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Large-amplitude and shock waves in a dc glow discharge dusty plasma

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In our previous investigations of the dc glow discharge dusty plasma we observed the self-excited dust acoustic waves and recently the dust density waves excited by the gas-dynamic impact. The latter appeared to have quite high amplitude and to be rather steep [1]. However the process of the steepening was not observed. Here we present an observation of a travelling perturbation produced in a dc glow discharge complex (dusty) plasma. The perturbation was formed after a short electromagnetic impulse and first appeared as ramp-shaped. While travelling the perturbation was observed to steepen and finally it appeared to develop into a dust-acoustic shock.

The experiment was performed in a verticlally positioned glass tube of the inner diameter 3.6 cm and 40 cm interelectrode distance [2]. The tube was filled with neon and the stratified glow discharge with cold electrodes was created inside it. Dust particles were injected into the plasma from a container placed above the discharge area. While levitating in the striations the dust grains were illuminated with a "laser sheet" and the scattered light was registered by a digital videocamera with the frame rate of 1000 fps and spatial resolution of 20 μm/pixel. For this experiment the tube was filled wth neon at pressure of 0.5 mbar. Discharge current was adjusted at 4.2 mA. Plastic spherical dust particles 1.87 μm in diameter were injected into the plasma.

To provide the electromagnetic impulse 16 loops of copper wire all in one horizontal plane were coiled around the discharge tube. A battery of high-voltage capacitors with the total capacity of 1.2 mF was charged up to 1.2 kV and then discharged onto the coil through the R = 14 Ohms resistor. The impulse shape was measured with the help of the Rogovsky coil. Due to the low inductivity of the coil the rapid current growth is observed. The current decay is determined by the battery capasitance C and resistance R and lasts about 10 ms. The current impulse amplitude is of the order of 90 A. The corresponding amplitude of the magnetic field inside the coil is estimated to be 150 G.

The impulse applied itself affects the striation only and produces no influence on the dust particles because of their high inertia. The striation could be observed by the videocamera as a bright background glow. When the impulse circuit is closed the striation rapidly i.e. for a time less than the frame duration moves upward towards the anode. As the striation moves away the dust particles loose equilibrium and start falling down under the effect of the gravitational force since the area with the high electric field moves away with the striation. Then as the current is decreasing the striation is moving backwards. The returning striation drags the particles upward. Lower particles have more time to fall down than the upper ones. This leads to the "stretching" of the structure. In the next stage we observe the pronounced division of the structure into two parts with different particle velocities and densities. Upper particles settle in their initial configuration whereas in the lower part of the structure the dust density is still reduced and the dust grains inside it are running upward. Therefore the discontinuity in the dust subsystem is formed (Fig.1). In the further development of the situation the front of the discontinuity escapes from the high density part. Such an escape repeats many times, i.e. the perturbation turns into the damping oscillations.

Having particle positions determined with the subpixel resolution for each videoframe we could derive the densities and velocities corresponding to each moment of time. Since our wave

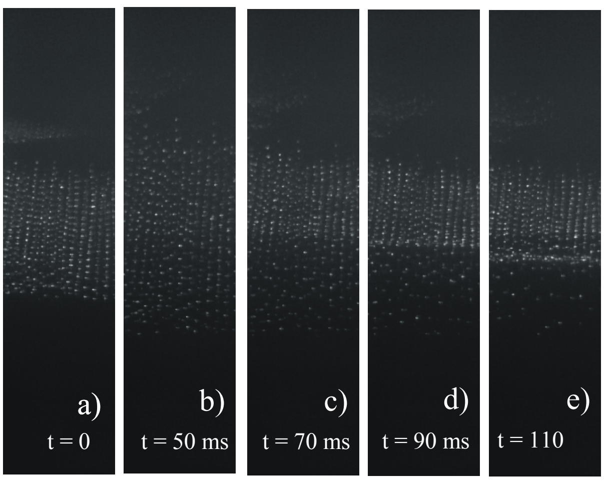

Fig.1. The videoimages representing the development of the shock wave. Moment t = 0 corresponds to the impulse start. Frame size 5x20.5 mm

