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Experiments on waves and instabilities in dusty plasmas

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Abstract. Laboratory experiments on waves in dusty plasmas performed at the University of Iowa are described. All of the experiments deal with low-frequency electrostatic waves and include studies of (i) electrostatic dust ion cyclotron (EDIC) waves, (ii) dust ion acoustic (DIA) waves and (iii) dust acoustic (DA) waves.

1. Introduction

Ionized gases containing small dust particles are a common occurrence in many astrophysical and geophysical environments such as planetary rings, comets, the interstellar medium, noctilucent clouds and rocket exhausts, for example, [1, 2]. In the laboratory, dust is an unwanted constituent of the RF processing plasmas used in the manufacture of semiconductor devices [3] and may also be present in fusion devices due to the interaction of the plasma with limiters. Dust can also be introduced into plasmas deliberately using dust dispersal devices [4, 5] to allow basic experiments to be performed. In typical laboratory plasmas the dust grains acquire a negative charge due to the dominant collection of the more mobile electrons. A typical isolated 1 μm dust grain in a plasma will have a mass corresponding to $\approx 10^{12}$ proton masses and a charge of a few thousand electrons [6].

The presence of this additional highly charged and massive species in the plasma can modify the properties of the usual plasma wave modes and can also give rise to new very low-frequency modes that are more specifically 'dust modes' since they involve the dynamics of the dust grains themselves. Recently, there has been a flurry of theoretical work on waves in dusty plasmas. Since it would be impossible to properly review all of this work, only some of the theoretical results relevant to our laboratory studies will be mentioned. For a more comprehensive summary the reader is referred to two recent review papers [7, 8].

The 'dust acoustic' (DA) mode was first studied by Rao *et al* [9] and subsequently by several others [10–14]. This mode is a long-wavelength, low-frequency collective oscillation in an unmagnetized dusty plasma in which the electron and ion pressures provide the tension with the inertia provided by the massive and negatively charged dust grains. The frequency range for this mode is given by $K v_{\mathrm{th,d}} \ll \omega \ll K v_{\mathrm{th,i}}$, where ω and K are the wave angular frequency and wavenumber and $v_{\mathrm{th,d}}$ and $v_{\mathrm{th,i}}$ are the thermal speeds of the dust and ions. Rosenberg showed that a dust acoustic instability could be excited by ions drifting relative to the dust grains with drift speeds even below the ion thermal speed [11]. A current-driven resistive dust acoustic instability in a weakly ionized dusty plasma has also been analysed [15, 16].

'Dust ion acoustic' (DIA) waves are ordinary ion acoustic waves modified by the presence of charged static dust [10, 17]. The DIA waves occur in the frequency range $K v_{\mathrm{th,i}} \ll \omega \ll K v_{\mathrm{th,e}}$. The phase velocity of the dust acoustic wave is higher than the usual

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ion acoustic waves in an electron–ion plasma since the attachment of electrons to the dust grains results in a depletion of the electron density. The increased phase velocity results in a reduction in the strength of the Landau damping. Instability of the DIA waves by a drift of the electrons relative to the ions was studied by Rosenberg [11].

The fluid dispersion relation for low-frequency electrostatic waves in a magnetized dusty plasma was derived by D'Angelo [10]. Four wave modes were found: the DA mode and the DIA mode that have already been discussed and which exist even in the absence of a magnetic field and two electrostatic ion cyclotron (EIC) modes. One of the EIC modes, the electrostatic dust ion cyclotron (EDIC) mode, corresponds to the usual EIC wave in an electron–ion plasma but is modified by the presence of the negatively charged, but static, dust. The other EIC mode is a completely new electrostatic dust cyclotron (EDC) mode which is associated with the gyromotion of the magnetized dust grains. The kinetic theory of the EDIC mode was derived by Chow and Rosenberg [18, 19], who computed the minimum magnetic field aligned electron drift required to excite the instability.

