Large-amplitude dust waves excited by the gas-dynamic impact in a dc glow discharge plasma

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A large-amplitude wave with two humps of dust density, separated by a dip was generated. To excite the wave in the dc glow discharge dusty plasma a gas-dynamic impact was used. The structure obtained had several interesting properties such as strong compression of dust in the humps, supersonic dust particles in the rarefaction zone, reconstruction of the initial dust configuration after the passing of the wave. The peculiarities of the phenomenon observed are discussed. The mechanism of generation and propagation for such kind of perturbation is proposed.

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I. INTRODUCTION

Wave phenomena in the dust component of the dusty plasma are at present of great interest for investigators. Micronsized dust grains are very heavy compared to electrons and ions and when immersed into a low temperature plasma they acquire a great charge of 10^3–10^5 electrons. The charge on dust grains is not fixed, since it is connected self-consistently with the conditions in surrounding plasma. For this reason, specific wave modes may appear in dusty plasmas.

Dust acoustic waves were for the first time theoretically treated in Ref. [1]. In the consequent development of the theory different authors (see Ref. [2], and references therein) considered the nonlinear effects. It was found that in an unmagnetized dusty plasma solitons and shock waves may be excited. Linear dust acoustic waves were experimentally observed in a *Q* machine [3,4]. Mach cones, excited by a supersonic object moving through the medium, were observed in dusty plasma [5,6]. The results of the observation of a weakly dissipative longitudinal soliton in a dust monolayer were published in Ref. [7].

Recently, the self-excited dust acoustic waves in the dc glow discharge striations have been observed [8–11]. Analogous phenomenon was reported in Ref. [12]. It was shown that the instability is caused by the joint effect of the ion drift and fluctuations of the dust particle charge. The present work to a certain extent is the continuation and development of these investigations under slightly different conditions. Here we used a gas-dynamic impact to excite waves. In Sec. II of the paper the experimental setup is described and main experimental results are presented. In Sec. III the discussion of the obtained results is given and a physical mechanism explaining the generation and propagation of the waves is presented. Sec. IV concludes the paper.

II. EXPERIMENTAL SETUP AND RESULTS

The experimental setup is similar to that used in Ref. [13]. Glow discharge with cold electrodes was created in a vertically maintained glass tube of 36 mm diameter (see Fig. 1). The upper electrode was the anode placed in a lateral nib. The lower electrode was the hollow cylindrical cathode. The electrodes were separated by 26 cm. In some experiments a grid was inserted into the tube 7 cm above the upper cut of the cathode. The grid was kept under the floating potential. Current of 0.1–1 mA could be driven through this system at neon gas pressure of 0.3 Torr. The discharge was stratified in these conditions. Melamineformaldehyde dust grains 1.03 μm diameter were held in a container with the grid bottom above the anode nib. After shaking the container the particles rained down and levitated in the striations. All the observations were conducted in the lowest striation, where an ordered dusty plasma structure was formed. To illuminate the particles a light sheet from a 50-mW laser diode was used. The scattered light was observed by a Phantom 5 camera at a frame rate of 300 fps.

For the excitation of the waves a plunger was set below

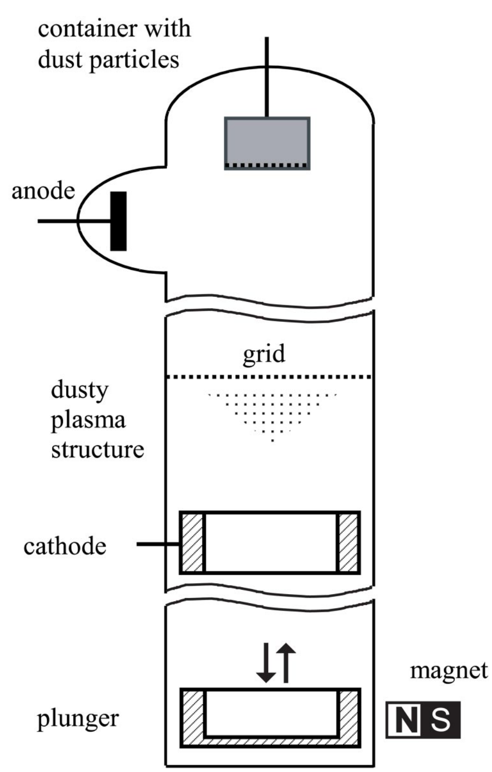

FIG. 1. Scheme of the experimental setup.

