Experiments on Ion and Dust Acoustic Waves

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Abstract. A summary of recent experimental work performed by our group at the University of Iowa on current-driven dust ion acoustic (DIA) and dust acoustic (DA) waves is given. A discussion of relevant theoretical work is also included.

I. INTRODUCTION

Dust grains immersed in typical laboratory plasmas acquire a negative charge due to the predominant attachment of electrons. As a result, the condition of charge neutrality in such a plasma becomes

$$n_+ = n_e + Z_d n_d \tag{1}$$

where n_j ($j = +$, e, d) is the positive ion, electron, and dust density, and $Z_d = q_d/e$ is the ratio of the charge on a dust grain (q_d) to the electronic charge (e). The presence of charged dust in a plasma 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 dynamics. In these cases, the dust grains simply provide an immobile, charge-neutralizing background, and their effect on the wave dispersion relation comes about through the inclusion of Eq. 1 in a fluid analysis. Examples of dust-modified plasma wave modes include the dust ion-acoustic (DIA) mode (1,2) and the electrostatic dust ion-cyclotron (EDIC) mode (1).

If one considers frequencies well below the characteristic frequencies of an electron/ion plasma, the dispersion relation derived from a three fluid (electrons, positive ions and charged dust grains) analysis yields roots corresponding to the so-called "dust" wave modes (1). In these low-frequency modes, the charged dust grains exhibit collective behavior and participate directly in the wave dynamics. Examples of these low frequency electrostatic "dust modes" include the 'dust acoustic' (DA) mode (1,3) and the electrostatic dust cyclotron (EDC) (1) mode. The EDC mode is a dust mode in which the dust grains are magnetized.

In addition to the references cited above, the readers are referred to the paper by Merlino *et al.*, (4) for a more complete discussion of the dispersion relations for the DIA, DA, EDIC, and EDC modes.

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In this paper we summarize the results of two experimental investigations of waves in dusty plasmas. The first investigation deals with current-driven DIA waves - an example of a dust-modified plasma wave mode. The second investigation is concerned with the DA mode - the simplest example of a "dust mode".

II. CURREN-DRIVEN DUST ION-ACOUSTIC WAVES (5)

The dust ion-acoustic mode (DIA) is the usual ion-acoustic mode for an electron/positive ion plasma that is modified by the presence of charged but relatively immobile dust. In the long wavelength limit ($K\lambda_{D,p} << 1$, where K is the wavenumber and $\lambda_{D,p}$ is the plasma Debye length), the dispersion relation for ion-acoustic waves in a plasma with negatively charged dust is

$$\frac{\omega}{K} = \left[\frac{kT_+}{m_i} + \frac{kT_e}{m_i\left(1-\varepsilon Z_d\right)} \right]^{1/2} \equiv C_{S,d} \qquad (2)$$

where ω is the wave angular frequency, T_+ and T_e are the positive ion and electron temperatures, m_i is the positive ion mass and $\varepsilon = n_d/n_i$ is the ratio of the dust density to ion density. The quantity $C_{S,d}$ is the dust-modified ion acoustic speed. We note in Eq. 2 that the DIA wave phase velocity, ω/K, increases with the relative dust concentration, ε. This has important consequences for the excitation of the DIA mode. The higher phase velocity results in a reduction in ion Landau damping, and consequently the critical electron drift needed for excitation of this mode decreases. Vlasov calculations of Rosenberg (6) indicate that for εZ_d (the fraction of negative charge per unit volume on dust grains) ~ 0.8, the critical electron drift is about 0.1 $v_{e,th}$, the electron thermal velocity. (For an electron/ion plasma with $T_e = T_+$ the critical drift ~ $v_{e,th}$.)

The experimental investigation of the current-driven DIA mode was carried out in a single-ended Q machine which included a rotating dust dispenser for introducing kaolin gust grains (micron size range) into a potassium plasma. The plasma conditions were: $T_e \approx T_+ \approx 0.2$ eV, with the plasma density in the range of 10^6 to 10^7 cm^{-3}. The parameter εZ_d appearing in Eq. 2 was determined from Langmuir probe measurements, and could be varied from 0 up to about 0.9 by changing the rotation rate of the dust dispenser.

