JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS VOLUME 89, NUMBER 3 SEPTEMBER 1999

Dust acoustic waves in a dc glow-discharge plasma

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(Submitted 10 March 1999)
Zh. Éksp. Teor. Fiz. **116**, 902–907 (September 1999)

The spontaneous excitation of low-frequency oscillations of the macroparticle density in ordered dust structures levitating in standing striations of a dc glow discharge is discovered. It is concluded on the basis of a simplified linear model of an ideal collisionless plasma that the observed instability is caused by the drift motion of ions relative to the dust, which leads to the excitation of dust acoustic oscillations of the plasma. © *1999 American Institute of Physics.* [S1063-7761(99)01109-9]

The presence of charged dust particles in a low-temperature plasma leads to the appearance of new oscillation modes and instabilities.[1–3] For example, the phase velocity of ion sound increases as a result of the decrease in the concentration of electrons, which are partially absorbed by the macroparticles. This leads to changes in the characteristics of the ion-acoustic current instability appearing because of the relative motion of ions and electrons at frequencies close to the ion plasma frequency. At lower frequencies, close to the dust plasma frequency, current instability can appear as a result of the motion of electrons and ions relative to the charged dust particles (see Ref. 3 and the literature cited therein). Dust sound and a corresponding current instability were recently observed in laboratory experiments.[4–8] Dust acoustic instability can appear in various systems, such as, for example, Saturn's rings, radio-frequency discharges used in plasma-sputtering and etching technologies, and plasma crystals.[3]

The appearance of natural oscillations in a dusty dc glow-discharge plasma sustained in neon was discovered in the present work, and an attempt was made to interpret this phenomenon as being a result of a plasma-dust current instability. The experimental setup scarcely differed from the one which we previously used in Ref. 9. The plasma-dust structures were formed in standing striations of a low-pressure discharge in a glass tube with a diameter of 3 cm and cold electrodes. Monodisperse microspheres of a melamine-formaldehyde resin ($\rho = 1.5\,\mathrm{g/cm^3}$) with diameters of 10.24 and 1.87 μm, whose charge ranged from 10^5 to $10^4\,e$, were used in the experiments. The structures were visualized using transillumination by a laser "knife" in a vertical plane. Video images of the structures were recorded using a CCD camera and a video cassette recorder. Figure 1 presents a video image of a structure consisting of particles with a diameter of 1.87 μm. Oscillations of the dust particle density are clearly seen in the lower part of the structure in the video image. These oscillations are particle density waves with a wavelength $L \sim 1$ mm and an oscillation period $T \sim 5 \times 10^{-2}$ s, which travel downward from the anode to the cathode. It should be stressed that these oscillations exist only in the lower part of the structures, whose linear dimension and position correspond to the head of a striation, where the electric field intensity is greatest. In addition, it was discovered that the oscillations appear when there is a definite (critical) number of dust particles in the structure. This can be seen in Fig. 2: the first frame [Fig. 2(a)] shows a well ordered structure, and the ensuing frames [Figs. 2(b) and 2(c)] show the development of instability in response to the additional injection of particles and their trapping by the structure.

We note that the oscillations disappear when the discharge current is raised or the gas pressure is increased.

The frequency of the oscillations discovered is close to the frequency of plasma-dust oscillations.[3] Therefore, an explanation for the effects described above should be sought in the possible instabilities of the low-frequency oscillations of a dusty plasma. The spectrum of longitudinal modes of a plasma is determined from the solution of the dispersion equation

$$\varepsilon(\omega,\mathbf{k}) = 0, \tag{1}$$

where ε is the dielectric constant of the plasma, and ω and $\mathbf{k}$ are the frequency and wave vector of the oscillations. The susceptibility of an ideal motionless plasma $\chi = \varepsilon - 1$ is additive with respect to the charged components of the plasma:

$$\varepsilon(\omega,\mathbf{k}) = 1 + \sum_{j=e,i,d} [\varepsilon^j(\omega,\mathbf{k}) - 1]. \tag{2}$$