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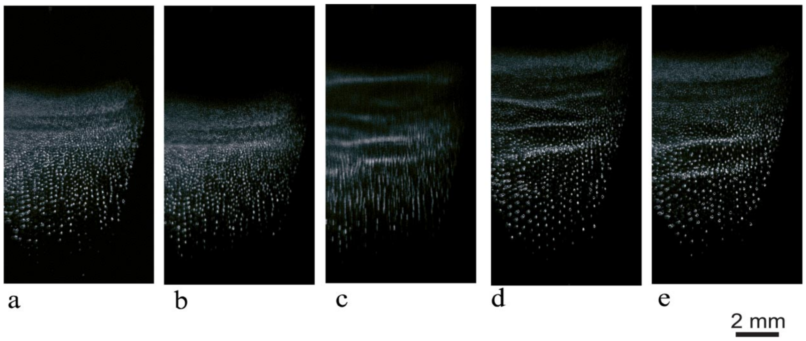

FIG. 2. Sequence of videoframes presenting the evolution of the disturbance in the experiments without the grid, (a) the initial structure, time interval between each frame (a)–(e) is 33 ms.

the cathode. The plunger was a hollow thin-walled nickel cylinder of 26 mm diameter and height with the bottom made of a polymeric pellicle. It was freely installed at the bottom of the tube (15 cm separated from the cathode) and moved with the help of a permanent magnet manually approached to the plunger from outside the tube. In this way the plunger could be moved upward and downward with the speed of about 30–40 cm/s and 4–5 cm space, creating a gas flow with the duration of about 0.1 s, which displaced the dust grains with respect to the striation.

At first we performed experiments without the grid. When the plunger was moved downward the dusty plasma structure was first slowly moving downward (Fig. 2). During the time of 33 ms it was displaced for about 500 μm. The structure becomes unstable at this position. It moves rapidly back in the upward direction and several dust compressions propagating downward appear inside it. At the end of the process the waves are damped and the structure as a whole returns to its initial position. The characteristic length and frequency of the wave are 1.3 mm and 14 Hz, respectively. These waves are very similar to the self-excited waves obtained in Ref. [9]. However they are different since the self-excited waves are usually observed in the lower parts of the structure in the area of higher electric field, whereas here they are formed in the upper part and beyond them the dust cloud is found to be in its initial state.

We should note that the magnet which is used to transmit the motion to the plunger produces an influence on the cathode sheath of the discharge. Due to this when the plunger is moved downward the striation performs an opposite motion. Consequently, the displacement of the dust grains with respect to the distributions of the plasma parameters is of the order of 2.5 mm. However we do not observe any changes in the shape of the dusty plasma structure when the magnet is being moved. The estimated value of the magnetic field created by the magnet in the striation region is of the order of 0.1 G. This is rather a weak magnetic field, which cannot produce any significant disturbance in the plasma. It was experimentally verified that the influence of only the magnet is not enough to produce the waves.

Quite a new solitary wave was obtained in the experiments with the grid. The pressure was again adjusted to 0.3 Torr and the discharge current was chosen in such a way that the lowest striation was formed exactly below the grid. This occurred at the current value of 0.1 mA. The dusty plasma structure was very close to the grid (at a distance of 4 mm). After moving the plunger downward the structure was again for some time streaming downward, then it stopped and began moving towards its initial equilibrium position and when it returned to the stable position a disturbance propagating through it appeared (Fig. 3). The disturbance observed is nearly plane and therefore it can be treated in terms of only one spatial variable. We have determined the distribution of the brightness over the vertical axis z for each frame. Figure 4 presents the shape of the compression factor ξ, which is the ratio of the distribution of brightness in the wave to the distribution of brightness in the initial structure, at different moments of time. The disturbance consists of three parts: A is the first compression, B is the rarefaction and C is the second compression. It is seen that the amplitudes for zones A and C reach the values of 2.1 and 1.2, respectively, and 0.65 for the rarefaction.

It would be more reliable to determine the compression factor ξ as a ratio of directly measured dust densities in the

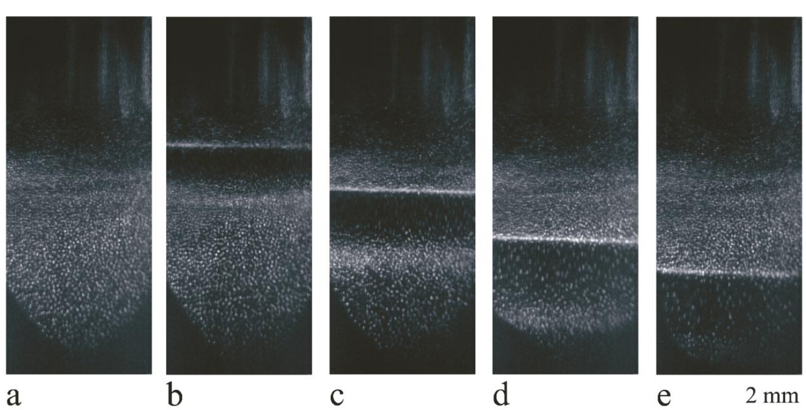

FIG. 3. Sequence of videoframes presenting the evolution of the disturbance in the experiments with the grid, (a) the initial structure, time interval between each frame (b)–(e) is 83 ms.

