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Solitary model of charged particle transport in dusty plasma

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Introduction

Dusty-acoustic waves, excited in dusty plasma at the presence of external electric field are a subject of many experimental and theoretical researches, for example [1]. Theoretical investigations are mostly limited by the linear stage of dusty-acoustic instability. However, self-excited fluctuations reach a strongly nonlinear stage quickly, if the excitation conditions are satisfied and the dust cloud’s size is relatively large. Stationary waves look like series of density crowdings moving relatively the dusty component. In our opinion, this phenomenon can be described by a solitary model in case of symmetric and sharply localized density compressions.

Experiment

Strongly nonlinear stage of dusty-acoustic instability has been experimentally observed on the installation “Plasma crystal – 4” in Max-Planck-Institute. Plasma is produced by DC glow discharge in glass tube at about 0.3 m in length and 0.03 m in diameter. Discharge operates at dc discharge current of 1 mA and neon pressure of 80 Pa. The installation allows to obtain the

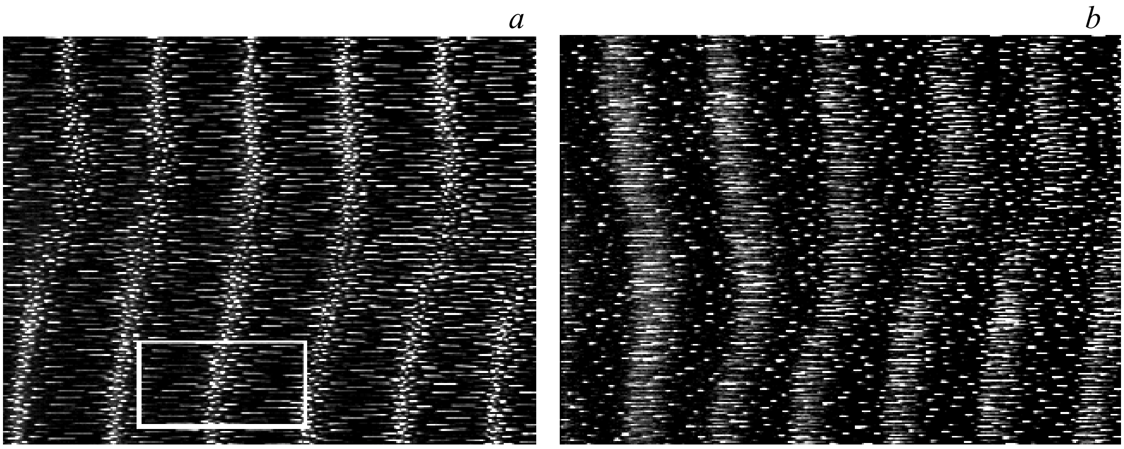

Fig. 1. Video frame of the excited nonlinear dusty-acoustic wave in fixed co-ordinates (a) and moving co-ordinates (b).

dust structures containing one or several kinds of dust particles. Nonlinear waves of dusty grains’ density were observed in dense clouds ($n_d \approx 3.5\cdot10^{11}$ m^{-3}) of monodisperse

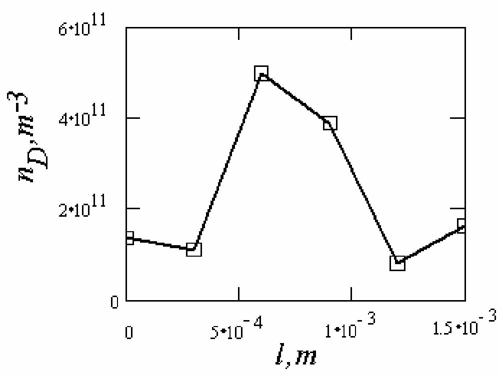

Fig.2. Density profile.

polymetylformamyd grains at microgravitation conditions. An axial section of the cloud in laser light is shown in fig. 1. Due to the influence of electric field the dust particles move from the left to the right (initial drift velocity is $\upsilon_{d0} \approx$2-3 cm/s). Density bursts which correspond to the nonlinear waves stay immovable in the fixed co-ordinates, but they move relatively the dust component from the right to the left. Dust velocity is minimal in the compression area.

