1 = b / \lambda_p$ due to the role played by the electron and ion fluids in modifying the inter dust potential structure.

In summary, we see that low frequency waves, for which dust dynamics is important, experience significant modifications in the strongly coupled plasma regime. For the longitudinal dust acoustic waves, for example, there are new dispersive corrections, a lowering of their real frequency and phase velocity, an additional source of damping (due to modified viscous effects) and the existence of parameter regions where $\partial\omega/\partial k < 0$. Strong coupling also gives rise to novel phenomena like the existence of transverse shear modes even in a fluid medium. These results emerge from the generalized hydrodynamics model for the dust dynamics where dust correlation effects are physically modeled by means of Γ dependent viscoelastic coefficients. The basic results are however not confined to the GH model but have also been obtained using other methods such as the quasi-localized charge approximation (QLCA) [Rosenberg and Kalman, 1997, Kalman et al., 2000], a kinetic approach using the so called "static" and "dynamic" local field corrections [Murillo, 1998, Murillo, 2000] and the generalized thermodynamic approach [Wang and Bhattacharjee, 1997]. The applicability and physical underpinnings of each of these

methods is a subject of much current interest and provides further motivation for the study of strongly coupled dusty plasmas. In our discussion so far we have ignored the effect of dust charge fluctuations on these modes of the strongly coupled regime. As discussed in section 2.2 for the case of weakly coupled dusty plasmas, charge fluctuations provide an extra degree of freedom in the system as well as an additional source of free energy, which can give rise to interesting new phenomena. These considerations apply to the strongly coupled system as well. A recent calculation [Mishra et al., 2000] points out an interesting instability mechanism for the transverse shear mode arising from finite dust charging times and the presence of an equilibrium charge gradient. Such effects can facilitate the experimental observation of shear modes.

More recently, there have been a number of experiments and molecular dynamic simulation studies to understand the collective response of dusty plasmas in the strong coupling regime. One of the earliest experimental measurements on the dust acoustic mode in such a regime was made by Pieper and Goree [1996] who excited the plasma with a real external frequency and measured the complex wave vector. However in their experiment they were unable to clearly isolate the strong coupling effects from the collisional effects. This is because the background neutral pressure in their experiment was kept quite high in order to cool down the dust component through dust neutral collisions. The damping (as well as the dispersive effects) arising from a large v_{dn} term then tends to mask out the strong coupling contributions (see Eqs.(27),(28)). This is one of the major difficulties at present in the unambiguous experimental identification of strong coupling effects and may be overcome if alternate methods (such as UV ionization) are used for the creation and cooling of dusty plasmas. Numerical simulations on the other hand have been more successful in tracking the various strong coupling modifications of the longitudinal dust acoustic mode and have also observed the transverse shear mode [Ohta and Hamaguchi, 2000]. The transverse shear mode has recently been experimentally seen in a monolayer dusty plasma [Nunomura et al., 2000] and also in a three dimensional fluid like equilibrium [Pramanik et al., 2000]. Both experimental and theoretical investigations of the collective properties of strongly coupled fluid regime are in their early stages with a great variety of interesting problems remaining to be explored. A particularly attractive area is the experimental exploration of various transport coefficients and their dependence on Γ and κ_1 through measurements of wave propagation characteristics – this can provide fundamental understanding of not only dusty plasmas but of strongly coupled systems in general.

4. DISCUSSIONS

In Sections 2 and 3 we discussed how dust introduces new physical phenomena markedly different from a classical single or multi-species plasma. The charge on a dust particle can be

very high yet the charge-to-mass ratio (q/m) of a dust component is much lower than the usual plasma constituent. This itself leads to unusual behavior. While the value of q/m in a multi-species plasma can be different for different components, this value remains constant. In a dusty plasma, however, q/m is an additional degree of freedom and may have a distribution in magnitude and which may be time dependent. In the ionosphere, chemistry is an additional important factor which affects charging and composition of dust particles [Castleman, 1973]. Dust particles charge exchange with ionospheric ions and severely alter the local chemistry due to the large charge that can accumulate on a dust particle. In effect, charged particulates can act analogously to catalytic surfaces and promote chemical reactions. Therefore, it is of considerable interest to delineate the physical and chemical processes, which affect and transform particulates in a plasma environment. Also, massive dust particles can no longer be treated as point objects as in classical plasma treatments. These massive dust grains will have their own unique shielding clouds which are different from the usual Debye shielding and exhibit surface physics and chemistry processes which can not be ignored. The high dust charge state can induce strong coupling in the dust component and thereby introduce short range ordering in the grains. Research to date indicates that inter dust grain forces in a plasma medium is influenced by wakefield force, shadow force, and nonlinear ion flows and demonstrates the existence of an attractive force between negatively charged dust grains due to wakefield and shadow forces [Vladimirov and Nambu, 1995; Ishihara and Vladimirov, 1997; Melandso and Goree, 1995; Lampe et al., 2000; 2001a, Lampe, 2001]. Another important feature, which has not been fully addressed, is the role of trapped ions [Goree; 1992]. Recent work indicates that the trapped ions can have a profound consequence and influence the inter grain potential and grain charge magnitude in a plasma medium provided $T_e \gg T_i$ [Zobnin et al., 2000; Lampe et al, 2001b]. In the future more research has to be conducted to understand and accurately model the effects of trapped ions on the inter grain potential. The dust grains may lose or gain charges, thereby altering the value of q/m and affecting various plasma processes such as collective effects, transport, etc.. The capacity to lose or gain charges depends greatly on the physio-chemistry of the plasma environment. Hence, charging of dust grains and the influence of the plasma background (e.g., the ionospheric conditions) on this process is a very important topic which has to be addressed more thoroughly both theoretically and experimentally in the future. Variation of q/m has other important consequences as well. For example, a distribution of q/m will imply a continuous range of cyclotron frequencies Ω ($=qB/mc$). Thus, the concept of cyclotron resonance and absorption in a dusty plasma is different from that of a classical electron/ion plasma and its implications on plasma collective effects is yet to be quantified.

Man made objects (e.g., the space station) will increasingly populate the near Earth space environment in the future. Attitude control thruster discharges, outgassing, and other water

bearing effluents from these space platforms can lead to the production of ice crystals and form a dense 'dust' cloud around these objects; these can also charge. Other activities in space, such as transfer of satellites from low Earth orbits to higher (geosynchronous) orbits involve solid rocket motor (SRM) burns. SRM burn deposit large quantities of aluminum oxide (Al_2O_3) particles in space. Studies show that the flux resulting from just one such SRM burn can exceed the natural meteoroid flux for particles of like size (1 – 10 μm) [Muller and Kessler, 1985]. Another study concludes that 1 – 10 μm size Al_2O_3 particles can get charged under typical magnetospheric conditions and acquire large surface potentials ($\sim 10\text{V}$) [Horanyi et al., 1988]. For a 10 μm size grain, a surface potential of 10V, corresponds roughly to a charge state of $Z \sim 70000$. These charged grains have a typical residence time of days in the magnetosphere and can have considerable influence on the plasma environment in the immediate vicinity of these space assets.

One expects that dust will significantly affect collective effects and transport phenomena in space plasmas if its density exceeds some minimum value. But, to date no definitive research has been done to establish a general threshold for dust effects. Does the number density of the dust grains need to be a significant fraction of the electron density before effects become observable? This condition would be hard to satisfy in the ionosphere in most of the cases. It seems more likely, however, that some much less stringent condition applies, e.g., that the total charge density associated with dust grains (which hold very large numbers of electrons when charged) or some other electrodynamic state variable is the controlling factor. However, it is likely that this threshold will be different for different events and hence it is itself an interesting and important target for future research. Research to date shows that even low dust densities may interfere with space based systems by enhancing the scattering cross-section of electromagnetic waves. Tsytovich et al., [1989] and Bingham et al., [1991] have shown that even small amounts of charged dust grains can significantly affect scattering of both electrostatic and electromagnetic waves. They show that even if the dust grain mass is assumed to be infinite (and therefore immobile) compared to plasma particles, they are very efficient scattering centers, since only the electron cloud surrounding the grains oscillates in the field of an incoming wave. This is called transition scattering and is, in spirit, similar to the well known Thomson scattering. For incident cross-section is enhanced by a factor of Z^2 over Thomson scattering, e.g., $\sigma = Z^2\sigma_T$ where σ_T is electromagnetic wavelengths greater than the Debye length ($\lambda > \lambda_D$), the transition scattering the Thomson scattering cross-section. As noted earlier, the dust charge state can be quite large; typically 10^3 to 10^4 for a (1- 10) μm size grain in Earth orbit leading to huge dust scattering cross-section enhancements, e.g., $\sigma = (10^6 - 10^{10})\sigma_T$. Thus, even a small concentration of charged dust may lead to a substantial scattered power and potentially interfere with communication and radar capabilities especially around space assets which are becoming

indispensable to our everyday life on Earth. These dust effects will have to be more rigorously assessed and quantified in the future. A general kinetic formalism necessary to address some of these issues has recently been developed [Tsytovich and de Angelis, 1999; 2000; 2001; Ricci et al., 2001].