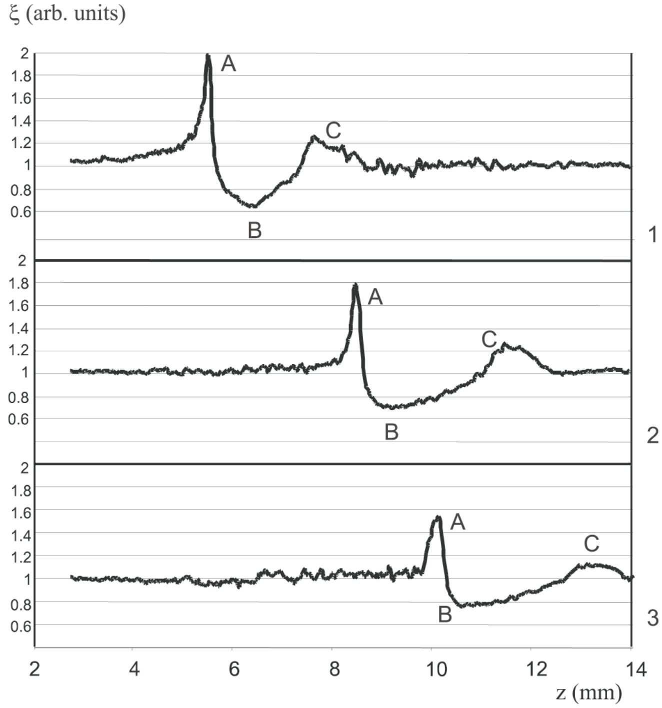

FIG. 4. Shapes of the compressional factor in the wave at different moments of time. *A*, *B*, *C* denote three different structures of the wave: first compression, rarefaction, and the second compression, respectively. Time interval between curves 1 and 2 is 120 ms, between curves 2 and 3 is 60 ms.

wave and in the unperturbed structure. However, it was not possible to measure dust densities throughout the whole structure (especially for zone *A*). For moments 1 and 2 (Fig. 4) such measurements were possible. We present this data for comparison: for zone *B*, $\xi = 0.3$ and 0.4 and for zone *C*, $\xi = 1.6$ and 1.4 for moments 1 and 2, respectively. This means that the wave is strongly nonlinear. It should be noted that such strong compressions and rarefactions were not previously observed in laboratory dusty plasmas. It should be emphasized that as follows from Figs. 3 and 4 after the passing of the first compression the structure takes the unperturbed state.

All three structures move approximately with the same speed of 2–2.5 cm/s (Figs. 5 and 6), but starting from the time of about 250 ms the second compression slightly accelerates. It is interesting that the rarefaction first moves with the speed of compression *A* and closer to the end of the process acquires the speed of zone *C* (Fig. 6).

Between the zones *A* and *C* in the rarefaction we observe the upward motion of the dust grains. They start the motion from the zone *C* with the zero velocity, rapidly accelerate in the rarefaction up to the velocity of 10–15 cm/s (estimation from the measured track length) and stop in the zone *A*.

At higher values of the discharge current the dusty plasma structure levitated further from the grid, e.g., at the current of 1 mA it was formed 15 mm away from the grid. In this case the described above solitary wave did not appear, but the waves analogous to those obtained without the grid were generated by the plunger motion.

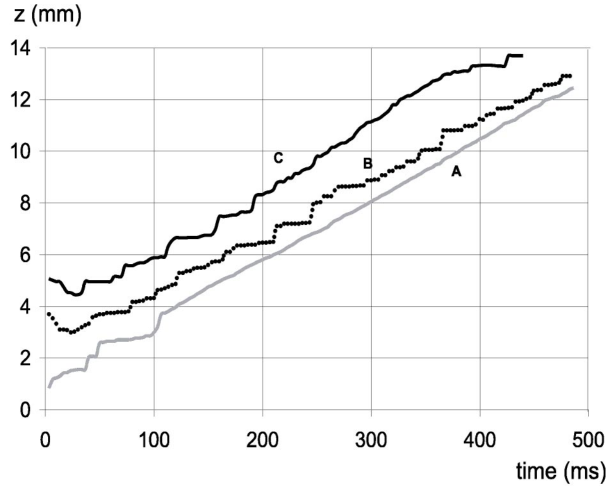

FIG. 5. Positions of extrema of the three structures of the wave at different moments of time.

