

DUST ION-ACOUSTIC NONLINEAR WAVE STRUCTURES UNDER CONDITIONS OF NEAR-EARTH AND LABORATORY PLASMAS

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A review on dust ion-acoustic nonlinear wave structures in dusty plasmas is presented. The basic experiments on the nonlinear wave structures in dusty plasmas are considered and the corresponding theoretical descriptions are given. A possibility of the existence of the dust ion-acoustic nonlinear structures under near-Earth and space conditions is discussed.

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INTRODUCTION

A dusty plasma is the plasma containing electrons, ions, neutrals, and dust microscopic particles which are composed of either solid or liquid material. It is always an open system because the currents of electrons and ions flowing onto the dust grains (as well as the energy flows) should be maintained by external sources of the plasma particles and the energy. The dissipation rate is high. Therefore, there is a tendency to self-organization and to formation of long-living nonlinear dissipative and coherent structures in a plasma such as shock waves, solitons, cavitons, collapsing cavities, etc. One can expect wider manifestations of nonlinear structures in dusty plasmas than in the case of usual plasmas. The significant property of dusty plasmas is the dust particle charging process. As a rule, under conditions of laboratory experiments the microparticles are negatively charged, their charges being determined by the fluxes of electrons and ions, which are absorbed by microparticles. Any changes of plasma parameters vary these fluxes that results in variable charge of the latter.

At present, the problem of the excitation and propagation of nonlinear waves occupies an important place in the physics of dusty plasma. Interest in this kind of research is often associated with the fact that the processes of dust grain charging are far from equilibrium, so that the anomalous dissipation, which, by its very nature, originates from the charging process, can play a decisive role. It is this anomalous dissipation mechanism that is responsible for the existence of a new kind of shocks [1, 2], namely dust ion-acoustic shocks, that are "collisionless" in the sense that they are almost completely insensitive to electron-ion collisions. However, in contrast to classical collisionless shock waves, the dissipation due to dust charging involves interaction of electrons and ions with dust grains through microscopic electron and ion currents to the grain surfaces. The anomalous dissipation plays a very important role in the propagation of other dust ion-acoustic nonlinear structures, e.g., in the case of the so-called "weakly dissipative" dust ion-acoustic solitons, whose shape is described by soliton solutions in a certain range of values of the Mach number [3-6]. Because of the anomalous dissipation, these solitons are slowed down and damped. Dust ion-acoustic shock waves were observed in a double plasma device at the Institute of Space and Astronautical Science (Japan) [7]

and in a Q machine device at the University of Iowa (USA) [8] almost simultaneously. Observation of dust ion-acoustic solitons was reported in [9].

There are plans to carry out experiments on dust ion-acoustic nonlinear wave structures during the mission of the International Space Station. The purpose of this brief review is to present the most important results on dust ion-acoustic nonlinear wave structures in dusty plasmas.

1. SHOCKS IN LABORATORY PLASMA

Let us formulate the main experimental results on dust ion-acoustic shocks in dusty plasmas. In experiments [7], Nakamura et al. revealed that the most important feature of dust ion-acoustic shocks in dusty plasmas is the following.

(i) In the absence of dust, the effect of the electron and ion charge separation gives rise to oscillations in the shock wave profile in the vicinity of the shock front, while the presence of dust suppresses these oscillations.

The experiments [8] showed that:

(ii) Dust ion-acoustic shocks are generated at sufficiently high dust densities (under the experimental conditions of [8], at dust densities such that $\varepsilon Z_{d0} \equiv n_{d0} Z_{d0} / n_{i0} \geq 0.75$, where $q_d = -Z_{d0}e$ is the dust grain charge, $-e$ is the electron charge, $n_{d(i)}$ is the dust (ion) density, and the subscript "0" stands for the unperturbed plasma parameters). In Ref. [8], the conclusion about the formation of a shock wave was drawn from the fact that the perturbation front steepens as time elapses. At sufficiently low dust densities, the perturbation front does not steepen but instead widens.

(iii) When the shock wave structure has formed, the shock front width $\Delta\xi$ is described by the theoretical estimate, which is based on the model developed in Ref. [1]

$$\Delta\xi \propto Mc_s / \nu_q, \quad (1)$$

where Mc_s is the shock wave speed, M is the Mach number, c_s is the ion-acoustic speed, ν_q is the grain charging rate.