In section 2 we describe the dusty plasma device (DPD) which was used to produce a magnetized plasma into which dust particles were dispersed. This DPD was used to study the effects of dust on the EIC instability (EDIC) and on ion acoustic waves (DIA). These waves are relatively high-frequency waves which do not involve dust dynamics, the effect of the charged dust being simply to alter the charge neutrality condition. The results of the investigations of the EDIC and DIA waves are then presented in sections 3 and 4. Since DA waves involve dust dynamics, the observation of these waves requires that the dust grains be confined in the plasma for times which are long compared with the wave period. A glow discharge device used to trap and confine dust grains and produce DA waves is described in section 5. Final remarks and conclusions appear in section 6.

2. The dusty plasma device (DPD)

The dusty plasma device is basically a single-ended *Q* machine modified to allow the dispersal of dust grains over a portion of the cylindrical plasma column. Details on the construction and operation of this device can be found elsewhere [5, 6]. A schematic diagram of the DPD is shown in figure 1. A singly ionized potassium plasma is produced by contact ionization of atomic potassium on a hot tantalum plate (temperature ≈ 2200 K) which is also the thermionic electron source. The plasma is confined radially by a longitudinal magnetic field with a strength of up to about 0.35 T. The electrons and ions are in thermodynamic equilibrium with the hot plate and thus have temperatures $T_e \approx T_i \approx 0.2$ eV. The plasma density can be varied over a wide range from $\sim 10^5$ cm^{-3} up to $\sim 10^{10}$ cm^{-3}. The plasma column diameter is 4 cm with a length of 80 cm. Dust grains can be dispersed over a 30 cm long portion of the plasma column using the rotating dust chamber (drum) also shown in figure 1. This dust dispenser consists of a rotating metal cylinder and a stationary mesh. Kaolin (aluminium silicate) powder which is initially loaded into the bottom of the drum is carried to the top of the mesh by the rotating cylinder. The dust particles that are deposited on the top of the mesh are gently sifted through the mesh which is continuously vibrated by a series of stiff metal bristles that rotate with the cylinder and scrape over the surface of the mesh. This action allows a continuous 'rain of dust' to fall through the plasma column as the cylinder is rotated. The dust is then collected at the bottom of the drum where it is recirculated. The kaolin powder consists of irregularly shaped grains of various sizes ranging from a fraction of a micron to tens of microns. Analysed samples of the dust indicate an 'average grain size' of the order of a few microns. This device produces a reasonably uniform dust cloud with a variable (depending on the drum rotation

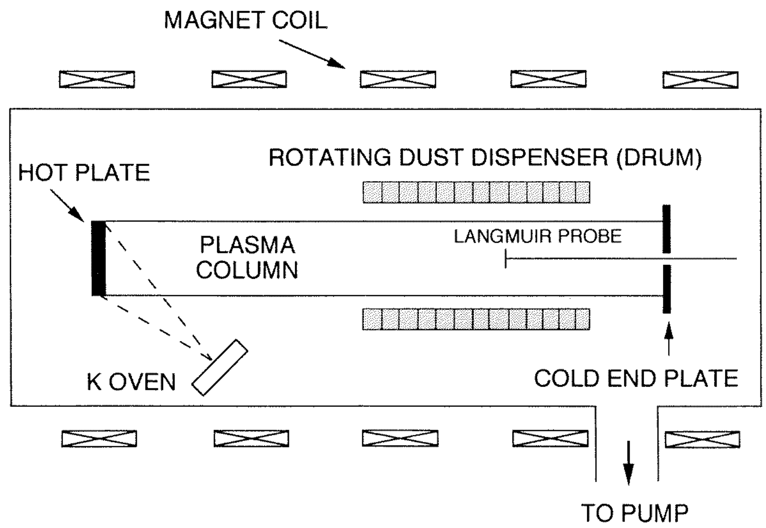

Figure 1. Schematic drawing of the dusty plasma device (DPD) consisting of a Q machine and rotating drum dust dispenser.

rate) density (inferred from *in situ* collected samples and plasma attenuation measurements) up to about 5×10^5 cm^{-3}. The dust grains acquire a negative charge due to the preferential attachment of electrons. Thus, when the dust is present the ion density exceeds the electron density with the balance of negative charge on the dust grains so that charge neutrality is maintained, i.e. $n_i = n_e + Zn_d$, where $Z = q_d/e$, q_d being the dust charge and n_i, n_e and n_d the electron, ion and dust densities. An important parameter characterizing a dusty plasma is then $\eta \equiv n_e/n_i$ ($\leqslant 1$). η can be determined from Langmuir probe measurements of the reduction in the electron saturation current that occurs when dust is present as compared with the 'no-dust' value [20]. This η parameter is also related, through the condition of charge neutrality, to the parameter $\varepsilon \equiv n_d/n_i$, by $1 - \eta = \varepsilon Z$, where the quantity εZ is then the fraction of negative charge per unit volume on dust grains.