It should be also mentioned that upward motion of a plunger and initial upward displacement of the dust grains did not lead to excitation of any wave.

III. DISCUSSION

The dust acoustic velocity is expressed as follows [2]:

$$C_{da} = \sqrt{\frac{Z_d^2 T_i}{m_d} \frac{n_d}{n_i}}, \tag{1}$$

where n_i, n_d are the ion and dust density, T_i is the ion temperature, and Z_d, m_d are the dust grain charge and mass, respectively. As it was already mentioned in Ref. [13] measurements of the local values of plasma parameters in standing striations are impossible with the known techniques. That is why we have to rely on the experimental data for the running striations [14]. The charge on a dust grain determined by the extrapolation of an empirical dependence obtained in Ref. [15] is 400–750 electrons. The ion density was

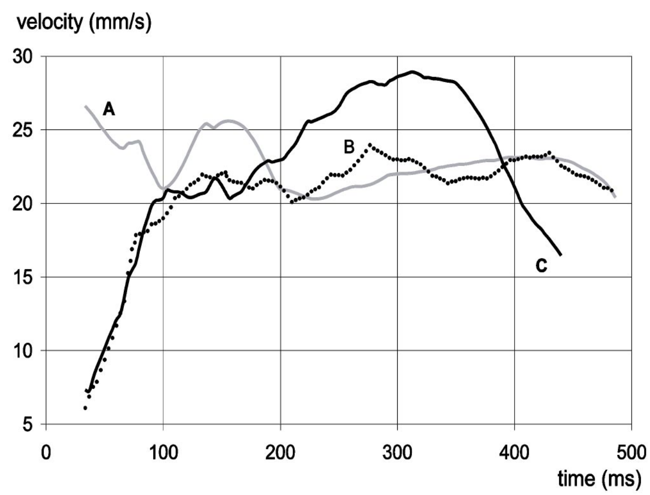

FIG. 6. Evolution of the velocities of the three structures of the wave.

estimated to vary along the striation in the range of $4 \times 10^7 - 10^8$ cm^{-3}. The dust density also slightly changes inside the initial dusty plasma structure around the average value of 3×10^4 cm^{-3}, $m_d = 7.5\times10^{-13}$ g. Thus $C_{da} = 1.8$–5.2 cm/s. The velocities of the wave lie in the given range of C_{da}. High mass speed of the dust grains in zone B can be explained by the necessity to balance the downward mass flow of the dust grains in compressions with an upward mass flow in a strong rarefaction.

As was pointed out the wave we observed could not be excited only by means of the motion of the magnet. It is not the result of a magnetic perturbation in a background plasma. Dust particles in this experiment cannot also be treated as tracers of the neutral gas pressure, since the stationary profile of gas density must propagate with the speed of the order of gas-acoustic speed, which is several hundreds meter per second at room temperature. So, the wave we obtained is a dust wave.

As follows from the most recent review of the literature on nonlinear dust acoustic structures given in Ref. [2], the theories of dust waves at present employ two main assumptions: the homogeneity and infinity of the medium. In our experiment the dust density changes along the z axis. Therefore the acoustical properties of our medium must be different in different points of space. Concerning the infinity of the medium we should note that this assumption also does not hold in our case. The distance between the two maxima of the dust density is 2.8 mm while the structure length is 9 mm. So our medium cannot be treated as unrestricted.

Appearance of two compressions after a single impulse is an interesting but not yet understood effect. Similar things were obtained for ion-acoustic shocks [16] and solitons [17], where a small "precusor" running in front of the main disturbance was observed, but the collisionless mechanism of its appearance can hardly be applied to dusty plasmas.

