J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 421–424

Dust Acoustic and Dust Ion Acoustic Nonlinear Structures: Theory and Experiments

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(Received: 9 December 2003 / Accepted: 26 February 2004)

Abstract

Dust acoustic and dust ion acoustic nonlinear structures in complex (dusty) plasmas are described. The emphasis is given to the new results. We describe the dust acoustic bow shock formed in the interaction of the solar wind with cometary dusty coma. We discuss the possibility of observation of shocks related to the dust charging process in active rocket experiments, which involve the release of some gaseous substance in near-Earth space, as well as the laboratory experiments modeling active those. We present an explanation of the experiments in rf plasma discharge where phase transition was occurred during dust acoustic shock propagation.

Keywords:
complex (dusty) plasmas, nonlinear structures, shock waves, solitons

1. Introduction

At present a major portion of the investigations of plasmas is devoted to multicomponent plasmas containing electrons, ions, charged microspheres or dust grains, and neutral particles. The term "complex plasmas" is finding increasing use for such plasmas. The dust particle charging process is a basis for the strong dissipativity of the complex plasma system. The strong dissipativity results in a new physics of nonlinear wave structures. First, anomalous dissipation originating from dust grain charging appears. Second, new kinds of nonlinearities take place. The anomalous dissipation leads to preferential importance of shock waves in complex plasmas, which have specific features that distinguish them from ordinary collisional and collisionless shock waves. That dust ion acoustic shock waves associated with anomalous dissipation can actually exist was proved analytically in [1]. Dust ion acoustic shock waves were observed for the first time in laboratory experiments at the Institute of Space and Astronautical Science (Japan) [2] and at the University of Iowa (USA) [3]. Besides dust ion acoustic solitons can propagate in complex plasmas. Theory description of the dust ion acoustic solitons has been given in [4]. They were observed in laboratory experiments at the Institute of Space and Astronautical Science [5].

At present the significant attention of researchers is paid to the case of dust acoustic nonlinear waves. A three-dimensional dust-acoustic shock was observed in a microgravity experiment [6]. The experiments on dust acoustic shocks in a laboratory two-dimensional (2D) complex plasma have been performed at the Max-Planck-Institute for Extraterrestrial Physics (Germany) [7].

The purpose of this paper is to reflect the most important results on dust ion acoustic and dust acoustic nonlinear structures performed with the participation of researchers of the Institute for Dynamics of Geospheres RAS (Russia). We present both the result of the theoretical treatment of dust ion acoustic shocks and the description of the dust acoustic bow shock formed in the interaction of the solar wind with cometary dusty coma. We discuss the possibility of observation of shocks related to the dust charging process in active rocket experiments, which involve the release of some gaseous substance in near-Earth space, as well as the laboratory experiments modeling active those. We present an explanation of the experiments in rf plasma discharge where phase transition was occurred during dust acoustic shock propagation.

2. Dust ion acoustic shocks

Let us formulate the main experimental results on shocks in complex plasmas. In experiments [2], Nakamura *et al.* revealed that the most important feature of dust ion acoustic shocks in complex 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 [3] showed that:

(ii) Dust ion acoustic shocks are generated at sufficiently high dust densities (under the experimental conditions

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of [3], at dust densities such that $\varepsilon Z_{d0} \equiv n_{d0}Z_{d0}/n_{i0} \geq 0.75$, where $q_d = -Z_d e$ 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 [3], 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 $\Delta\xi \sim Mc_s/\nu_q$ is described by the theoretical estimate, which is based on the model developed in [1], where Mc_s is the shock-wave structure 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 waves 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 [8,9].

We have tested [9] our theoretical model against the experimental result (i), which was obtained in [2]. We have shown 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 of [2]. The theoretically calculated rise time of the shock front is about 5 μs, which corresponds to the experimental data.