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REFERENCES

- J.E. Allen, [1992], "Probe theory – The orbital motion approach", *Physica Scripta*, 45, 497,
- J.E. Allen, B.M. Annaratone, and U. deAngelis, [2000], "On orbital motion limited theory for a small body at floating potential in a Maxwellian plasma", *J. Plasma Phys.*, 63, 299.
- M. F. Baines, I. P. Williams, and A. S. Asebiomo, [1965], "Resistance to the motion of a small sphere moving through a gas", *Mon. Not. R. Astron. Soc.*, **130**, 63.
- B.B. Balsley, W.L. Ecklund, and D.C. Fritts, [1983], "VHF echoes from the high-latitude mesosphere and lower thermosphere observations and Interpretations", *J. Atmos. Sci.*, 40, 2451.
- A. Barkan, N. D'Angelo, and R. L. Merlino, [1995a], "Laboratory experiments on electrostatic ion cyclotron waves in dusty plasmas", *Planet. Space Sci.* **43**, 905.
- A. Barkan, N. D'Angelo, and R. L. Merlino, [1996], "Experiments on ion acoustic waves in dusty plasmas", *Planet. Space Sci.* **44**, 239.
- A. Barkan, R. L. Merlino, and N. D'Angelo, [1995b], "Laboratory observation of the dust acoustic wave mode", *Phys. Plasmas* **2**, 3563.
- M.A. Berkovsky, [1992], "Spectrum of low frequency modes in strongly coupled plasmas", *Phys. Lett. A*, 166, 365.
- P. Bernhardt, G. Ganguli, M.C. Kelley, and W.E. Swartz, [1995], "Enhanced radar backscatter from space shuttle exhaust in the ionosphere", *J. Geophys. Res.*, 100, 23811.

- R. Bingham, U. De Angelis, V.N. Tsytovich, and O. Havnes, [1991], "Electromagnetic wave scattering in dusty plasmas", *Phys. Fluids B*, **3**, 811.
- A.W. Castleman, [1973], "Aerosol Chemistry", in *The Physics and chemistry of the upper atmosphere*, B. McCormak, Ed., D. Reidel Publishing Company, Boston, USA., pp. 143
- G. S. Chae, [2000], "Numerical simulation of ion waves in dusty plasma", Ph.D. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA.
- J.Y.N. Cho and M.C. Kelley, [1993], "Polar mesosphere summer radar echoes: Observations and current theories", *J. Geophys. Res.*, **31**, 243.
- V. W. Chow and M. Rosenberg, [1995], "Electrostatic ion cyclotron instability in dusty plasmas", *Planet. Space Sci.* **43**, 613.
- V. W. Chow and M. Rosenberg, [1996a], "A note on the electrostatic ion cyclotron instability in dusty plasmas: comparison with experiments", *Planet. Space Sci.* **44**, 465.
- V. W. Chow and M. Rosenberg, [1996b], "Electrostatic ion cyclotron instability in negative ion plasmas", *Phys. Plasmas* **3**, 1202.
- J.H. Chu and Lin I, [1994], "Direct Observation of Coulomb Crystals and Liquids in Strongly Coupled rf Dusty Plasmas", *Phys. Rev. Lett.*, **72**, 4009 .
- N. D'Angelo, [1990], "Low frequency electrostatic waves in dusty plasmas", *Planet. Space Sci.* **38**, 1143.
- N. D'Angelo and R. L. Merlino, [1996], "Current-driven dust acoustic instability in a collisional plasma", *Planet. Space Sci.* **44**, 1593.
- N. D'Angelo, [1994], "Ion acoustic waves in dusty plasmas", *Planet. Space Sci.* **42**, 507.
- G. Ganguli, P. Bernhardt, W. Scales, P. Rodriguez, C. Sieftring, and H. A. Romero, [1993], "Physics of negative ion plasmas created by chemical releases in space", in *Physics of Space Plasmas (1992)*, **12**, pp 161, SPI Conference Proceedings and Reprint Series, edited by T. Chang, Scientific Publishers, Inc., Cambridge, MA.
- G. Ganguli, Y.C. Lee and P.J. Palmadesso, [1988], "Electron-Ion hybrid mode due to transverse velocity shear", *Phys. Fluids.*, **31**, 2753.
- C.K. Goertz, [1989], Dusty plasmas in the solar system, *Rev. Geophys.*, **27**, 271.
- J. Goree, [1992], Ion trapping by a charged dust grain in a plasma, *Phys. Rev. Lett.*, **69**, 277.

- O. Havnes, U. de Angelis, R. Bingham, C. Goertz, G.E. Morfill and V. Tsytovich, [1990], "On the role of dust in the summer mesopause", *J. Atmos. Terr. Physics.*, 52, 637.
- O. Havnes, T. Aslaksen, and A. Brattli, [2001], Charged dust in the earth's middle atmosphere, *Physica Scripta*, T89, 133.
- Y. Hayashi and K. Tachibana, [1994], Observation of Coulomb crystal formation from carbon particles grown in a methane plasma, *Jpn. J. Appl. Phys.*, 33, L804.
- U.P. Hoppe, D.C. Fritts, I.M. Reid, P. Czechowsky, C.M. Hall, and T.L. Hansen, [1990], "Multiple-frequency studies of the high-latitude summer mesosphere: implications for scattering process", *J. Atmos. Terr. Physics.*, 52, 907.
- M. Horanyi, H.L.F. Houppis, and J.R. Hill, [1988], "Charged dust in the Earth's magnetosphere", *Astrophysics and Space Science*, 144, 215.
- D.M. Hunten, R.P. Turco, and O.B. Toon, [1980], "Smoke and dust particles of meteoric origin in the mesosphere and stratosphere", *J. Atmos. Sci.*, 37, 1342.
- O. Ishihara and S.V. Vladimirov, [1997], "Wake potential of a dust grain in a plasma with finite flows", *Phys. Plasmas*, 4, 69.
- H. Ikezi, [1986], Coulomb solid of small particles in plasmas, *Phys. Fluids*, 29, 1764.
- M.R. Jana, A. Sen, and P.K. Kaw, [1993], "Collective effects due to charge-fluctuation dynamics in a dusty plasma", *Phys Rev. E.*, 48, 3930.
- G. Kalman, M. Rosenberg and J.E. DeWitt, [2000], "Collective Modes in Strongly Correlated Yukawa Liquids: Waves in Dusty Plasmas", *Phys. Rev. Lett.*, 84, 6030.
- P.K. Kaw and A. Sen, [1998], "Low frequency modes in strongly coupled dusty plasmas", *Phys. Plasmas*, 5, 3552.
- M.C. Kelley, Alcalá, C. and Cho, J.Y.N, [1998], "Detection of meteor contrail and meteoric dust in the Earth's upper mesosphere", *J. Atm. Solar-Terr. Phys.*, 60, 359.
- M.C. Kelly and J.C. Ulwick, [1988], "Large- and small-scale organization of electrons in the high-latitude mesopause: Implications of the STATE data", *J. Geophys. Res.*, 93, 7001.
- J.G. Laframboise and L.W. Parker, [1973], "Probe for orbit-limited current collection", *Phys. Fluids*, 16, 629.
- M. Lampe, G. Joyce, G. Ganguli, V. Gavrishchaka, [2000], "Interactions between dust grains in a dusty plasma", *Phys. Plasmas*, 7, 3851.
- M. Lampe, G. Joyce, and G. Ganguli, [2001a], "Analytic and simulation studies of dust grain interaction and structuring", *Physica Scripta*, T89, 106.