(iv) The velocity of the dust ion-acoustic shocks increases considerably with increasing εZ_{d0} .

In this context, the requirement to the theoretical model is the adequate description of the relevant experiments. We use the so-called ionization source model developed in Refs. [10, 11] and based on the hydrodynamical approach. We note that under the experimental conditions of Refs. [7, 8], the ionization source term in the evolutionary equation for the ion density should be independent on the electron density.

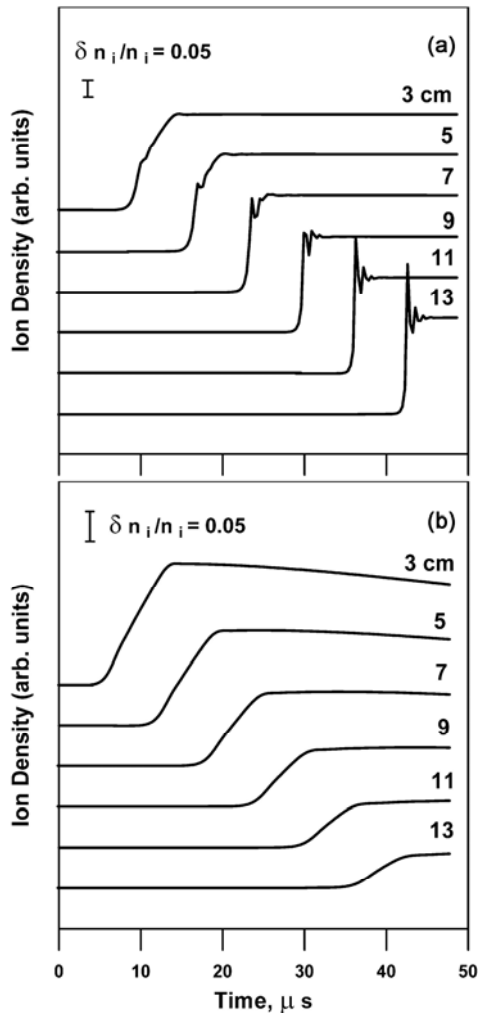


Fig. 1. Time evolutions of the ion density at different distances from the grid for the data of the experiments [7] in the absence (a) and in the presence (b) of dust

Now, we test our theoretical model against the experimental result (i), which was obtained in Ref. [7]. The experiments described in that paper were carried out with a double plasma device, which was modified so that the dust component was present in the plasma. The calculations were carried out for different dust densities and for the parameter values which correspond to the values of the experiments [7]. The width of the perturbation and its shape were determined self-consistently, in accordance with the method for exciting a shock wave. In Fig. 1 (which is analogous to Fig. 3 from Ref. [7]), we illustrate the time evolution of the ion density at different distances from the grid. We can see that the electron and ion charge separation gives rise to oscillations in the shock wave profile and that the dust

suppresses these oscillations, as is the case in the experiments [7]. The theoretically calculated rise time of the shock front is about 5 μ s, which corresponds to the experimental data.

Theory modeling of the experiments [8] performed with a Q-machine has been carried out for the cesium vapor plasma parameters, which correspond to the experimental those. The calculations were carried out for different values of the parameter ϵZ_{d0} . In Fig. 2 (which is analogous to Fig. 2 from Ref. [8]), we illustrate the time evolution of the ion density at different distances from the grid. The time evolutions (heavy curves) were calculated for $\epsilon Z_{d0} = 0$ (a) and $\epsilon Z_{d0} = 0.75$ (b). The light curves show the widening of the wave front (at $\epsilon Z_{d0} = 0$) and its steepening (at $\epsilon Z_{d0} = 0.75$). This agrees with the experimental data from Ref. [8].