3. Current-driven electrostatic dust ion cyclotron (EDIC) waves [20]

We began our investigations of waves in dusty plasmas by studying the effects of negatively charged dust on the EIC mode. This was a logical starting point since this particular mode is one of the easiest modes to excite in a Q machine. One simply needs to insert an electrode disc into the plasma with its surface perpendicular to the magnetic field lines and bias it to collect electrons. Usually a Langmuir probe with a disc electrode of diameter comparable to several ion gyroradii will work quite well. The diameter must be less than the diameter of the plasma column, however, so that a well defined current channel is formed *within* the plasma. Under these conditions large-amplitude electrostatic waves are excited which propagate radially outward from the current channel with a wavevector that is nearly perpendicular to the B field and with a frequency slightly above the ion gyrofrequency. Theoretical work on EIC waves in dusty plasmas by D'Angelo [10] and Chow and Rosenberg [18] predicted that the presence of a substantial amount of negatively charged dust would make the plasma more unstable to the EIC instability, lowering the critical drift of the electrons along the magnetic field lines. This prediction was tested in the DPD by measuring the EIC wave

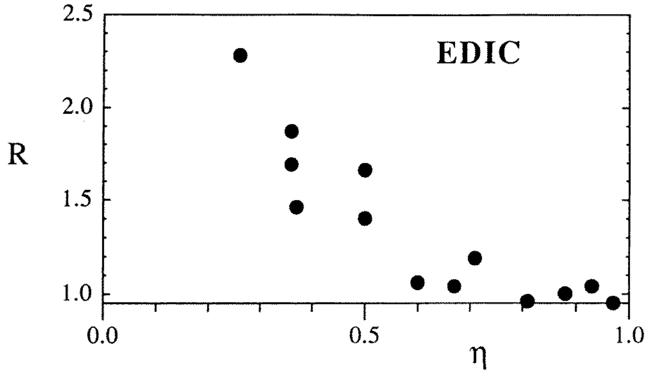

Figure 2. The ratio $R = A_d/A_{nd}$ of the EDIC amplitudes with and without dust as a function of $\eta = n_e/n_i$. As η decreases the fraction of the total negative charge which is on the dust increases.

amplitude with dust present and in the absence of dust, as a function of the parameter η. The EIC waves in the presence of negatively charged dust are termed electrostatic dust ion cyclotron (EDIC) waves.

The experimental set-up used was the same as that shown in figure 1, except that near the end of the cloud away from the hot plate an 'exciter disc' (5 mm diameter) was located on the axis of the plasma column. When this disc was biased at some 0.5–5 V above the space potential, to draw an electron current, the EIC instability was excited. The amplitude of the wave (with no dust present), A_{nd}, was recorded, and without introducing any other changes in the plasma conditions, the dust dispenser was turned on, producing a dusty plasma whose η parameter was measured. The EDIC wave amplitude (with dust present), A_d, was then measured. The ratio $R = A_d/A_{nd}$ could then be used as an indicator of any differences produced by the dust. The measured R versus η points are shown in figure 2. Recall that $\eta = 1$ corresponds to the condition of no charged dust, while $\eta = 0$ corresponds to the case where all the electrons are attached to dust grains. Evidently for η larger than about 0.7 very little effect is observed. However, as η decreases from about 0.7 down to about 0.25, the amplitude ratio R increases by as much as a factor of two. The tentative conclusion was that the presence of the negatively charged dust made the EIC mode more unstable. It was even possible to bias the disc at a voltage so that, in the absence of dust, no waves were excited, and then by simply turning on the dust dispenser the EDIC waves would appear. Recently, Chow and Rosenberg [19] performed a numerical kinetic analysis of the EDIC instability to predict the critical electron drift required to drive the instability. Using parameters corresponding to our experiments, they found that the linear growth rate should increase by a factor of about 2.2 for a roughly threefold decrease in η. Thus both theory and experiment show that as more and more negative charge is carried by dust particles the instability is progressively easier to excite.