- M. Lampe, [2001], "Limit of validity of OML theory for small floating collector", *J. Plasma Phys.*, 2001, (To Appear).
- M. Lampe, V. Gavrishchaka, G. Ganguli, G. Joyce, [2001b], "Effects of trapped ions on charged spherical object in a plasma", *Phys. Rev. Lett.*, 86, 5278, 2001.
- F. Link, [1973], "Aerosols and particles", in *The Physics and chemistry of the upper atmosphere*, B. McCormak, Ed., D. Reidel Publishing Company, Boston, USA., pp. 34.
- N.C. Maynard, C.L. Croskey, J.D. Mitchell and L.C. Hale, [1981], "Measurements of Volt/meter verticle electric fields in the middle atmosphere", *Geophys. Res. Lett.*, 8, 923.
- N.C. Maynard, L.C. Hale, J.D. Mitchell, F.J. Schmidlin, R.A. Goldberg, J.R. Bracus, F. Soraas and C.L. Croskey, [1984], "Electrical structures in the high-latitude middle atmosphere", *J. Atmos. Terr. Phys.*, 46, 807.
- F. Melandso, [1996], "Lattice waves in dust plasma crystals", *Phys. Plasmas*, 2, 1212.
- F. Melandsø, T. K. Aslaksen, and O. Havnes, [1993], "A new damping effect for the dust acoustic wave", *Planet. Space Sci.* **41**, 321.
- F. Melandsø and J. Goree, [1995], "Polarized supersonic plasma-flow simulation of charged bodies such as dust particles and spacecraft", *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, 52, 5312.
- D.A. Mendis, H.L.F. Houpis, and E.C. Whipple, Jr., [1982], The gravitoelectrodynamics of charged dust in planetary magnetospheres, *J. Geophys. Res.*, 87, 3449.
- R. L. Merlino, [1997], "Current-driven dust ion acoustic instability in a collisional dusty plasma", *IEEE Trans. Plasma Sci.* **25**, 60.
- R. L. Merlino, A. Barkan, C. Thompson, and N. D'Angelo, [1998], Laboratory studies of waves and instabilities in dusty plasmas, *Physics of Plasmas* 5, 1607
- A. Mishra, P.K. Kaw and A. Sen, [2000], "Instability of shear waves in an inhomogeneous strongly coupled dusty plasma", *Phys. Plasmas*, 7, 3188.
- G.E. Morfill, H.M. Thomas, U. Konopka, H. Rothermel, and M. Zuzic, [1998], "Plasma crystals and liquid plasmas", *Physics of Dusty Plasmas* p. 184, AIP Conference proceedings 446, Woodbury, New York.
- A.C. Muller and D.J. Kessler, [1985], "The effect of particulates from solid rocket motors fired in space", *Adv. Space Res.*, 5, #2.

M.S. Murillo, [1998], "Static local field correction description of acoustic waves in strongly coupling dusty plasmas", *Phys. Plasmas*, 5, 3116.

M.S. Murillo, [2000], "Longitudinal collective modes of strongly coupled dusty plasmas at finite frequencies and wavevectors", *Phys. Plasmas*, 7, 33.

S. Nunomura, D. Samsonov, and J. Goree, "Transverse Waves in a Two-Dimensional Screened-Coulomb Crystal (Dusty Plasma)", *Phys. Rev. Lett.*, [2000], 84, 5141.

H. Ohta and S. Hamaguchi, [2000], "Wave Dispersion Relations in Yukawa Fluids, *Phys. Rev. Lett.*, 84, 6026.

J.B. Pieper and J.Goree, [1996], "Dispersion of Plasma Dust Acoustic Waves in the Strong-Coupling Regime", *Phys. Rev. Letts.*, 77, 3137.

F. Postogna and M.P. Tosi, [1980], "Dynamics of Classical Ionic Plasmas in an Electron Gas", *Nuovo Cimento B*, 55, 399.

J. Pramanik, G. Prasad, A. Sen and P.K. Kaw, [2000], "An Experimental Study of Low Frequency Oscillations in a Dusty Plasma", *Bull. Am. Phys. Soc.*, 45, 35.

N. N. Rao, P. K. Shukla, and M. Y. Yu, [1990], "Dust acoustic waves in dusty plasmas", *Planet. Space Sci.* **38**, 543.

P. Ricci, G. Lapenta, U. de Angelis, and V.N. Tsytovich, [2001], "Plasma kinetics in dusty plasmas", *Phys. Plasmas*, 8, 769.

H. Romero, G. Ganguli, and Y.C. Lee, [1992], "Ion Acceleration and coherent structures generated by lower hybrid shear-driven instabilities", *Phys. Rev. Lett.*, 69, 3503.

M. Rosenberg and G. Kalman, [1997], "Dust acoustic waves in strongly coupled dusty plasmas", *Phys. Rev. E*, 56, 7166.

M. Rosenberg, [1993], " Ion and dust acoustic instability in dusty plasmas", *Planet. Space Sci.* **41**, 229.

M. Rosenberg, [1996], "Ion-dust streaming instability in dusty plasmas", *J. Vac. Sci. Tech. A* **14**, 631.

W.A. Scales, P.A. Bernhardt, and G. Ganguli, [1995], "Early time evolution of a chemically produced electron depletion", *J. Geophys. Res.*, 100, 269.

W.A. Scales, G. Ganguli, P.A. Bernhardt., [1998], " Wave generation associated with dust cloud expansion into a plasma", *Physica Scripta*, T75, 238.

W.A. Scales, G.S. Chae, and G. Ganguli, [2001], "Numerical simulation investigation of dust charging effects on electrostatic ion waves in dusty plasmas", *Physica Scripta*, T89, 142.

G.S. Selwyn, [1993], A phenomenological study of particulate in plasma tools and processes, *Jpn. J. Appl. Phys.*, 32, 3068.

P. K. Shukla and V. P. Silin, [1992], "Dust ion acoustic wave", *Phys. Scripta*, **45**, 508.

W.L. Slattery, G.D. Doolen and H.E. DeWitt, [1980], "Improved equation of state for the classical one-component plasma", *Phys. Rev. A* , 21, 2087

Thomas, G.E., [1984], "Solar mesosphere explorer measurements of polar mesospheric clouds (noctilucent clouds)", *J. Atmos. Terr. Physics.*, 46, 819.

H. Thomas, G.E. Morfill, V. Demmel, J. Goree, B. Feuerbacher, and D. Mohlmann, [1994], "Plasma Crystal: Coulomb Crystallization in a Dusty Plasma", *Phys. Rev. Lett.*, 73, 652.

C. Thompson, A. Barkan, N. D'Angelo, and R. L. Merlino, [1997], "Dust acoustic waves in a direct current glow discharge", *Phys. Plasmas* **4**, 2331.

C. Thompson, A. Barkan, R. L. Merlino, and, N. D'Angelo, [1999], Video imaging of dust acoustic waves, *IEEE Transc. Plasma Sci.*, 27 146.

V.N. Tsytovich, U. De Angelis, and R. Bingham, [1989], "Transition scattering of waves on charged dust particle in a plasma", *J. Plasma Phys.*, 42, 429.

V.N. Tsytovich and U. De Angelis, [1999], "Kinetic theory of dusty plasmas. I. General approach"" *Phys. plasmas*, 6, 1093.

V.N. Tsytovich and U. De Angelis, [2000], "Kinetic theory of dusty plasmas. II. General approach"" *Phys. plasmas*, 7, 554.

V.N. Tsytovich and U. De Angelis, [2001], "Kinetic theory of dusty plasmas. I. General approach"" *Phys. plasmas*, 8, 1141.

J.C Ulwick, K.D. Baker, M.C. Kelly, B.B. Balsley, and W.L., Ecklund, [1988], Comparasion of simultaneous MST radar and electron density probe measurements during STATE, *J. Geophys. Res.*, 93, 6989.

R.K. Varma, P.K. Shukla, and V. Krishan, [1993], Electrostatic oscillation in the presence of grain charge perturbation in dusty plasmas, *Phys. Rev E.*, 47, 3612.

F. Verheest, [1996], "Waves and instabilities in dusty space plasma", *Space Sci. Rev.*, 77, 267

S.V. Vladimirov, P. Shevchenko, and N.F. Cramer, [1997], "Vibrational modes in the dust-plasma crystal", *Phys. Rev. E*, 56, R74.

S.V. Vladimirov and M. Nambu, [1995], "Attraction of charged particulates in plasmas with finite flows", *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, **52**, 2172.

X. Wang and A. Bhattacharjee, [1997], "Hydrodynamic waves and correlation functions in dusty plasmas", *Phys. Plasmas*, **4**, 3759.

D. Winske, S. Peter Gary, M. E. Jones, M. Rosenberg, V. W. Chow, and D. A. Mendis, "Ion heating in dusty plasmas due to dust/ion acoustic instability", [1995], *Geophys. Res. Lett.* **22**, 2069.

W. Xu, B. Song, R. L. Merlino and N. D'Angelo, [1992], "A dusty plasma device for producing extended, steady state, magnetized dusty plasma columns", *Rev. Sci. Instrum.* **63**, 5266.

A.V. Zobnin, A.P. Nefedov, V.A. Sinel'shchikov, and V.E. Fortov, [2000], "On the charge of dust particles in a low-pressure gas discharge plasma", *JETP*, **91**, 483.