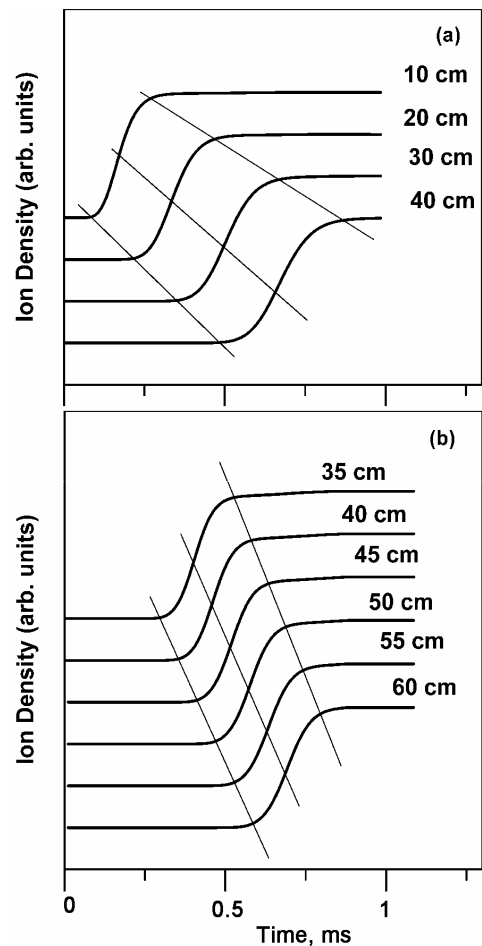


Fig. 2. Time evolutions of the ion density (heavy curves) at different distances from the grid for the data of the experiments [8] and $\epsilon Z_{d0} = 0$ (a) and 0.75 (b). The light lines show the widening of the wave front (at $\epsilon Z_{d0} = 0$) and its steepening (at $\epsilon Z_{d0} = 0.75$)

The extent to which the shock front widens was calculated to be $\Delta\xi/Mc_s \approx 0.3$ ms (see Fig. 2,b), which corresponds to that observed experimentally (see Fig. 2,b) in Ref. [8]) and also to the estimate obtained using the theoretical model of Ref. [1].

In the data shown in Fig. 2,b in Ref. [8], we notice that in the case where dust is present, the amplitude of the shock decreases as we move away from the grid. Such a decrease in the shock amplitude is due to momentum loss by ions as a result of their absorption on the grain surfaces and their Coulomb collisions with the grains and is associated, in particular, with an attenuation of the ion flux as the ions pass through the region of the dust. Numerical analysis shows that the decrease in the shock amplitude and the attenuation of the ion flux manifest themselves stronger with increase in the dust size and the ion density.

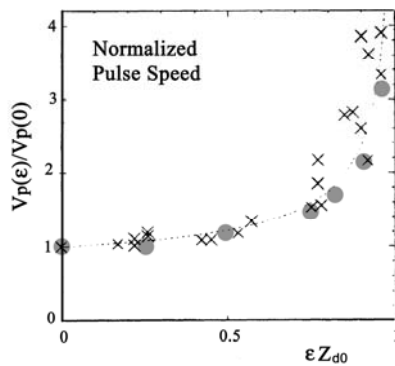


Fig. 3. Dependence of the perturbation front velocity (normalized to its value in the absence of dust) on ϵZ_{d0} for the data of the experiments [8].

The initial perturbation evolves in such a way that its front velocity V_p becomes nearly constant about 1 ms after it starts propagating through the background plasma. Fig. 3 shows the dependence of the perturbation front velocity (normalized to its value in the absence of dust, $\epsilon = 0$) on the parameter ϵZ_{d0} . For comparison, we also plot the experimental points (crosses) taken from Fig. 3 in Ref. [8]. The calculated results are represented by closed circles. The agreement between theory and experiment is quite good.

Thus, the ionization source model [10, 11] makes it possible to describe all the main experimental results on dust ion-acoustic shock waves.

2. SOLITONS

Here, we describe briefly the main results of the investigation of the dust ion-acoustic solitons in dusty plasmas [3-6]. The anomalous dissipation caused by the charging processes means that the existence of completely steady-state nonlinear structures is impossible. In reality, this note is truth for any real system. However, in dusty plasmas it leads to qualitatively new results which are related, in particular,

to the necessity to take into account the effect of adiabatically trapped electrons for the case when the plasma potential in the soliton is positive. In this case, the electron density is described by Gurevich distribution [3]. The main results of the investigations [3-6] are the following:

(1) The properties of the compressive solitons with the trapped electrons are very different from those with not trapped those (Boltzmann electrons). In particular, the maximum possible amplitude of the soliton with the trapped electrons is much larger than that of the “Boltzmann” soliton, while the region of allowable Mach numbers for the former is much wider than for the latter. This shows the principal possibility to study experimentally the role of trapped electrons in the soliton formation.