Let's estimate the dust particle density in the area bordered by white rectangle in Fig. 1a. This rectangle was divided on six vertical bands with sizes of 0.3 × 1.2 mm^2. The number of dust particles was determined in each band. Knowing the thickness of laser beam (0.1 mm) and the size of the several band we can determine the dust density (Fig. 2). As one can see, the ratio of maximal and minimal densities is approximately equal to five. Width of the compression area is about 0.5 mm or $10 \cdot \lambda_D$, where $\lambda_D = \left(\varepsilon_0 T_e T_i / e^2 \left(n_{0e} T_i + n_{0i} T_e\right)\right)^{1/2}$ – Debye length, n_{0e}, n_{0i} and n_{0d} – initial densities of electrons, ions and dust grains, T_e, T_i – electron and ion temperature in energetic unit, e – electron charge, ε_0 – vacuum inductive capacity. The wave velocity is close to the dusty-acoustic one and the dusty particle concentration in front of the compression area is equal to the one behind (Fig. 2). These conditions allow us to use a solitary model to describe the observed phenomenon.

Theoretical model

Let's consider the 1D unmagnetized MHD model of plasma consisted of three kinds of charge particles: electrons, ions, dusty particles. According to [3], dusty-acoustic velocity is given by

$$C_d = \sqrt{\frac{Z^2 n_{0d} T_e T_i}{m_d \left(n_{0e} T_i + n_{0i} T_e\right)}}, \tag{1}$$

where n_e, n_i and n_d –perturbed densities of electrons, ions and dust grains, m_d, $Z = |q_d/e|$ – mass and normalized charge of a dust grain (q_d – charge of grain). Since C_d is less than both the electron and ion thermal velocity, therefore it is possible to consider electron and ion densities to be approximated by constant and Boltzmann distributions:

$$N_e \equiv \frac{n_e}{n_{0e}} = 1 \tag{2}$$

$$N_i \equiv \frac{n_i}{n_{0i}} = \exp\left(-\frac{e\varphi}{T_i}\right) \equiv \exp\left(-\frac{Z\cdot\beta\cdot\Phi}{\delta_1+\beta\delta_2}\right), \qquad (3)$$

where N_e, N_i – normalized electron and ion density, $\Phi = e\varphi/(C_d^2 m_d)$ – normalized potential,

$$\delta_1 = \frac{n_{0e}}{Zn_{0d}},\ \delta_2 = \frac{n_{0i}}{Zn_{0d}},\ \beta = \frac{T_e}{T_i}.$$

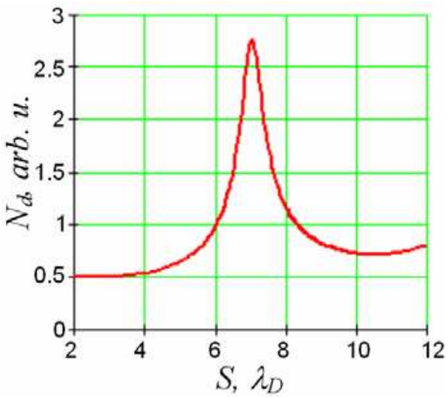

Fig. 3. The soliton solution of (7).