4. Dust ion acoustic (DIA) waves [21]

Ion acoustic waves were launched into the dusty plasma by means of a grid that was inserted into the plasma column, perpendicular to the magnetic field and located approximately 3 cm in front of the dust dispenser (on the hot plate side). The grid was biased at several Volts negative with respect to the space potential and a tone burst sinusoidal voltage of about 4–5 V peak-to-peak amplitude and 20–80 kHz frequency was applied to it. This produced a density perturbation near the grid which then travelled down the column, into the region of the dusty plasma as a dust ion acoustic (DIA) wave. By means of an axially movable Langmuir probe, amplitude and phase measurements were performed at various axial locations within the dusty plasma to determine the wave phase velocity, $v_{\rm ph}$, the wavelength, λ, and attenuation length, δ, as a function of the η parameter. The two quantities, $v_{\rm ph}(\eta)/v_{\rm ph}(1)$ and $(\delta/\lambda)_{\rm d}/(\delta/\lambda)_{\rm nd}$, plotted as a function of η, are shown in figures 3(a) and (b). As the value of η decreases and the fraction of negative charge per unit volume of dust increases, the wave phase velocity also increases, while the damping becomes less severe (larger δ/λ). The curves in figure 3(a) were obtained from fluid theory calculations, for three different values of the plasma drift velocity along the magnetic field. The curve in figure 3(b) was obtained from kinetic theory calculations. There is substantial agreement between theory and experiment. The main effect of the negative dust on damping is a reduction of the Landau damping, which is most pronounced at the lowest η values. This reduction in Landau damping is related to the increase in the wave phase velocity as the value of η is reduced.

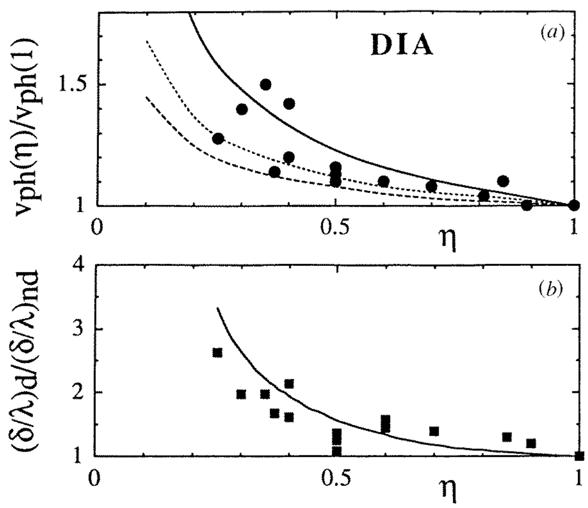

Figure 3. Variation of (a) the normalized DIA wave phase velocity (circles) and (b) normalized spatial damping parameter (squares) with η. The curves in (a) are from fluid theory calculations for three values of the plasma drift along the magnetic field, $v_{\rm drift} = 0, C_{\rm s}$ and $2C_{\rm s}$ (top to bottom) where $C_{\rm s}$ is the ion acoustic speed. The curve in (b) is obtained from Vlasov theory calculations for $v_{\rm d} = 0$.

5. Dust acoustic (DA) waves

In the two dusty wave experiments just discussed, the effect of the dust was mainly to alter the zero- and first-order charge neutrality conditions. The dust grain dynamics did not enter into considerations for either the EDIC or DIA waves. The DPD, however, is not suitable for studies of waves and instabilities in which the dust dynamics plays an essential role since the lifetime of a dust grain falling through the plasma column is ~ 0.1 s. The observation of the very low-frequency dust acoustic mode requires that the grains be confined within