FIGURE CAPTIONS

FIG. 1. Schematic diagram of the dusty plasma device (DPD). (From Merlino et al., 1998)

FIG. 2. The electrostatic dust ion cyclotron(EDIC) wave amplitude with dust divided by the amplitude without dust as a function of ϵZ_d . (From Merlino et al., 1998)

FIG. 3. Dispersion properties of grid-launched dust ion acoustic (DIA) waves. (a) Measured phase velocity as a function of ϵZ_d (dots). The solid curves are obtained from fluid theory for the case of no plasma drift along the magnetic field (upper curve) and for a drift equal to twice the acoustic speed (lower curve). (b) Measured spatial damping rate (K_i) normalized to the wavenumber (K_r) as a function of ϵZ_d (triangles). Solid curve is obtained from the solution of the Vlasov equation. In both (a) and (b) values are normalized to the respective values for $\epsilon Z_d = 0$ (no dust case). [From Merlino, et al., 1998]

FIG. 4. Experimental observation of the dust acoustic mode. (a) Schematic diagram of the glow discharge device used to trap negatively charged dust. (b) Single frame dust acoustic wave video image. (From Merlino et al., 1998)

FIG. 5. Measured (open circles) dust acoustic wave dispersion relation (wavenumber k vs. angular frequency ω). The solid curve was computed from the fluid dispersion relation given in Eq. 10. (From Merlino et al., 1998)

FIG. 6. Numerical simulation of spatial relaxation of an initial spatial dust charge perturbation \tilde{Q}_d / Q_{d0} at the rate $\eta = 0.05\omega_{1h}$. (From Scales et al., 2001)

FIG. 7. Numerical simulation showing the temporal damping of a lower hybrid wave due to dust charging. For $\beta=0.01\omega_{1h}$, ion density perturbation for the lower hybrid wave damps while the associated dust charge fluctuations \tilde{Q}_d / Q_{d0} grow. (From Scales et al., 2001)

FIG. 8. Electron and ion densities and dust charge during a dust expansion simulation for $\beta=0.15\omega_{1h}$. (From Chae, 2000)

FIG. 9. Electron and ion densities and dust charge during a dust expansion simulation for $\beta=0.7\omega_{1h}$. (From Chae, 2000)

FIG. 10. Inhomogeneous electron flow velocities develop at the boundary layer of an expanding dust cloud for weak and strong charging. (From Chae, 2000)

FIG.11. Numerical simulation of the EIH instability in a dusty plasma. Dust expands in the x direction producing a sheared EXB flow in the -y direction. Note vortex structures in dust charge as well as ion and electron densities. (From Scales et al., 2001)

FIG. 12. Dispersion curve [$Re(\omega / \omega_{pd})$ vs $k\lambda_p$] for the dust acoustic wave for different values of Γ . (From Kaw and Sen, 1998)