(2) A specific feature of ion-acoustic solitons in the presence of dust is the possibility of existence of rarefaction solitons, or so-called hybrid solitons [4]. In this case, the plasma potential in the soliton is negative and the electron density is described by Boltzmann distribution.

(3) The evolution of the initial perturbation in the form of the steady-state soliton in dusty plasmas occurs in the following manner. The soliton is damped due to the dissipation originating from the dust particle charging processes. The speed of the perturbation decreases. However, at any time the form of the evolving perturbation is similar to that of the steady-state soliton corresponding to the Mach number at this moment of time.

(4) In contrast to conventional solitons, the total energy and total momentum of a weakly dissipative soliton decrease in time.

(5) After the interaction of two damped solitons, each perturbation has the form, which is close to that of the same soliton perturbation propagating individually from the beginning (not subjected to the interaction). This property is the property inherent in solitons. Thus there is a possibility of the existence of the dust ion acoustic solitons which are damped and slowed down, but their form corresponds to the soliton one for the running value of their speed. They can be called as “weakly-dissipative solitons”.

Fig. 4 presents the results of simulation [6] of interaction between a compression and rarefaction solitons. The dashed lines in Fig. 4 show the envelopes of the amplitudes of the corresponding perturbations in the absence of interaction. After the interaction, each of the solitons restores the shape of the corresponding soliton propagating without interaction. The grey vertical lines show the positions of the soliton peaks after the interaction, while the black vertical lines show the positions of the corresponding peaks in the absence of interaction. The perturbations arising between the solitons after their interaction are residual electrostatic oscillations, the amplitude of which decreases with distance between the solitons.

The above five properties are inherent in dusty plasmas with negatively charged dust. In the case of positively charged dust grains [5], perturbations are attenuated more slowly and propagate over longer distances than in the case of negatively charged grains.

An important point is that, in the case of positively charged dust grains (in contrast to the case of negatively charged grains), no rarefaction dust ion-acoustic solitons can exist.

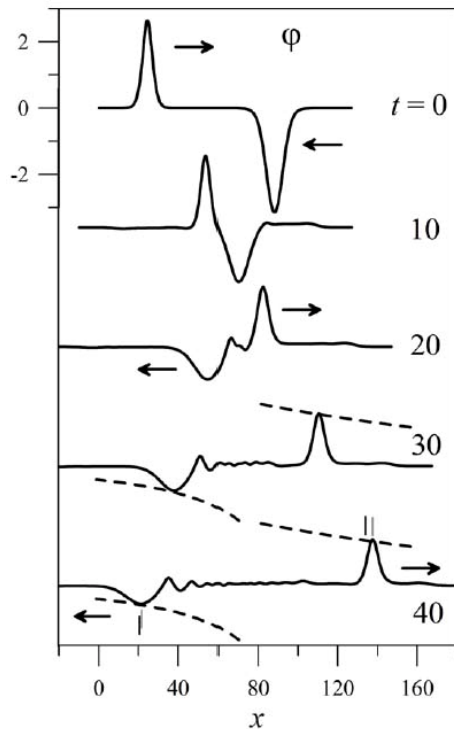


Fig. 4. Profiles of the dimensionless electrostatic potential ϕ at different instants of time t during the interaction between a weakly dissipative compression dust ion-acoustic soliton and a counter-propagating weakly dissipative rarefaction dust ion-acoustic soliton

Dust ion-acoustic solitons can be studied experimentally by using a double plasma device and Q-machine [7, 8]. Observations of solitons in ionospheric and space plasmas can also be used to determine the sign of the dust grain charge and diagnose the dust grain substance.

3. NEAR-EARTH AND SPACE PLASMAS, APPLICATIONS

Here, we present some possibilities of observation of the dust ion-acoustic shocks and some applications where their physics can be important.