The experiments were carried out by terminating the plasma column (4 cm diameter) with a cold endplate that was biased at about 20 V (well above the space potential) to draw an electron current along the magnetic field (< 0.4 T) of the device. In the absence of dust, this configuration led to the excitation of the potential relaxation (PRI) instability, as observed in similar devices. However, when a sufficient amount of dust was introduced into the plasma (εZ_d ~ 0.2) the PRI was quenched and plasma oscillations with frequencies in the range of 3 to 5 kHz (depending on the value of εZ_d)

were observed. The oscillation frequency was measured at various values of εZ_d. The observed increase in frequency with εZ_d matched very closely the expected dependence based on Eq. 2, supporting our identification of the observed oscillations as current-driven DIA waves.

III. DUST-ACOUSTIC WAVES (7,8)

Dust-acoustic waves are low frequency acoustic-like (compressional) oscillations in in a dusty plasma (3,9). For this "dust wave" the inertia is provided by the massive dust grains and the restoring force provided by the electron and ion presures. In the long wavelength regime ($K\lambda_{D,d} << 1$, where $\lambda_{D,d}$ is the dust Debye length) the dispersion relation is

$$\frac{\omega}{K} = \left[\frac{kT_d}{m_d} + \varepsilon Z_d^2 \frac{kT_+}{m_d} \frac{1}{1 + (T_+ / T_e)(1 - \varepsilon Z_d)} \right]^{1/2} \equiv C_{DA} \qquad (3)$$

where T_d is the temperature of the dust and m_d is the mass of a dust grain. C_{DA} is known as the dust-acoustic velocity. The phase velocity of this mode varies as $(m_d)^{-1/2}$, which for typical laboratory dusty plasmas results in values of the phase velocity ~ several cm/s, and corresponding frequencies ~ several Hz.

In order to observe this mode in the laboratory it was necessary to confine (levitate) the dust grains for times on the order of at least several wave periods. A DC glow discharge plasma proved to be suitable for both attracting dust grains into the plasma and confining them. The glow discharge was formed by applying a positive potential (200 – 300 V) to a 3 cm diameter disk electrode located in the center of a large, grounded vacuum vessel filled with nitrogen gas at a pressure ≈ 100 mtorr. Dust grains from a tray located below the anode were attracted into the plasma and trapped in this positive potential region. Using light scattered from a high intensity source, the dust cloud could be observed visually and recorded with a video camera.

For sufficiently large discharge currents, DA waves were excited spontaneously in the dusty plasma. They were observed as a series of bright and dark vertical bands (compressions and rarefactions) propagating away from the anode. The waves were recorded on VCR tape and from an analysis of single frame images the phase velocity and wavelength were determined to be $v_{ph} \approx 12$ cm/s and $\lambda \approx 0.6$ cm, so that the wave frequency $f = v_{ph}/\lambda \approx 20$ Hz. (A quicktime movie of these DA waves is available on our website at the URL: http://www.physics.uiowa.edu/xplasma/.) The measured phase velocity is in agreement with that obtained from Eq. 3 (see ref. 8 for details).

The excitation of the DA waves is probably due to a positive ion/dust streaming instability (6,10,11). Langmuir probe measurements within the glow discharge indicated an axial electric field on the order of several V/cm pointing in the direction away from the anode. This electric field would cause positive ions to drift away from the anode. The connection between the DA wave excitation and ion streaming was supported by an additional observation that the waves were quenched if the discharge current was decreased below about 1 mA. Langmuir probe potential measurements indicated that as the discharge current was reduced there was also a reduction in the axial electric field. A fluid theory of a current-driven DA instability in a collisional dusty plasma (11) which included an equilibrium electric field E_o, predicted instability, for our experimental comditions, for E_o's > 1 V/cm, in reasonable agreement with the obervations.

The quenching of the DA waves by lowering the discharge current was accompanied by another interesting phenomenon . When the DA waves were present the dust cloud appeared to be in a gas-like phase. Under these conditions, individual dust grains could not usually be resolved with the video camera, probably indicating that the grains were moving rapidly. However, as the current was lowered, the wave amplitude decreased and individual dust grains could be seen. When the current was lowered below the DA instability threshold, the dust cloud rapidly (over a period of a few seconds) settled into a relatively quiescent and ordered phase in which the grains appeared to be locked into a three-dimensional structure. It may be possible that in the gas-like phase the dust grains are energized by the DA waves which inhibits the formation of a more ordered state.

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