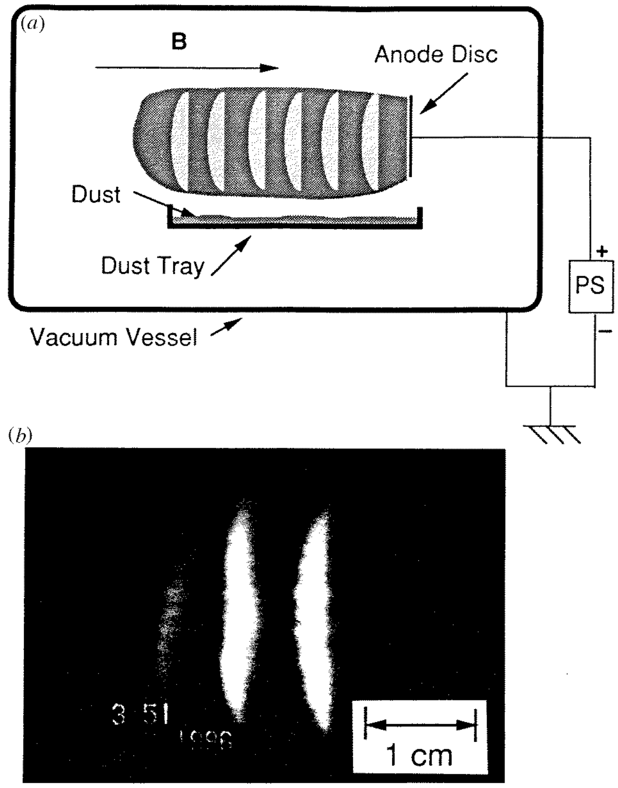

Figure 4. (*a*) Schematic drawing of the DC glow discharge device used to trap dust and observe DA waves. Six schematic wave crests are shown in the dusty plasma. (*b*) Single-frame image of a dust acoustic wave with a wavelength of $\approx$ 6–7 mm.

the plasma for much longer times, presumably levitated in some manner. Previously this was accomplished using a modified version of the DPD in which a double layer was formed near the end of the plasma column. Negatively charged dust grains were trapped in the high potential region of the double layer and DA waves were spontaneously excited within the confined dust cloud [22]. We discovered, however, that the DA waves could also be studied in a much simpler configuration that is shown schematically in figure 4(*a*). A DC glow discharge was formed between a positively biased (400–500 V) cold anode disc (32 mm diameter) and the grounded walls of a vacuum chamber (60 cm diameter and 90 cm long) that was filled with static (no-flow) N_2 gas at a pressure of ≈ 100 mTorr. The discharge current was limited to ≈ 25 mA corresponding to a plasma density of $\approx 10^8$ cm^{-3}. The plasma potential in the glow discharge was ~ 50–80 V positive with respect to the grounded walls. An electrically floating stainless steel tray (25 cm $\times$ 15 cm) was located about 3 cm below the anode disc and about 25 g of kaolin dust was spread over its surface. When the discharge was initiated, some of the dust on the tray was attracted into the glow discharge and trapped as a cloud of fine particles. The dust cloud could be observed visually and recorded on videotape by either forward scattered light or 90° scattered light from a projection lamp.

Dust acoustic waves appeared spontaneously when the dust cloud was formed. A single-frame image of a typical DA wave is shown in figure 4(*b*). Three wave cycles are

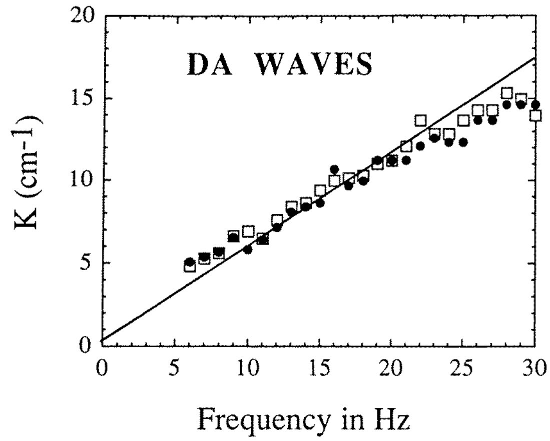

Figure 5. Dispersion plot, K versus frequency of DA waves produced by applying a sinusoidal modulation voltage to the anode disc. The full circles and open squares correspond to two separate experimental runs but under otherwise identical conditions.

clearly seen as bright vertical wavefronts due to the enhanced light scattering from the compressive phase of the DA wave. The spontaneously produced waves have a wavelength of ≈ 6 mm and propagate away from the anode disc with a phase velocity $v_{ph} \approx 12$ cm s^{-1}, as determined by measuring the position of the wavefronts over successive video frames (1/30 s intervals). This corresponds to a frequency, $f = v_{ph}/\lambda$ of 20 Hz.