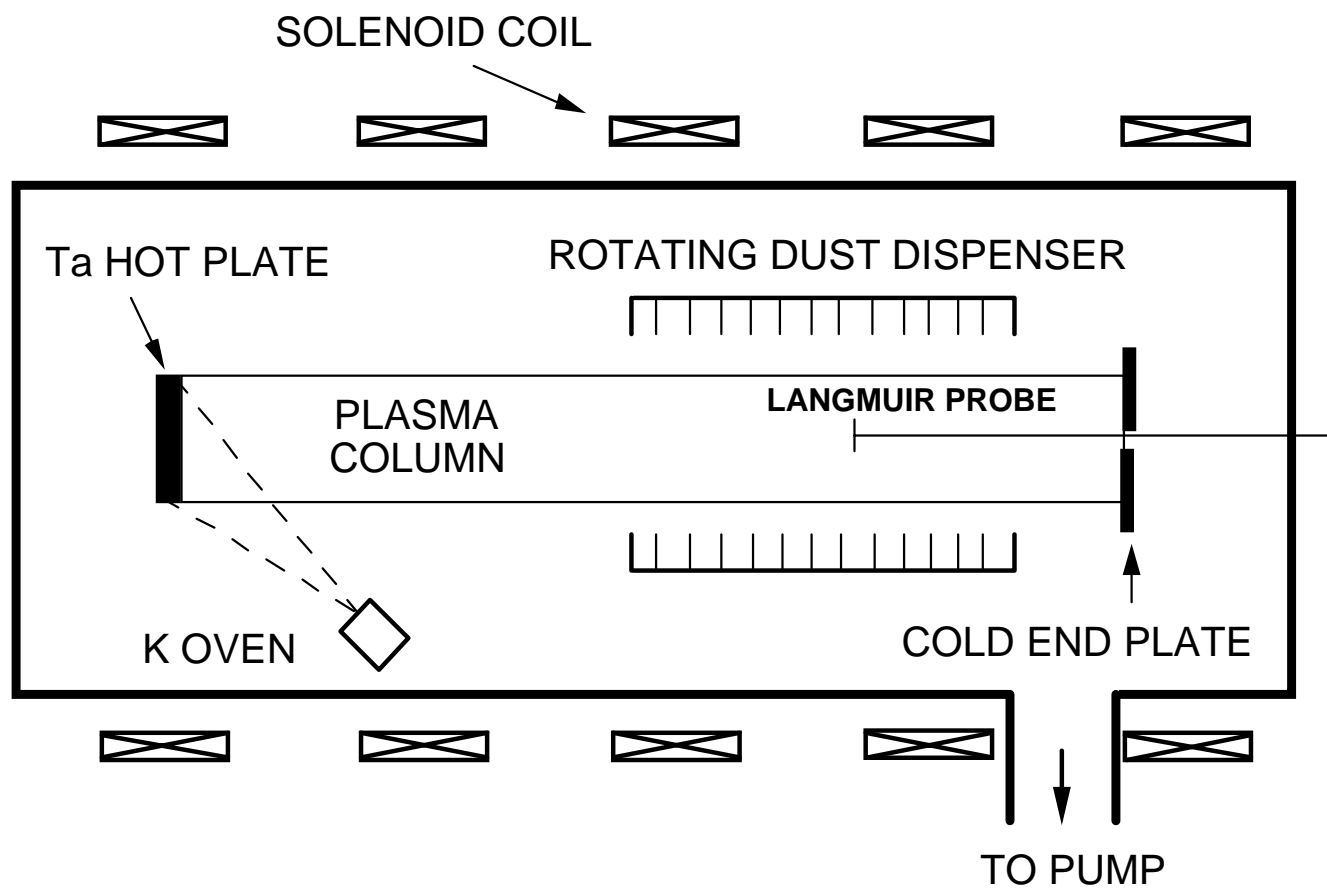


Fig.1

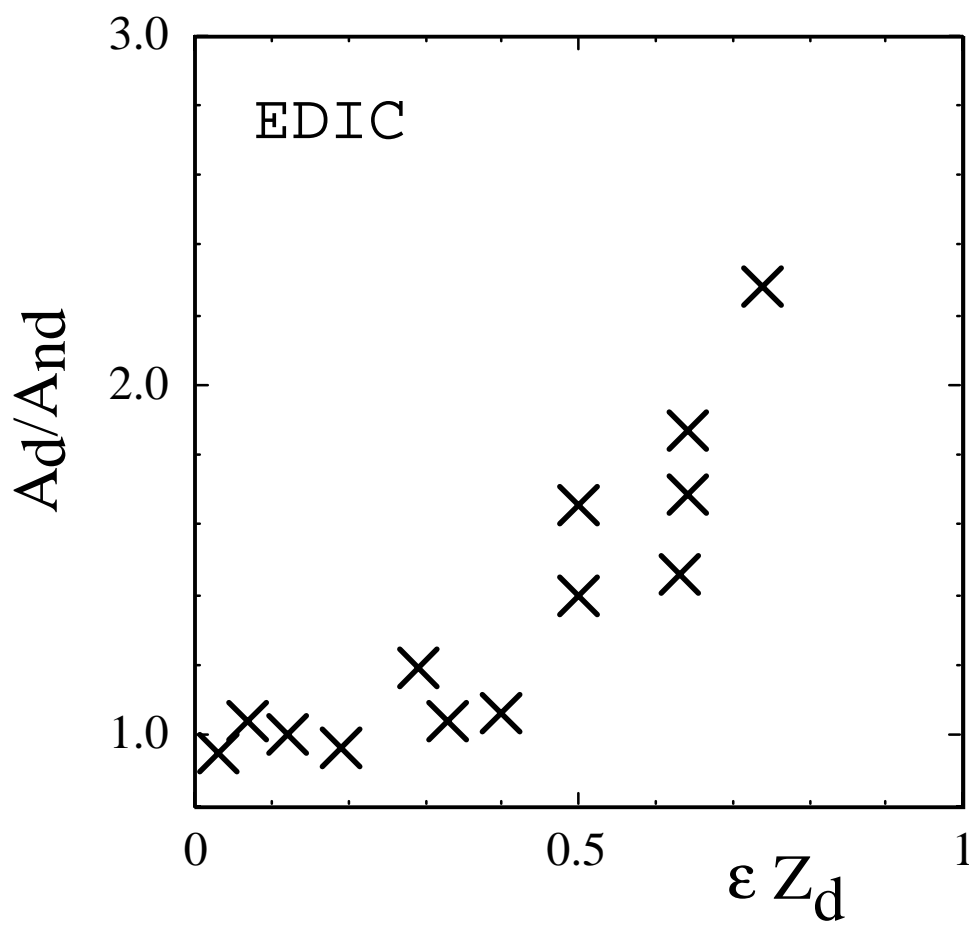


Fig. 2

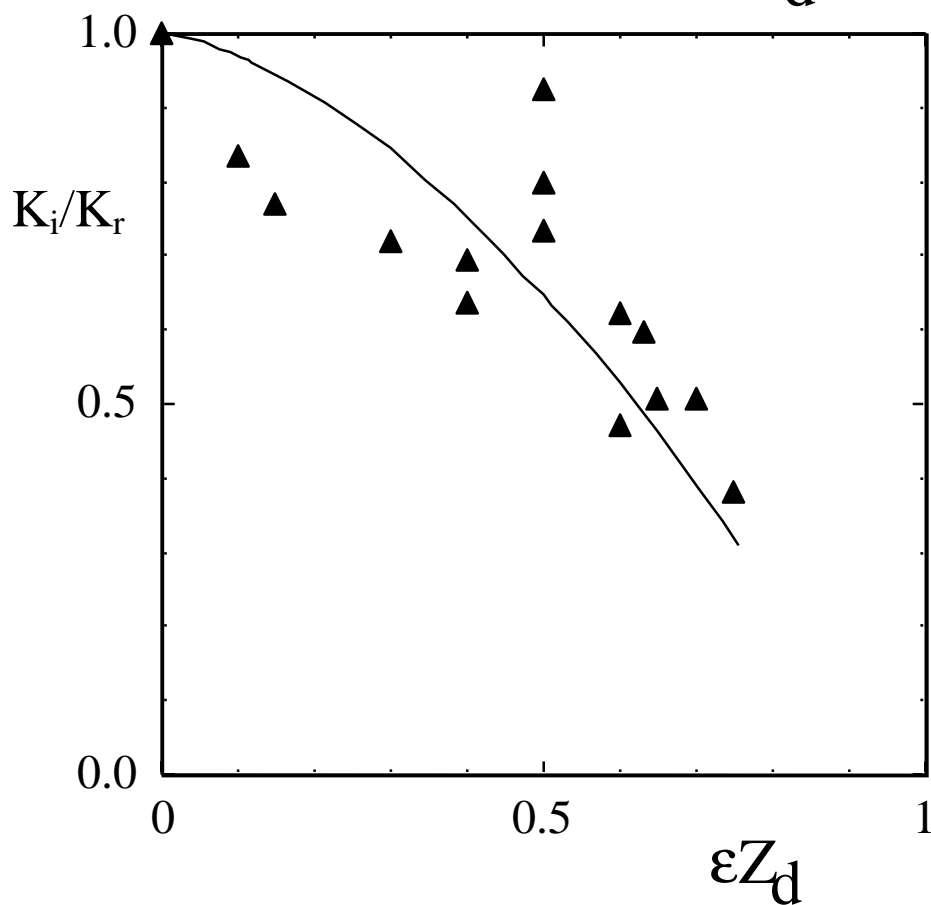
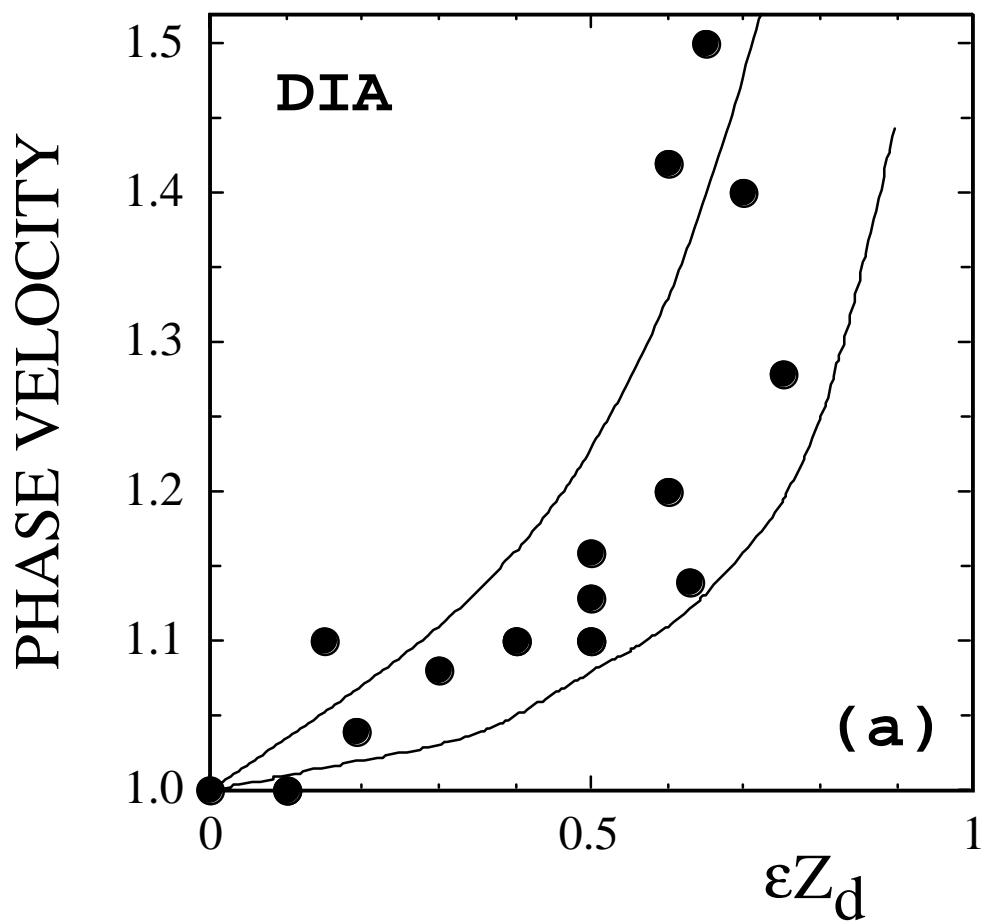