The conditions of our experiment are characterized by comparatively high neutral gas pressure and consequently great damping of the waves due to the neutral drag. If we use the *Epstein* formula for the neutral drag force [18] which is applicable in our case (mean free path of Ne atoms at the pressure $p = 0.3$ Torr is 170 μm and particle radius 0.5 μm), we can express the frictional damping rate as [9]

$$\beta = \frac{4\sqrt{2\pi}}{3}\frac{pa^2}{m_d v_{th}}, \tag{2}$$

where a is the dust grain radius and v_{th} is the thermal speed of neon atoms. In our case $a = 0.5$ μm, $v_{th} = 590$ m/s and therefore $\beta = 75$ s^{-1}. The disturbance must be damped within 15 ms that is much smaller than the observed time of the wave propagation (500 ms). It means that the wave must have an energy source other than the initial impulse. The dust acoustic instability, which is a typical phenomenon for the dc discharge striations, could serve as a mechanism by means of which the energy is supplied to the wave [9]. Note that the damping rate estimated here is the minimal estimation since the charge fluctuations may contribute not only to the development but also to the damping of the dust acoustic waves.

At the present moment the mechanism of the wave appearance is not finally clear. One of possible reasons for the excitation of the disturbances observed is the stability violation at the boundary of the dusty plasma structure, connected with dependence of the charge of the dust grains on their density.

The perturbations observed in the present work are being started from the upper parts of the structure. That is why it would be reasonable to analyze the behavior of the upper boundary of the structure on the upward and downward displacement of the dust cloud which is experimentally realized by the impact of the gas flow. Note that the charge on a dust grain is determined not only by the conditions in the background plasma, but also by the dust density. This effect has been taken into account theoretically in several works [9,19]. The increase of the dust density leads to the decrease of the dust grain charge.

In the absence of any influences the upper boundary of the structure observed is stable, i.e., the small displacement of a layer of dust particles from the edge leads to the appearance of a restoring force. Let us consider the forces acting on the edge particles: they are the gravitational force, electrostatic force, and force of interaction with the inner particles. If the boundary layer of the dust particles is displaced upward its interaction with the inner particles disappears. The charge of the dust particles in the displaced layer increases since they are introduced into the area of lower dust density. To provide the restoring force the gravitational force must prevail over the electrostatic force even for this higher charge value. This is the condition which determines the stability of the upper boundary.

It is obvious that the dust particles levitate in the region, where the electrostatic force decreases in the upward direction. Thus the upward displacement of the dusty plasma structure strengthens the stability of the upper boundary. The opposite situation occurs when the structure is displaced downward. All the dust particles in the structure experience the excess electrostatic force. The edge particles have higher charge than the inner particles and consequently experience higher acceleration. The boundary particles escape from the inner ones and the flux of fast particles in front of the slowly returning inner particles is formed. The fast particles are retarded in the vicinity of the initial upper boundary of the structure and a compression is produced in that region. In the compression the charge on the dust grains decreases and the compression starts moving downward under the effect of a prevailing gravitational force.

The mechanism presented does not explain how two or more compressions might appear. However if several compressions are formed their propagation can be understood by applying the same considerations. According to this mechanism the upper boundary of each compression is unstable and must "emit" the dust particles. In this way it feeds upper compressions. All the compressions propagate downward since the charge on the dust grains inside them is low.

It is also necessary to explain why the initial dust density profile is reconstructed beyond the wave. The upper compression starts to travel from the initial equilibrium boundary of the structure, where the stability conditions are satisfied. It means that beyond the upper compression no other compression may appear and the dust particles return to their unperturbed configuration.

The close proximity of the dusty plasma structure to the grid, which is kept under the floating potential, apparently leads to the fact that under the gas dynamic influence the dust grains are affected by the electric field of the grid. The screening length for the electric field of the grid is of the order of electron Debye length. At the given plasma parameters it is 1.5–2 mm, which is comparable to the distance from the grid to the upper edge of the structure. Therefore the electric field of the grid must contribute to the potential wall for the dust particles on the upper boundary making it steeper. This may lead to the appearance of a stronger compression, what is exactly observed in the experiment.

IV. CONCLUSION

Thus, we have observed a large-amplitude dust wave in the dc glow discharge dusty plasma. The wave consisted of two compressional regions separated by a rarefaction and propagated with the velocity of the order of the dust acoustic velocity. One of the compressions had a higher amplitude and before it the weaker one was running. After the passing of the stronger compression the dust returned to the unperturbed configuration. The wave is instability-driven since the observed time of the propagation is much more than the estimated frictional damping time. Supersonic dust grains moving in the inverse direction with respect to the wave propagation were observed in the rarefaction area. The mechanism explaining the generation and propagation of these waves was presented.

Note that use of the neutral gas flows for affecting the dusty plasma structures is a special feature. Since the flow speed is rather small it produces no significant influence on the background plasma and acts upon the dust particles only. It may give new experimental possibilities (e.g., low-frequency acoustic influences, discharge-independent dust levitation in the gas flow) and is especially appropriate for the direct current discharge, where the dust grains levitate at rather a high neutral gas pressure.

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