By applying a sinusoidal voltage modulation of sufficient amplitude to the anode disc (in addition to the DC bias) it was possible to *drive* DA waves at frequencies in the range 6–60 Hz. For each driving frequency the wavelength was measured and the dispersion relation, wavenumber K versus f, was mapped out, as shown in figure 5. For frequencies below about 30 Hz the DA waves exhibit a linear K versus f relationship with a phase velocity $v_{ph} \approx 12$ cm s^{-1}. For our situation with $T_i \ll T_e$, the dispersion relation [14] in the long-wavelength ($K\lambda_D \ll 1$) limit can be expressed simply as $v_{ph} = \omega/K \approx [kT_i\varepsilon Z^2/m_d]^{1/2}$. For 1 μm dust grains, the dust mass and charge are $m_d \approx 6 \times 10^{-15}$ kg and $Z \approx 2500$. Using $\varepsilon Z \approx 0.9$ and $T_i \approx 0.1$ eV, we obtain $v_{ph} \approx 8$ cm s^{-1}. For 0.5 μm dust grains the corresponding mass and charge are $m_d \approx 1 \times 10^{-15}$ kg and $Z \approx 1500$, giving $v_{ph} \approx 15$ cm s^{-1}. These estimates are in good agreement with the measured phase velocity. We note that with $\varepsilon Z \approx 0.9$ and $Z \approx 2500, \varepsilon \approx 3.6 \times 10^{-4}$ so that with a plasma density of $\approx 10^8$ cm^{-3} the dust density $n_{do} \approx 3.6 \times 10^4$ cm^{-3}. For frequencies above about 30 Hz the K versus f plot exhibits a turnover (K beginning to decrease with increasing f). This behaviour is expected to occur for frequencies near f_{pd}, the dust plasma frequency. For 1 μm dust grains f_{pd} has a value of ≈ 50 Hz. A more complete analysis should also take into account damping of the DA waves due to dust–neutral interactions. Experimentally we find that the waves suffer little attenuation as they propagate away from the disc, presumably indicating that the strength of the excitation mechanism dominates any wave damping effects.

Trapping of dust and observations of dust acoustic waves in a *hot* cathode discharge have also been reported [23].

6. Summary and conclusions

Three types of waves in dusty plasmas have been investigated experimentally: electrostatic dust ion cyclotron (EDIC) waves, dust ion acoustic (DIA) waves and dust acoustic (DA) waves. The EDIC and DIA waves are examples of how a negatively charged dust modifies the behaviour of normal plasma modes even though the dust grains do not participate in the wave motion. In the DA mode, however, the dust grain dynamics plays an essential role with the dust behaving as a true charged particle plasma species.

It is important to note that for negatively charged dust grains, the results presented here are very similar to those obtained for plasmas containing positive ions, electrons and negative ions, apart from effects related to the difference in charge and mass of the dust. For example, the DIA and DA modes discussed here are similar to the ion acoustic modes in the presence of negative ions, which were examined theoretically by D'Angelo *et al* [24] and studied in the laboratory by Wong *et al* [25]. The EDIC modes are analogous to the EIC modes in a negative ion plasma studied by Song *et al* [26] and Sato [27]. Recently, Sato *et al* [28] produced a plasma containing electrons, K^+ positive ions and negative C_{60}^- ions by introducing C_{60} into a Q machine. These heavy negative particles were regarded as dust particles and fast and slow modes of propagation of ion waves were observed [29]. One important difference between negative ion plasmas and dusty plasmas is the fact that the charge on a dust grain may not be constant. This can give rise to entirely new effects [12].

Finally, we note in anticipation that experiments are yet to be performed in which the role of the magnetic field on dust dynamics is important, e.g. magnetic confinement of a charged dust or observation of the electrostatic dust cyclotron (EDC) mode [10]. This requires using very small dust grains so that the gyroradius, ρ_d, of the dust grains is less than the diameter of a typical plasma column; for example, a 0.01 μm dust grain at $T_d = 0.05$ eV in a field of 0.5 T, will have $\rho_d \approx 2$ cm.

Acknowledgment

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