LETTERS

Laboratory observation of the dust-acoustic wave mode

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A laboratory observation of the dust-acoustic instability is reported. The results are compared with available theories. © *1995 American Institute of Physics.*

In addition to modifying the properties of plasma wave modes such as the ion-acoustic (IA) or the electrostatic ion cyclotron (EIC), the presence of charged dust grains in a plasma gives rise to new ones that are more specifically dust modes, in the sense that they involve in an essential manner the dust dynamics. The "dust-acoustic" (DA) mode was first considered theoretically by Rao et al.[1] and subsequently by several others.[2–6] The inertia in this mode is provided by charged and massive dust grains that exhibit a slow response to electric fields, thus producing oscillations of very low frequency.

For negatively charged dust, plasmas with electron-to-ion temperature ratios $T_e/T_i \gg 1$ and perturbations with a wavelength large compared with the Debye length ($K^2\lambda_{De}^2 \ll 1$), Eqs. (11) and (12) of Rosenberg[4] which provide the real and imaginary part of the mode frequency, become

$$\omega_r^2 = K^2 C_s^2 Z_d(\delta-1)\,\frac{m_i}{m_d}\,\frac{1}{1+\delta \cdot T_e/T_i} \tag{1}$$

and

$$\frac{\omega_i}{\omega_r} \simeq -\sqrt{\frac{\pi}{8}}\,\sqrt{Z_d(\delta-1)}\,\frac{1}{(1+\delta \cdot T_e/T_i)^{3/2}}\,\delta\left(\frac{m_i}{m_d}\right)^{1/2}$$
$$\times \left(\frac{T_e}{T_i}\right)^{3/2}\left[1-\frac{u_0}{\omega_r/K}\right], \tag{2}$$

where ω_r and ω_i are the real and imaginary parts of the frequency, K is the wave number, $C_s \approx (\kappa T_e/m_i)^{1/2}$ the ion-acoustic speed, Z_d (>0) the average[7] negative charge of the dust grains in terms of the electron charge, $\delta = n_i/n_e$ (>1) the ratio between the ion and the electron densities, m_i and m_d the ion and dust grain masses, respectively, and u_0 the drift velocity of the ions relative to the dust grains. A dust (Landau) damping term which would in general appear in Eq. (2), is negligible for a dust thermal velocity much smaller than the phase velocity of the waves and has been omitted. An electron Landau damping term is also neglected in Eq. (2), under the assumption that $\delta(m_i/m_d)^{1/2}(T_e/T_i)^{3/2} \gg (m_e/m_i)^{1/2}$.

We have observed very low frequency waves in a dusty plasma using the experimental setup shown schematically in Fig. 1. The potassium plasma column of a Q machine[8] is surrounded over its end portion (~30 cm in length) by a rotating dust dispenser that continually recycles hydrated aluminum silicate (kaolin) dust through the plasma (see Xu et al.,[9] for further details). Approximately 90% of the grains had sizes in the 1–15 μm range with an average grain size ~5 μm. The lifetime of a dust grain in the plasma column is the time it takes the grain to fall through it in any single passage, which is ~0.1 s. Dust-acoustic waves with periods comparable to or longer than 0.1 s could not evidently be studied in this device without a suitable modification, which allows the negatively charged dust grains to be "trapped" for much longer times. What this modification consists of is indicated in Fig. 1 and is described in detail by Barkan and Merlino.[10] A neutral gas (generally nitrogen) at pressures of 60–80 mTorr is introduced into the device, while an end electrode consisting of a metallic disk of 1.6 cm diameter is biased at ~+200 V. This produces a cylindrical double-layer ("firerod") within which the space potential is some 50–60 V above the space potential of the surrounding (K^+-electron) plasma. Thus, negatively charged dust grains can be indefinitely trapped within the firerod, provided their mass is not too large. Not only at the edges of the firerod but also within it an electric field exists that, on axis, is directed away from the disk electrode and has an average magnitude of $E \sim 1$ V/cm.

Under these conditions, a propagating wave is observed through a side port, within the dust-loaded firerod. The wave appears as soon as the kaolin dust is introduced into the firerod. The observations were facilitated by shining through the wave pattern a He–Ne laser beam, but often it was sufficient to use a simple flashlight and a video camera. A typical wave pattern is shown in Fig. 2 with a wavelength λ of ~0.6 cm. From a succession of pictures of this type we were able to measure the speed with which the pattern moved from right to left away from the disk electrode toward the Q-machine hot plate. Figure 3 shows a characteristic plot of the position of some given wave feature versus time of arrival, from which a propagation speed of ~9 cm/s is inferred. With λ≈0.6 cm and a speed of ~9 cm/s, we obtain a frequency of ~15 Hz.