Fig. 3

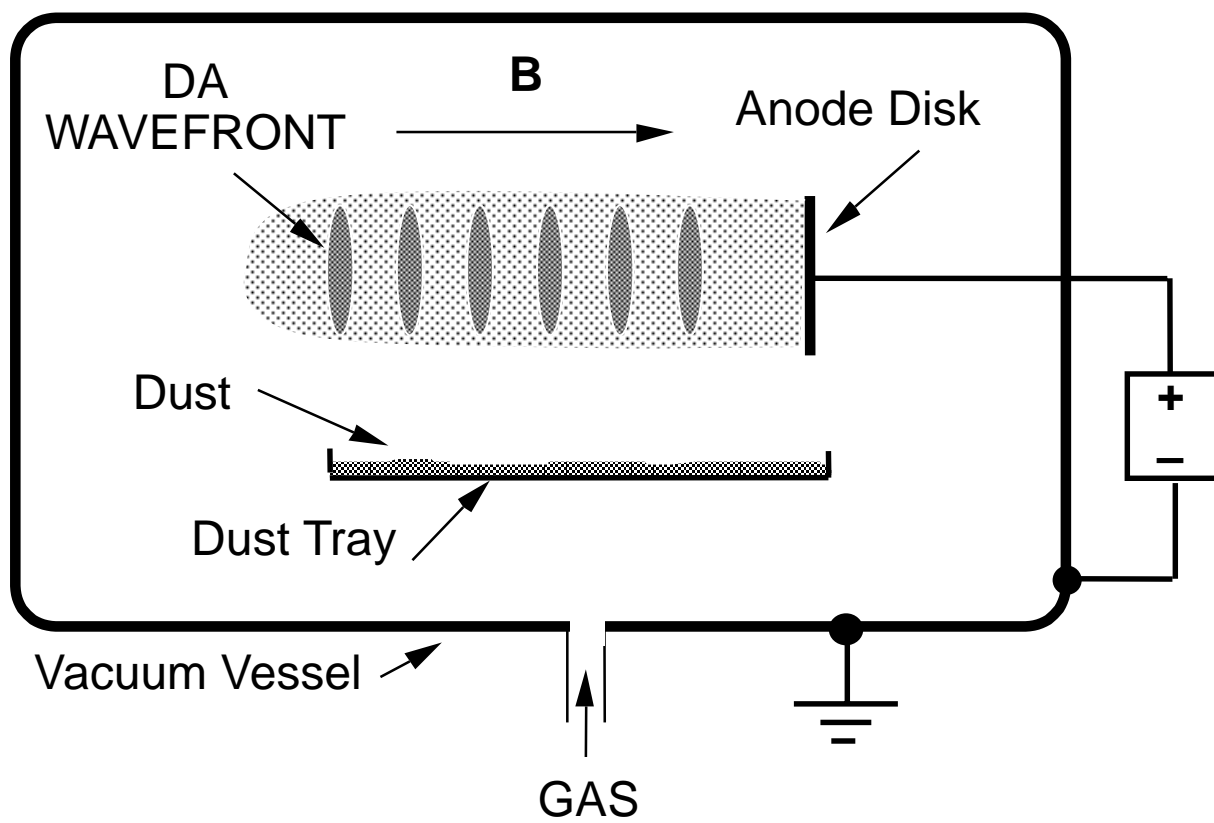


Fig. 4a

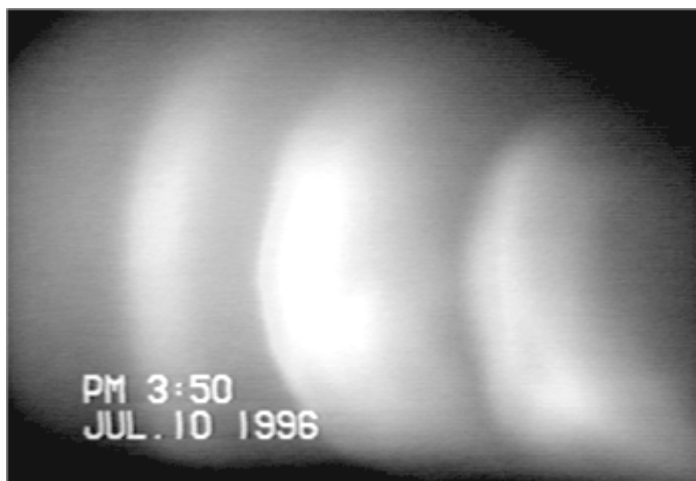


Fig. 4b

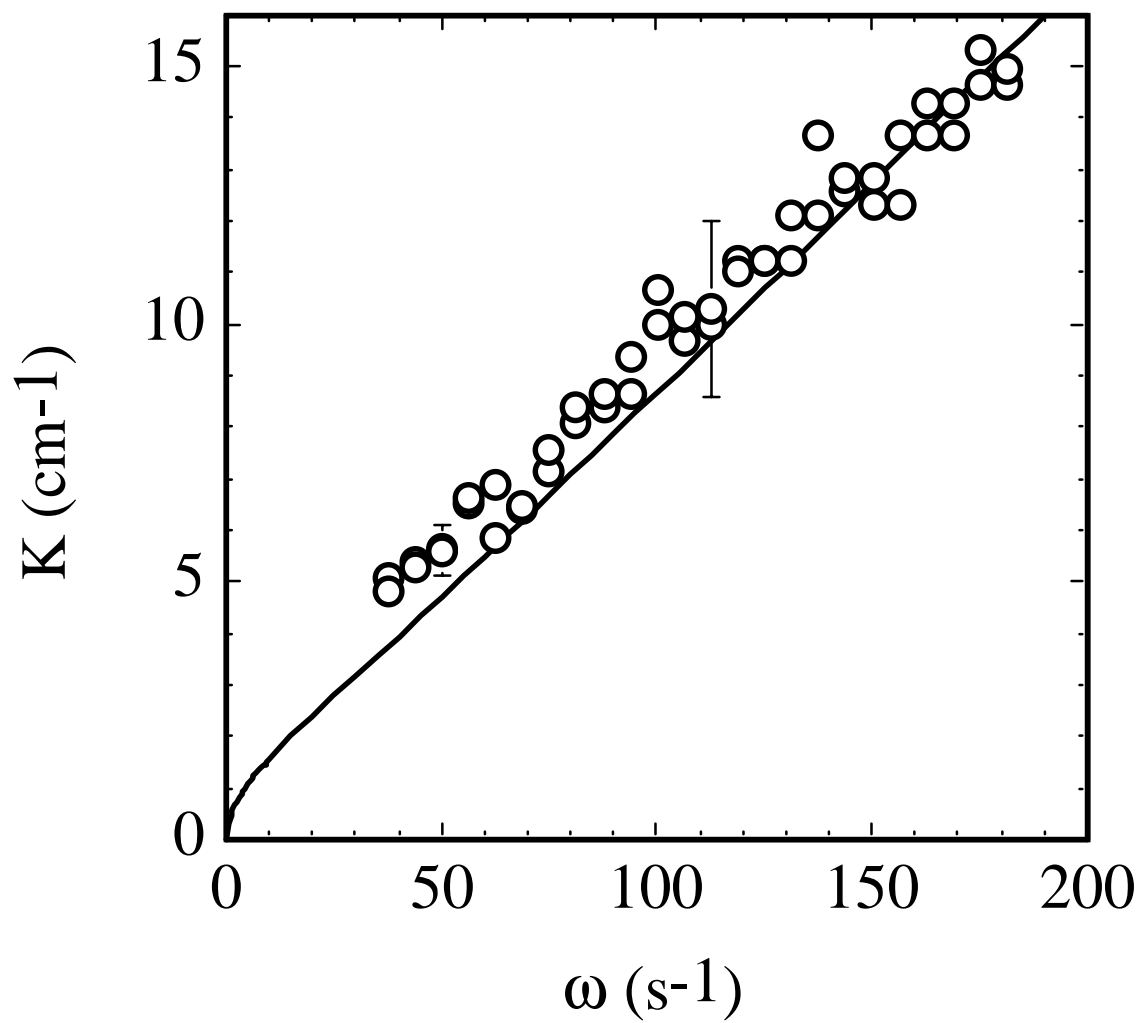


Fig. 5