The density and velocity n_d, υ_d for negative charged dust grains can be found from the following equations

$$\frac{\partial\upsilon_d}{\partial t} + \upsilon_d\frac{\partial\upsilon_d}{\partial x} = -\frac{ZeE}{m_d} - \nu_{dn}\upsilon_d \qquad (4)$$

$$\frac{\partial n_d}{\partial t} + \frac{\partial n_d\upsilon_d}{\partial x} = 0 \qquad (5)$$

Here ν_{dn} – dust-neutral collision frequency. After transformation of equations (4) and (5) using single independent variable $S = (x - V\cdot t)/\lambda_D$, where V – velocity of the soliton in the fixed system, one can obtain

$$\frac{dN_d}{dS} = \frac{Z\cdot\bar{E}}{M_d^2}N_d^3 - \frac{N_d^3}{M_d}\cdot\gamma\left(1-\frac{1}{N_d}\right) \qquad (6)$$

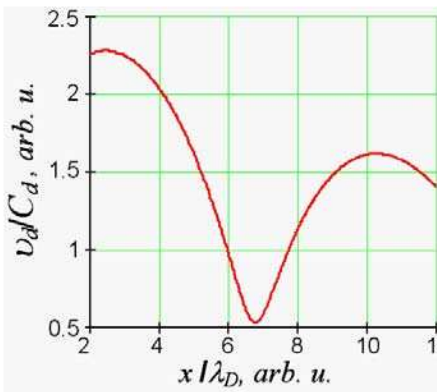

Fig. 4. Normalized dust velocity inside soliton in fixed co-ordinates.

$N_d = n_d/n_{0d}$, $\bar{E} = -d\Phi/dS = e\cdot E\cdot\lambda_D/m_d\cdot C_d^2$ – normalized electric field, $M_d = (\upsilon_{d0}-V)/C_d$ – Mach number, $\gamma = \nu_{dn}/\omega_d$, $\omega_d = \sqrt{Z^2e^2n_{0d}/m_d\varepsilon_0}$ – plasma frequency for the dust component, $\upsilon_{0d} = -e\cdot E\cdot Z/m_d\nu_{dn}$ is dust drift velocity. To close the system we use Poisson's equation in the dimensionless form:

$$\frac{d^2\Phi}{dS^2} = \frac{1}{Z}\left(\delta_1 N_e - \delta_2 N_i + N_d\right) \qquad (7)$$

with the quasineutrality condition $\delta_1 - \delta_2 + 1 = 0$. The numerical solution of (7) for $Z = 10^3$, $M = 1.2$, $\beta = 10$, $\delta_2 = 1.6$, $\gamma = 0.3$ is represented in Fig. 3. Using (2), (5) and the velocity summation rule $\upsilon'_d = \upsilon_d - V$ this velocity can be determined as

$$\upsilon'_d = \left(\upsilon_{0d} - V\right)\frac{1}{N_d}. \qquad (8)$$

Here υ'_d is the velocity in co-ordinates moving relative to dust. At absence of perturbation, $\upsilon'_d = \upsilon_{0d} - V$. The velocity in co-ordinates fixed relative to dust can be presented as following

$$\upsilon_d = V\left(1 - \frac{1}{N_d}\right). \tag{9}$$

Dust velocity υ_d as function *S*, corresponding to the concerned solitary solution, is shown in Fig. 4. Deceleration of dust particles corresponds to their compression. This conclusion is in good agreement with experiment (Fig. 1a). Other situation is observed in the moving system, namely, maximal value of the dust velocity corresponds to maximum of the dust concentration, which is agreed with experiment as well (Fig. 1b). Every compression area is described by the dusty-acoustic soliton in our model. So it follows that each dusty-acoustic soliton produces a dust displacement relatively the dust component in the soliton moving direction only. Value of displacement *L*, according to [4], is about $10\cdot\lambda_D$. The result of the displacement is the dust current pulse J_d with the direction opposite to υ_d. Cascade of solitons cause an appearance of pulsing dust particle current imposed on the initial drift current of glow discharge.

Conclusions

The strong nonlinear stage of dusty-acoustic instability obtained on installation "Plasma crystal - 4" in dc discharge plasma in neon is investigated. Observed nonlinear wave picture can be described according to the solitary model [4] by the dusty-acoustic soliton cascade propagating relatively the dust component with velocity at about dust-acoustic one. Each soliton produces a dust displacement, and therefore dust current is pulsing. Value of the displacement is a few λ_D per soliton.

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