Plasma potential fluctuations of the same frequency could be observed within the "firerod" by using an electri-
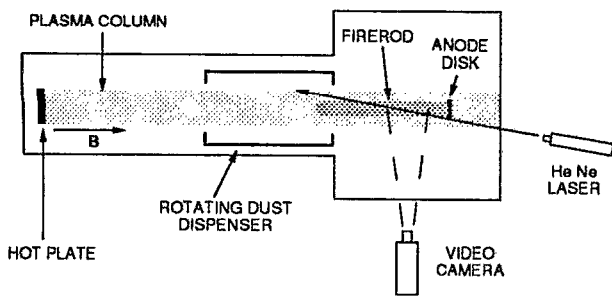
FIG. 1. Top view of the experimental setup. A firerod is produced within the plasma column of a Q machine by biasing at +200 V the anode disk. Negatively charged dust grains are trapped within the firerod, where the dust-acoustic waves are observed.

cally floating Langmuir probe to measure oscillations in the plasma potential. The probe record often indicates a wave of very large amplitude. At times the wave amplitude, $|\Delta n_d/n_d| \approx |e\Delta\phi/\kappa T_+|$, may approach 100%.

The general features of these waves appear to be the same as those of the dust-acoustic waves discussed in recent years in the theoretical papers referred to in the opening paragraph, although the preliminary nature of our present results does not allow us, as yet, to comment on the possible importance of nonlinear phenomena. From the point of view of estimating the wave phase velocity, linear theory appears to be adequate.

For a somewhat closer comparison we note the following. Equation (1) can be cast in the form
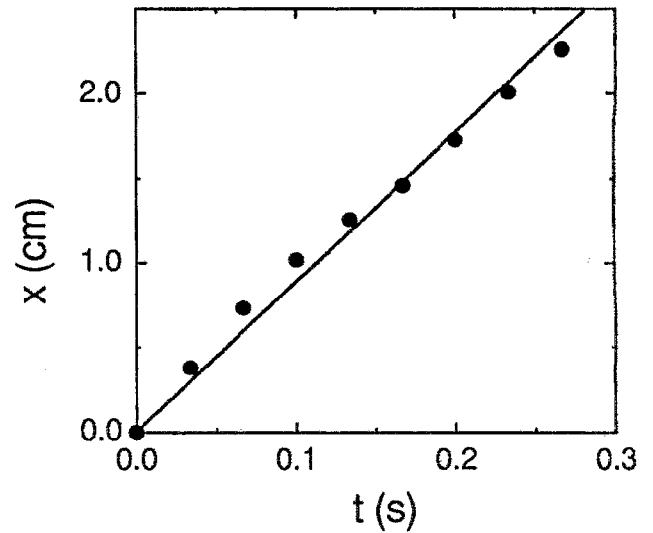

FIG. 3. Position vs time of arrival of a given wave feature. A speed of ~9 cm/s is inferred.

$$\omega^2/K^2 = (\kappa T_i/m_d)\epsilon Z_d^2,$$ where $\epsilon = n_d/n_i$ (see, e.g., D'Angelo[11]). For dust grains of ~5 μm size, $m_d \approx 10^{-12}$ kg, $Z_d \approx 4\times10^4$ and an $\epsilon \approx 10^{-4}$, we obtain a wave speed of ~8 cm/s, in good agreement with the observations.