Here the indices e, i, and d correspond to electrons, ions, and dust particles. In a gas discharge the velocity distribution of the charged particles deviates from equilibrium because of the directed motion in the electric field with the drift velocities $\mathbf{u}_j$. The dielectric constant ε^j of each of the components in a coordinate frame moving with the velocity $\mathbf{u}_j$ has the same form as in the laboratory coordinate frame with $\mathbf{u}_j = 0$. In going over to the laboratory frame, allowance should be made for the Doppler frequency shift, which leads to generalization of the expression (2) to the case of nonzero drift velocities:

$$\varepsilon(\omega,\mathbf{k}) = 1 + \sum_{j=e,i,d} [\varepsilon^j(\omega - \mathbf{k}\cdot\mathbf{u}_j,\mathbf{k}) - 1]. \tag{3}$$

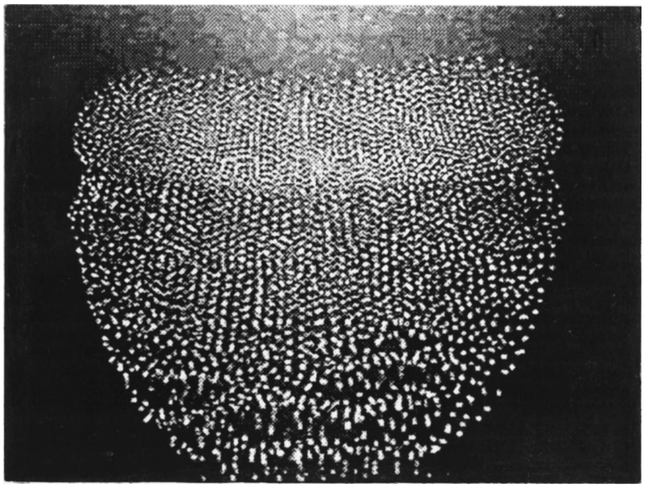

FIG. 1. Video image of an ordered structure of monodisperse particles with a diameter of 1.87 μm at a discharge current of 5 mA and a pressure of 0.3 Torr. Each frame corresponds to 10.6 mm in the vertical direction.

In the case of a collisionless Maxwellian plasma in the absence of a magnetic field, the solution of Vlasov's equation leads to the following expression for the longitudinal dielectric constant:[10]

$$\varepsilon^j(\omega,\mathbf{k})=1+\frac{1}{(k\lambda_j)^2}\left[1+F\left(\frac{\omega}{\sqrt{2}kv_j}\right)\right], \tag{4}$$

where the parameters

$$\lambda_j=\sqrt{\frac{T_j}{4\pi N_j e^2}},\quad v_j=\sqrt{\frac{T_j}{m_j}} \tag{5}$$

are the Debye length and the mean thermal velocity of the jth component, and T_j, N_j, and m_j are the temperature, concentration, and mass of the particles of the jth component. The function $F(x)$ is defined by the integral

$$F(x)=\frac{x}{\sqrt{\pi}}\int_{-\infty}^{\infty}\frac{\exp(-z^2)dz}{z-x-i0}$$

$$\simeq\begin{cases}-1-\dfrac{1}{2x^2}-\dfrac{3}{4x^4}+i\sqrt{\pi}xe^{-x^2}, & x\gg 1,\\ -2x^2+i\sqrt{\pi}x, & x\ll 1.\end{cases} \tag{6}$$

In laboratory experiments dust particles levitate and perform chaotic thermal motions, and their drift velocity u_d is equal to zero. The thermal velocity of the electrons v_e is usually significantly greater than their drift velocity u_e, and the latter can also be considered equal to zero. The following inequalities usually hold in a dc gas-discharge plasma in the region of parameters where dust acoustic instabilities are observed:

$$kv_e\gg kv_i>ku_i\gg\omega\gg kv_d. \tag{7}$$

Thus, in accordance with (3)–(6), the complex dielectric constant can be represented in the form

$$\varepsilon(\omega,\mathbf{k})=1-\frac{\omega_d^2}{\omega^2}+\frac{1}{k^2\lambda^2}+i\sqrt{\frac{\pi}{2}}\frac{\omega-u_ik}{k^3v_i\lambda_i^2}, \tag{8}$$

where

$$\omega_d=\left(\frac{4\pi N_dZ_d^2e^2}{m_d}\right)^{1/2},\quad \lambda=\frac{\lambda_e\lambda_i}{\sqrt{\lambda_e^2+\lambda_i^2}} \tag{9}$$

are the dust plasma frequency and the electron-ion Debye length, respectively, and Z_d is the charge of the dust particles.