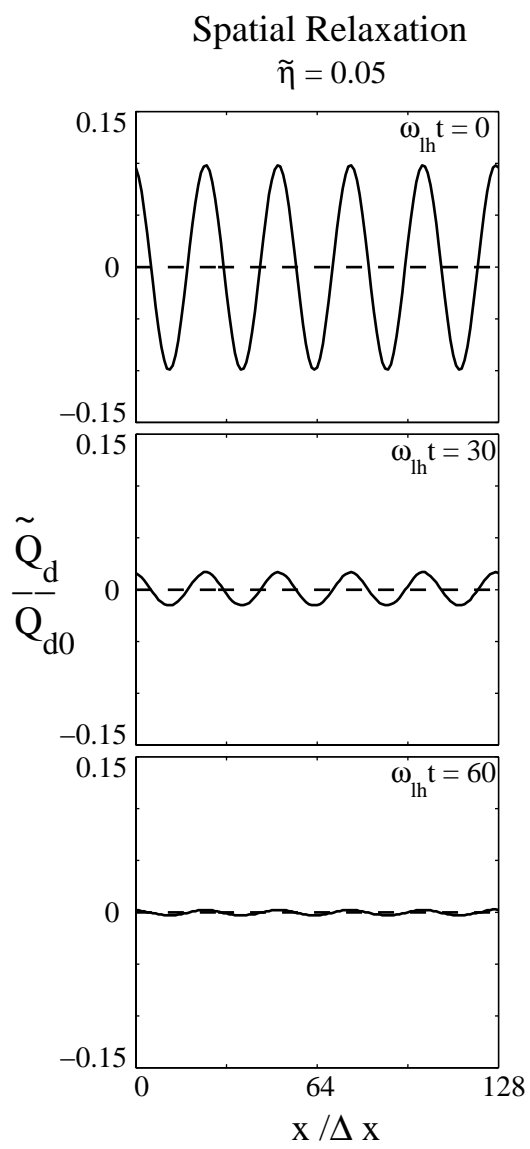


Fig.6

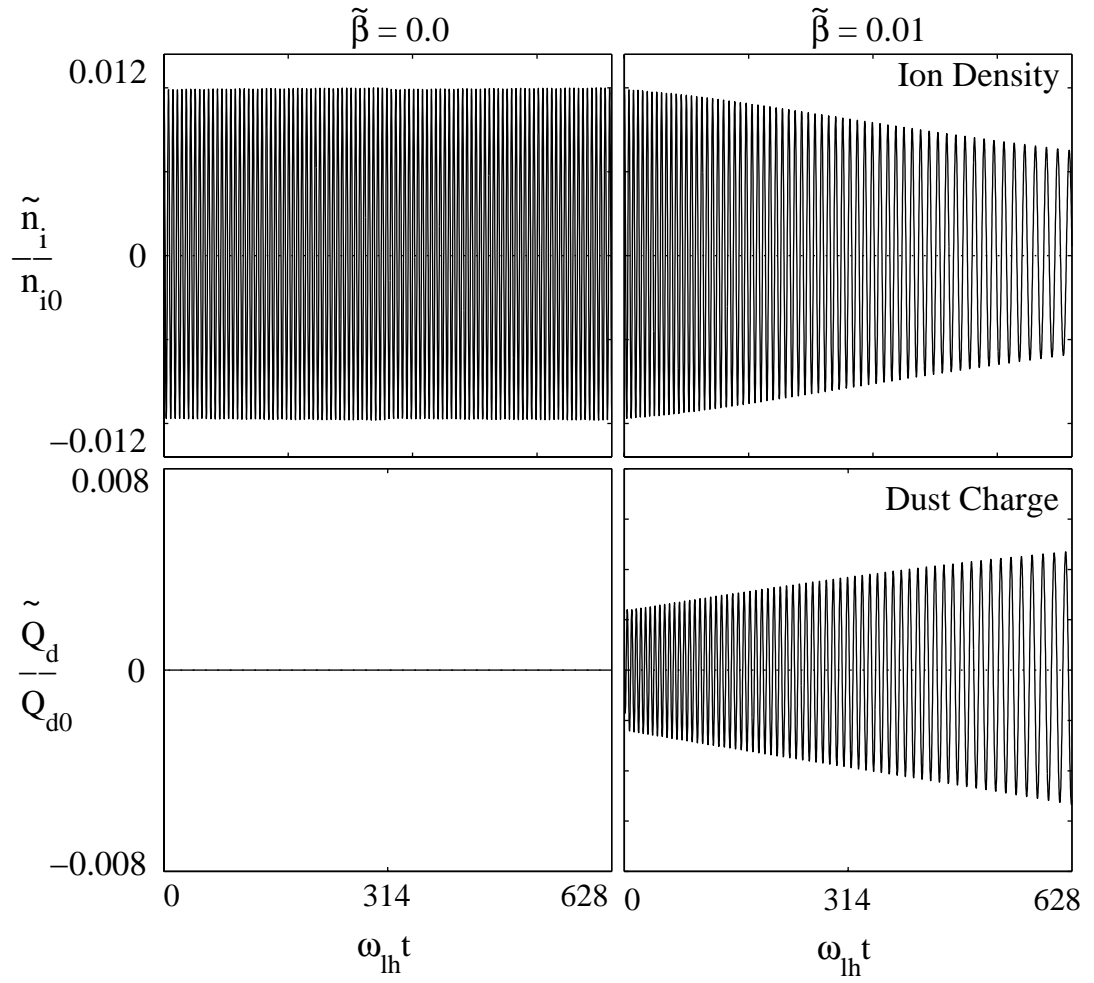


Fig. 7

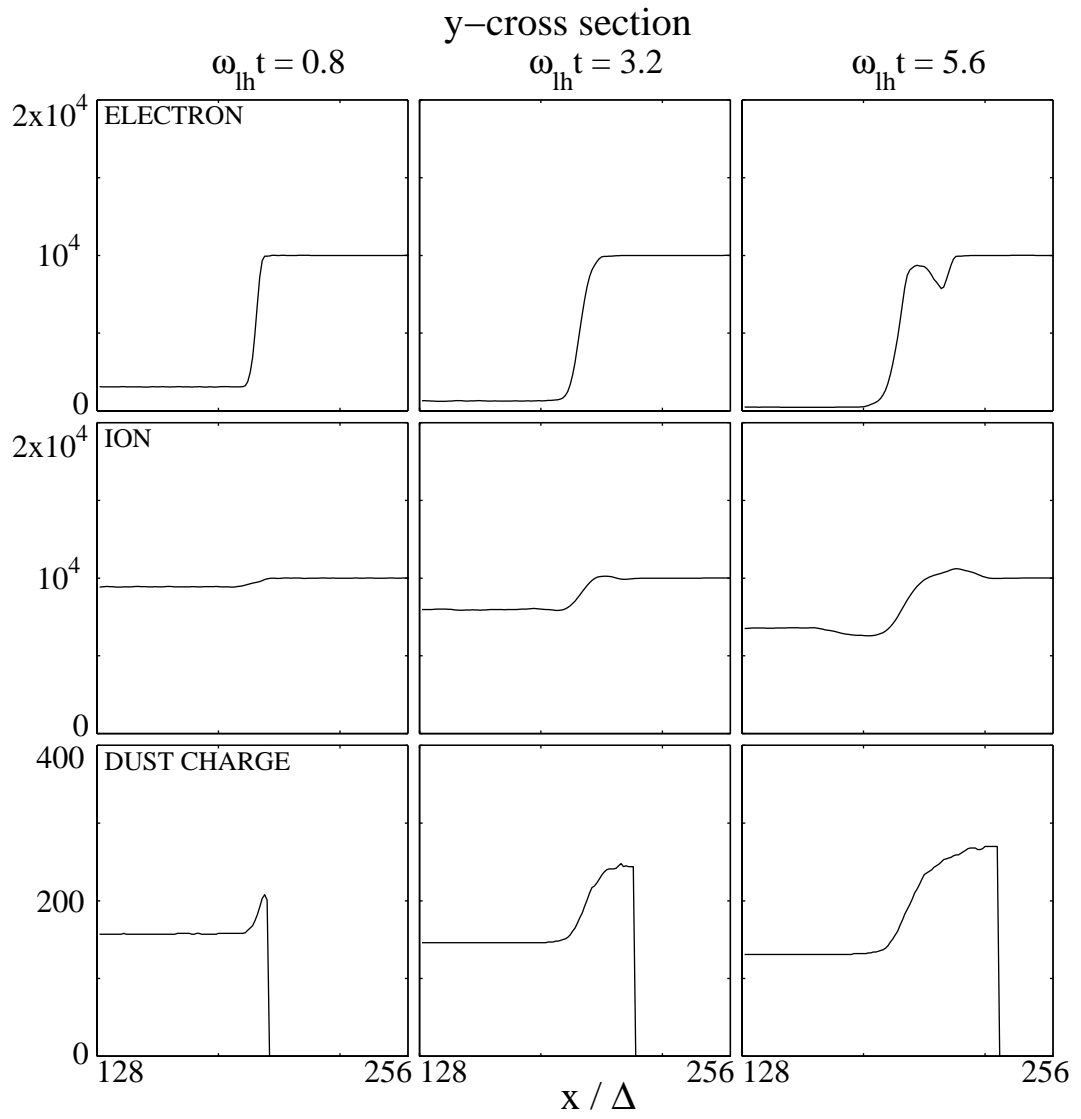


Fig. 8

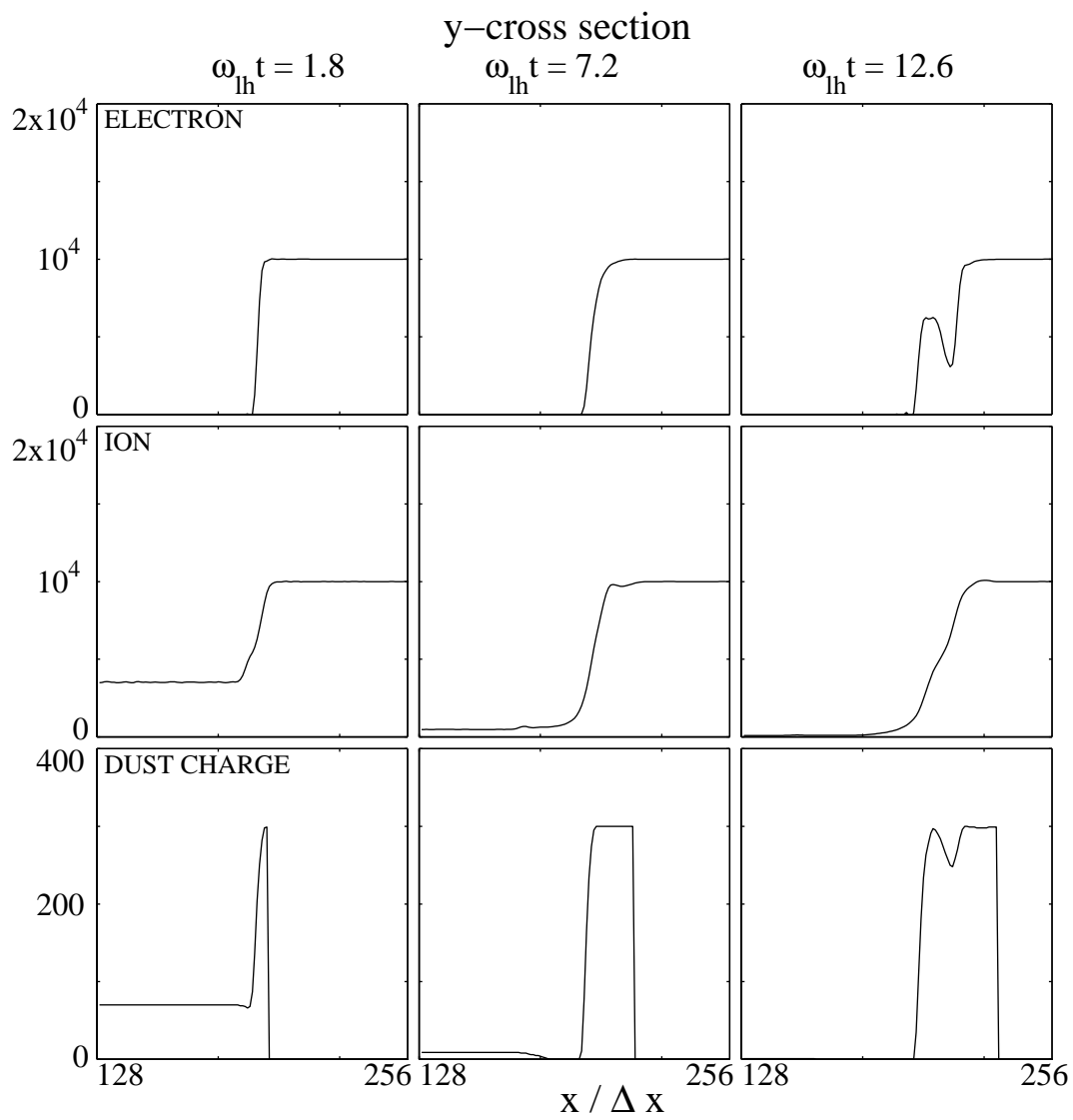