(1) The idea of the formation of shocks related to dust charging in active rocket experiments, which use the scheme of the experiments Fluxus-1 and -2 and involve the release of some gaseous substance in near-Earth space, was forwarded in [12]. The source for the charged particle release in the ionosphere in these experiments is the generator of high-speed plasma jets. The shock wave front is associated with the fore (border)-part of the jet propagating in the plasma of the ionosphere. Macro (dust) particles appear as a result of condensation. Drops are charged due to their interaction with the ambient plasma and the photoelectric effect. The optimum speeds of the jet are 10 km/s. The optimum altitudes for such experiments are

500...600 km. The active experiments, where the shocks in charge-varying dusty plasmas can be observed, can be helpful to model different physical phenomena occurring in nature, e.g., in the process of a large meteoroid impact with the Moon surface [13]. The evolution of the impact plume can lead to the formation of shock wave structure associated with an appearance of charged microparticles which are created in the process of condensation of the substance of vapor plume as well as are thrown from the crater and surrounding it regolith layer.

(2) The presence of dust in cometary coma can modify shock wave formed as a result of the solar wind interaction with a comet [14]. The outer shock wave (bow shock) can be considered as the dust ion-acoustic shock wave, because it is formed as a result of the interaction of cometary ions with the solar wind protons. For dust densities $n_d > 10^6 \text{ cm}^{-3}$ near the comet nucleus, charged dust particles influence drastically the structure of the bow shock front. Its width is in accordance with the theory of shocks related to dust particle charging.

(3) The dust ion-acoustic shocks also may find significant technological applications in, e.g., the so-called hypersonic aerodynamics. The main difficulties of hypersonic flight in the atmosphere are associated with the generation of shock waves, which leads to heavy mechanical and thermal loads on the structural components of an aircraft, considerably increases the resisting forces, and lowers the engine efficiency. Usually, these negative effects are reduced through an optimum streamlining of the aircraft. However, a more promising possibility seems to be changing the properties of the air surrounding the aircraft. In this way, the negative effects may be lessened by modifying the mechanisms for the formation and propagation of shock waves by plasma methods (such as local heating of air around the aircraft). However, the dust (aerosol) that is produced due to condensation from the surrounding air can, in turn, modify the behavior of the shock-wave structures. That is why an understanding of the dissipation mechanisms in shock-wave structures is of key importance in such situations.

SUMMARY

Thus, an anomalous dissipation originating from the charging processes results in a possibility of the existence of a new kind of shocks. The theoretical ionization source model allows us to describe all the main results on the dust ion-acoustic shocks obtained in the laboratory experiments. There is a possibility of the existence of the dissipative dust ion-acoustic solitons. The dust ion acoustic nonlinear structures are important in different real and artificial objects of near-Earth and space plasmas. Observations of dust ion-acoustic nonlinear wave structures in ionospheric and space plasmas can, in particular, be used to determine the sign of the dust grain charge and diagnose the dust grain substance.

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ПЫЛЕВЫЕ ИОННО-ЗВУКОВЫЕ НЕЛИНЕЙНЫЕ ВОЛНОВЫЕ СТРУКТУРЫ В УСЛОВИЯХ ОКОЛОЗЕМНОЙ И ЛАБОРАТОРНОЙ ПЛАЗМЫ

С.И. Попель

Представлен обзор по пылевым ионно-звуковым нелинейным волновым структурам в пылевой плазме. Рассмотрены основные эксперименты по нелинейным волновым структурам в пылевой плазме и приведено соответствующее теоретическое описание. Обсуждаются возможности существования пылевых ионно-звуковых нелинейных структур в условиях околоземной и космической плазмы.

ПИЛОВІ ІОННО-ЗВУКОВІ НЕЛІНІЙНІ ХВИЛЬОВІ СТРУКТУРИ В УМОВАХ НАВКОЛОЗЕМНОЇ І ЛАБОРАТОРНОЇ ПЛАЗМИ

С.І. Попель

Представлено огляд по пиловим іонно-звуковим нелінійним хвильовим структурам у пиловій плазмі. Розглянуто основні експерименти з нелінійних хвильових структур в пиловій плазмі та наведено відповідний теоретичний опис. Обговорюються можливості існування пилових іонно-звукових нелінійних структур в умовах навколоземної і космічної плазми.