Equation (2) for ω_i can be simplified, when $\delta \gg 1$, $T_e/T_i \gg 1$ and $u_0 \gg \omega_r/K$, into
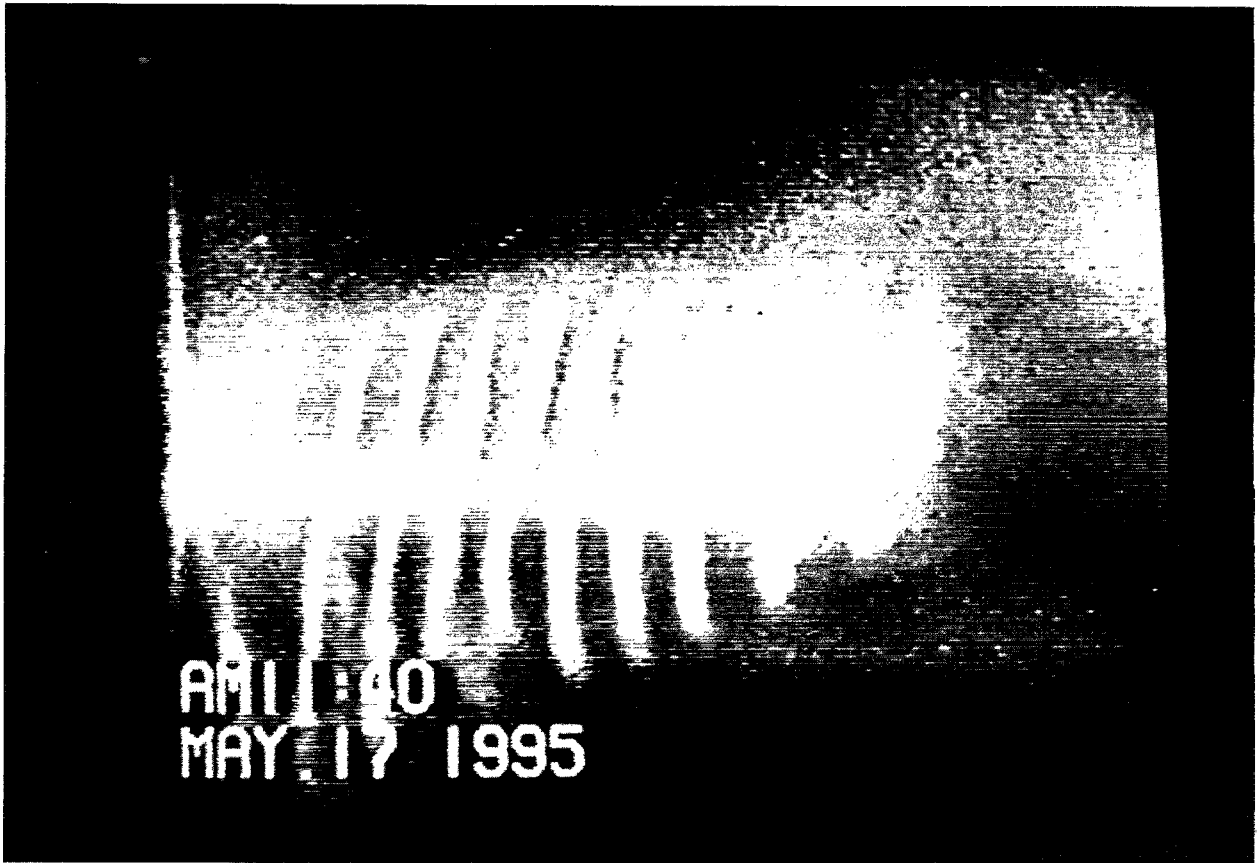

FIG. 2. A typical single-frame image of a dust-acoustic wave pattern recorded on the video camera ($\lambda \approx 0.6$ cm).

$$\frac{\omega_i}{\omega_r} \simeq 0.63 \times \sqrt{Z_d} \times \left(\frac{m_i}{m_d}\right)^{1/2} \frac{u_0}{(\omega_r/K)}. \qquad (2')$$

With our parameters and a $u_0 \sim 2 \times 10^5$ cm/s, Eq. (2') provides $\omega_i/\omega_r \sim 1$. The value $u_0 \sim 2 \times 10^5$ cm/s for the ion velocity is obtained from

$$u_0 = \left(\frac{e}{m_i \nu_{in}}\right) E, \qquad (3)$$

where ν_{in} is the ion-neutral collision frequency, and a mobility of $\sim 20 (m^2/V \cdot s)$ has been used together with $E \sim 1$ V/cm.

This relatively large value of ω_i/ω_r is consistent with the observation of waves of very large amplitude.

We have estimated the strength of the damping mechanism due to variations of the dust grains charge in the presence of the wave,[3,5] using Eq. (20) of Ref. 3. The damping rate is very much smaller than the growth rate given by Eq. (2'), and therefore negligible.

It should finally be noted that low-frequency fluctuations with a typical frequency of ~ 12 Hz and a wavelength of ~ 0.5 cm (thus, with a phase velocity of ~ 6 cm/s) were observed by Chu et al.[12] and later interpreted by D'Angelo[11] as dust-acoustic waves.

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