Assuming that the absolute value of the imaginary part of ε is small and setting

$$\omega=\omega_r+i\gamma,\quad \omega_r\gg\gamma, \tag{10}$$

from (1) and (8) we find the low-frequency oscillation spectrum of a dusty plasma:

$$\omega_r^2\simeq\omega_d^2\frac{k^2\lambda^2}{1+k^2\lambda^2}, \tag{11}$$

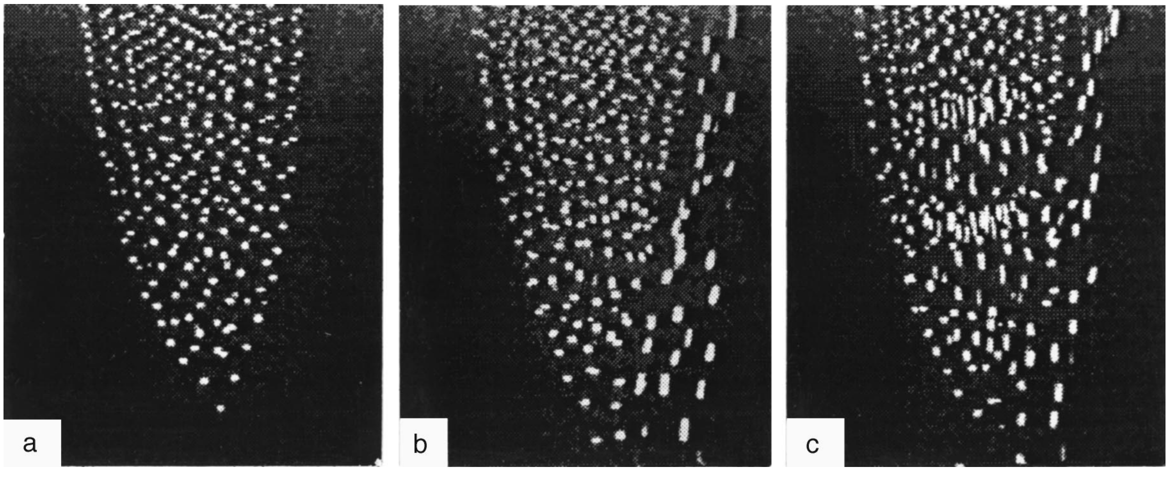

FIG. 2. Video image of fragments of structures of monodisperse particles with a diameter of 1.87 μm at a discharge current of 0.6 mA and a pressure of 0.3 Torr. Each frame corresponds to 6 mm in the vertical direction.

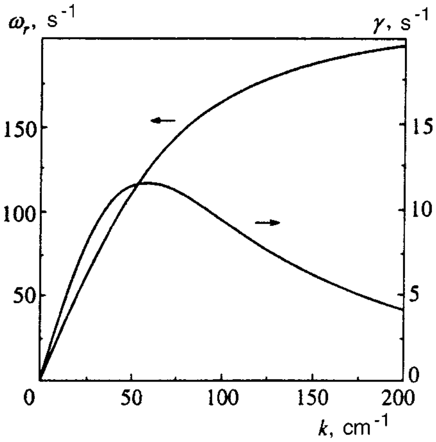

FIG. 3. Dispersion $\omega_r(k)$ and growth rate $\gamma(k)$ of low-frequency plasma-dust oscillations in standing striations of a dc gas discharge.

$$\gamma \simeq -\sqrt{\frac{\pi}{8}}\,\frac{\omega_r^3}{\omega_d^2 k^3 \lambda_i^2}\,\frac{\omega_r - u_i k}{v_i}. \qquad (12)$$

When $u_i=0$, this spectrum coincides with the spectrum of dust acoustic oscillations. A nonzero value of the drift velocity of the ions u_i leads to a decrease in the damping decrement γ, and at values of u_i exceeding the phase velocity of the waves $v_{\mathrm{ph}}=\omega/k$, the damping decrement γ changes sign, i.e., instability appears. In complete analogy to the ion acoustic instability of an ordinary plasma,[11] the instability discovered is caused by the Cherenkov radiation of dust acoustic waves by ions moving with a supersonic velocity. It is possible only under the conditions

$$Z_d T_i \gg T_d, \quad u_i > v_{\mathrm{ph}} \gg v_d, \qquad (13)$$

which are satisfied with a large safety margin in a dusty dc glow-discharge plasma.