Fig. 9

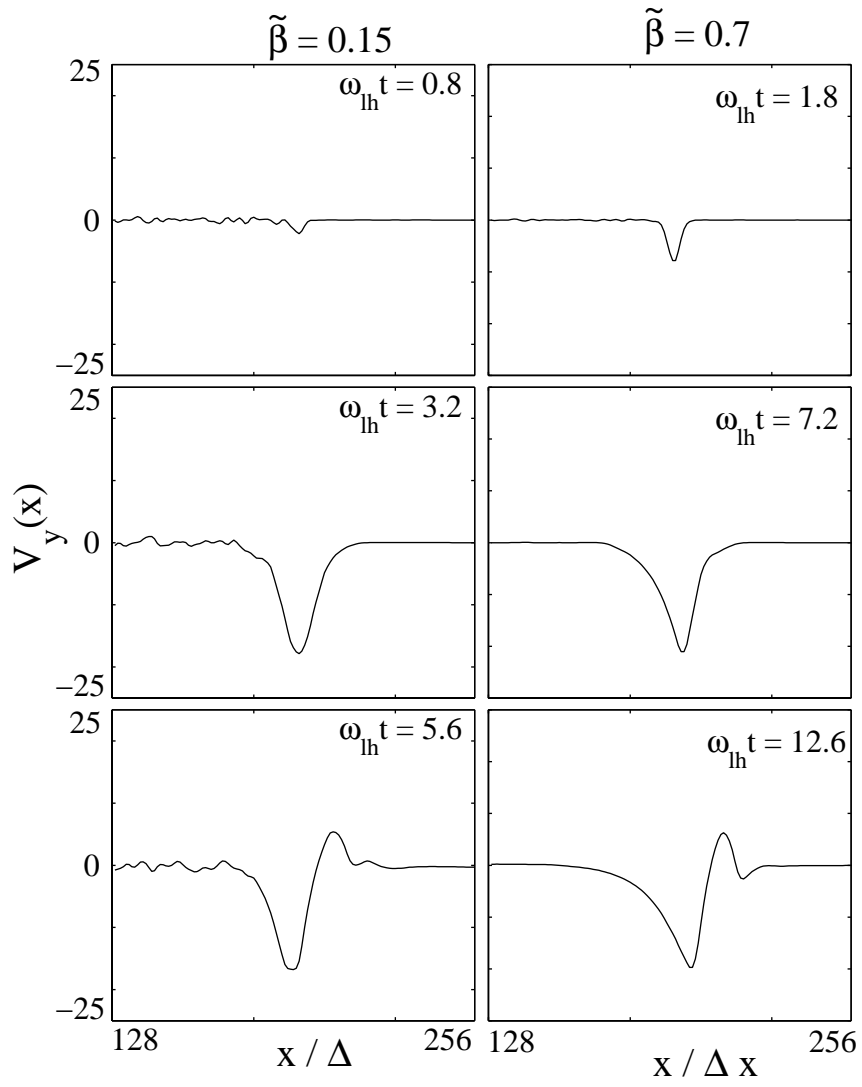


Fig. 10

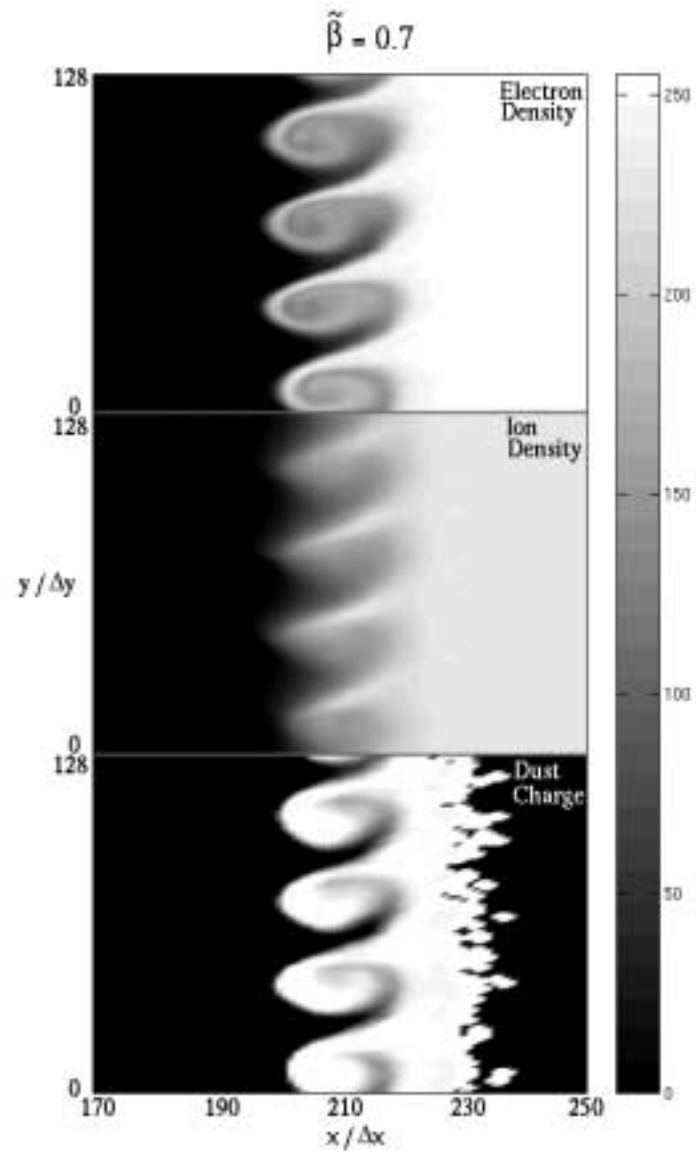


Fig. 11

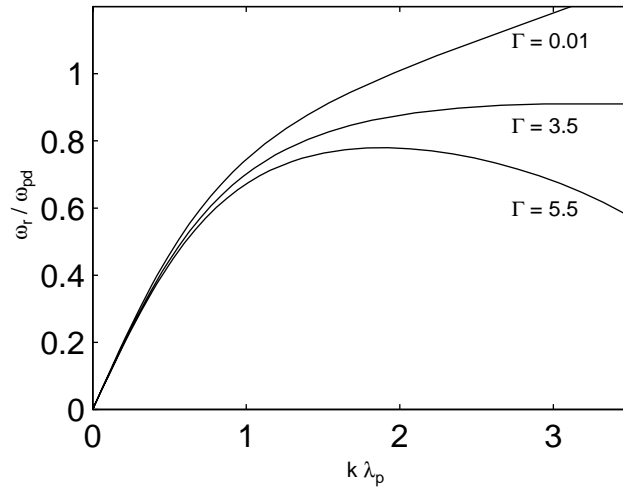


Fig. 12