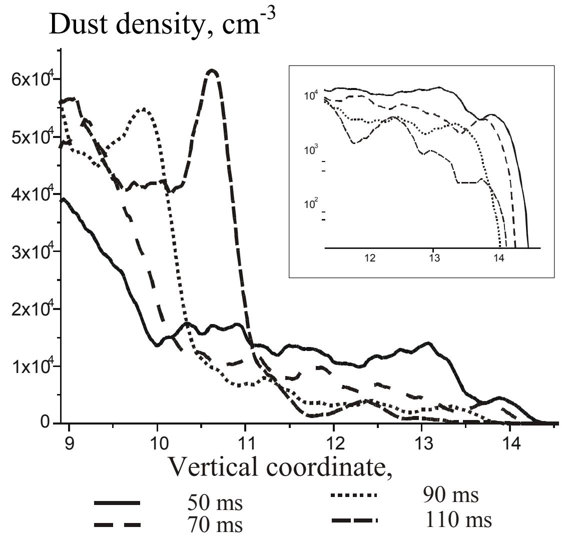

Fig.2. Plots of the dust density corresponding to different moments of time. In the frame the low density part of the perturbation is shown.

performs the one-dimensional motion we treated the distribution of the density along the vertical axis only. The steepening of the perturbation is obvious in Fig.2, where the shapes of the dust density versus the vertical coordinate corresponding to the images in Fig.1 are presented. As we see the front steepens from 50 ms to 90 ms. At 90 and 110 ms the inclinations of the front are about to be equal, so that we may state that the front of the perturbation becomes stationary. The average velocity of the front after it has become stationary is V=3.8 cm/s.

We also analyzed the distributions of the dust particles over the velocities along the vertical and horizontal axes. From these distributions we obtain the drift velocities of the dust particles and their average energies. The average velocity of the dust particles ahead of the front is in the upward direction and equals U_1=5.1 cm/s. Behind the front we see a slow drift of dust particles in the downward direction with the average velocity U_2 = 0.8 cm/s. Therefore the speed of the front in the reference system connected with the upstreaming dust particles in the rarefaction $D_1=U_1+V$=8.9 cm/s. With respect to the downstreaming particles in the high density part the front is moving with the velocity $D_2=V-U_2$=3.0 cm/s.

The values of the characteristic kinetic energies obtained from the velocity distributions show that ahead of the front the dust particles are not thermally equilibrium since the kinetic energy of the dust particles along the vertical axis is significantly larger than that along the horizontal axis. Behind the front the kinetic energies along both axes are the same. So we may suppose the thermal equilibrium there.

The dust density ahead of the shock front is decreasing, it means that the shock is travelling in the nonuniform medium in the direction of the density decrease. Since we observe the steepening of the shock front the dust acoustic velocity must be decreasing with the dust density decrease. This is the condition required for the steepening of shocks in our case.

The dust acoustic velocity is expressed as follows:

$$C_{da}=\sqrt{\frac{Z_d^2 T_i}{m_d}\frac{n_d}{n_i}} \qquad (1)$$

where Z_d is the dust particle charge, T_i is the ion temperature, m_d is the dust particle mass, n_i and n_d are the ion and dust densities respectively. Directly from this equation we see that C_{da} increases with n_d. This is true if other parameters do not depend on the dust density. However both Z_d and n_i may depend on n_d in such a way that Z_d decreases with the increase of n_d and n_i oppositely increases. This makes the dependence of C_{da} on n_d more complicated. The analysis of equation (1) with the effect of the dependence of the dust particle charge on the dust density shows that in the wide range of the electron densities we observe a growth of the dust-acoustic velocity with the dust density.

As we can see the shock is travelling in the medium with the decreasing dust density. However in the high density region the dust density remains almost unchanged during the wave propagation. It means that the compression (ratio of the densities ahead of and behind the front) created by the shock is permanently increasing during the wave propagation and reaches the value of 60. Such compression would be abnormal for usual shocks known in gases or solids. As known conservation laws put a limit for the shock compression which is usually several times or 10 maximum [3]. This phenomenon was not observed in the previous shock experiment under microgravity conditions [4], so here we observed it for the first time in the dusty plasma investigations.

Another unusual feature is the decrease of the average energy of the dust particles from the area ahead of the shock to the area behind the shock. This means that instead of usual 'shock heating' 'shock cooling' is taking place.

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