Under the conditions of our experiment, at a pressure $p\simeq 1$ Torr and an electric field intensity $E\simeq 3$ V/cm, the ion drift velocity u_i is roughly equal to 8×10^3 cm/s. For a characteristic oscillation frequency $\omega=2\pi/T\simeq 60\,\mathrm{s}^{-1}$ and a wave vector $k=2\pi/L\simeq 60\,\mathrm{cm}^{-1}$ the phase velocity of the waves is small compared with the ion drift velocity: $v_{\mathrm{ph}}=\omega/k\simeq 1$ cm/s$\ll u_i$. Estimates made in accordance with (9) and (5) for particles with a diameter of 1.87 μm give $\omega_d \simeq 210\,\mathrm{s}^{-1}$ and $\lambda\simeq 1.2\times 10^{-2}$ cm (the values $Z_d\simeq 2.5\times 10^3\,e$, $N_d\simeq 10^4\,\mathrm{cm}^{-3}$, and $N_i\simeq 10^8\,\mathrm{cm}^{-3}$ were used). The results of the calculation of the frequency ω_r and the growth rate γ of the dust acoustic oscillations are presented in Fig. 3. The instability growth rate has a maximum at $k=k_m=1/\sqrt{2}\lambda\simeq 60\,\mathrm{cm}^{-1}$ at the characteristic frequency $\omega_r(k_m)=\omega_d/\sqrt{3}\simeq 120\,\mathrm{s}^{-1}$. Just such waves are excited in our experiment.

Despite the good agreement with experiment, the model proposed above cannot claim to provide a faithful quantitative description of the spectrum of dust acoustic oscillations, since the linear theory of an ideal collisionless plasma was used to substantiate it. Nevertheless, it provides explanations for several qualitative features of the phenomenon observed. For example, the development of the instability only in the lower part of the dust structure resting on the head of a striation is probably due to the fact that the electric field E and thus the ion drift velocity u_i reach maxima in this region. According to (12), the instability growth rate also reaches its greatest value in this region.

In our opinion, dust acoustic instability is not observed in radio-frequency discharges, because in the layers near the electrodes of these discharges, where the levitation of dust particles is usually observed, due to the Bohm effect[12] the ion drift velocity satisfies the condition

$$u_i \simeq \sqrt{\frac{T_e}{m_i}} \gg v_i = \sqrt{\frac{T_i}{m_i}}.$$

This leads to alteration of the spectrum of dust acoustic oscillations (11) and the appearance of an exponentially small multiplier $\exp(-T_e/T_i)$ in the instability growth rate (12). The recent discovery of dust acoustic oscillations in a radio-frequency discharge under microgravitational conditions[13] does not contradict the foregoing statements, since in this case dust structures are located throughout the volume of the plasma and the phenomenon under consideration occurs far from the electrodes, where $u_i < v_i$.

Dust acoustic instability can be initiated by the decrease in the gas pressure in the discharge or by the increase in the number of macroparticles in the dust structure. The former effect is associated with an increase in the ion drift velocity and a decrease in the viscosity of the neutral gas. The latter effect, which is illustrated in Fig. 2, possibly occurs because the increase in the concentration of dust particles creates an additional channel for a loss of charges (apart from the principal channel associated with ambipolar diffusion on the walls of the discharge tube), which, at a fixed discharge current, necessitates an increase in the ionization frequency and, consequently, leads to intensification of the field in the region where the dust particles are found.[9] This, in turn, leads to a rise in the ion drift velocity u_i and, as a result, to an increase in the instability growth rate.

Finally, we note that the disappearance of the oscillations in response to an increase in the discharge current is probably a consequence of the lowering of the electric field intensity ordinarily observed under such conditions.

We thank S.A. Khrapak for some useful discussions.

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Translated by P. Shelnitz