We have studied the evolution problem under the conditions of the experiment [3]. We showed the widening of the wave front at $\varepsilon Z_{d0} = 0$ and its steepening at $\varepsilon Z_{d0} = 0.75$. This agrees with the experimental data from [3]. The extent to which the shock front widens was calculated to be $\Delta\xi \sim Mc_s/\nu_q \sim 0.3$, which corresponds to that observed experimentally (see Fig. 2b in [3]) and also to the estimate obtained using the theoretical model of [1]. We demonstrated that the dependence of the perturbation front velocity (normalized to its value in the absence of dust, $\varepsilon = 0$) on the parameter εZ_{d0} is an a quite good agreement with the experimental data (see Fig. 2 in [9]).

Thus, the theoretical ionization source model makes it possible to describe all the main experimental results (i)–(iv) on dust ion acoustic shock waves.

3. Dust ion acoustic bow shock in interaction of solar wind with cometary coma

Studies of interaction of the solar wind with cometary comae do not take into account usually the influence of dust. Cometary nuclei are found to be, most likely, dominated by refractories, very porous and fragile [10]. Under the action of the solar light volatile components of the cometary nucleus evaporate and vapor stream entrains dust particles.

The dust/gas ratio is introduced to characterize the ratio of masses of refractories to volatiles in the cometary nuclei. In quantitative terms, an average value of dust/gas ratio exceeds unity [11]. The dust/gas ratio obtained from the coma observations is in the range 0.1–1 [12–14]. Assuming ten per cent content of the dust in the cometary substance and bulk density of about 1 g/cm^3, we obtain that the density of micron-sized particles is of the order of 10^{11} cm^{-3} [15].

The crucial point of the investigation of the interaction of the solar wind with cometary comae is the description of bow shock formed as a result of this interaction. The presence of dust constituting tens per cent of the total mass of the coma can modify the bow shock. The size distribution of coma grains is such that the total area is dominated by the smallest grains present, and the 1P/Halley in-situ results showed that this continued to hold down to radii $a \sim 0.01$ μm. The size distribution is well determined observationally [16] as an approximate power-law function with index ~ –4 in terms of radius. We consider in all subsequent estimates and calculations the characteristic dust grain size as $a \sim 1$ μm.

Due to the processes of photoionization the gas surrounding the comet becomes ionized at the distances exceeding several kilometers from the cometary nucleus [17]. It is the interaction between the cometary ions and the solar wind protons that is considered as the strongest one in the interaction between the cometary coma and the solar wind. Because the main particles participating in the interaction are ions, one may conclude that the bow shock is the ion acoustic bow shock. The presence of dust in the coma leads to another important kind of interaction — the interaction between the solar wind protons and charged dust of the coma. For the parameters of the solar radiation spectrum in the vicinity of the Earth, electron and ion temperature in the solar wind $T_e^{SW} = T_i^{SW} = 15$ eV, the ion temperature in the cometary coma $T_i^c = 0.03$ eV, the electron and ion (proton) density in the solar wind $n_e^{SW} \sim n_p = 20$ cm^{-3}, the ion density in the coma near the nucleus $n_{i0}^c = 1.43\cdot10^5$ cm^{-3}, the ion density in the coma depending on the distance r from the nucleus as $n_i^c = n_{i0}^c(r_0/r)$, the radius of the nucleus $r_0 = 1$ km, and H_3O^+ cometary coma ions, we find that the bow shock is formed at the distance R ~ 10^4 km and the dust particles acquire positive charges reaching the values exceeding $Z_d e = 2000e$ for $r \approx R$.

The structure of the bow shock is described by the set of equations which are a generalization of the ionization source model to two kinds of ions and positive charges of dust grains. For $r_0 = 1$ km and dust densities $n_d > 10^6$ cm^{-3} near the comet nucleus, charged dust particles influence drastically the structure of the bow shock front. There is a good agreement between the estimate for the shock front width $\Delta\xi \sim c_s/\nu_q$, where c_s is the ion acoustic speed in the solar and ν_q is the dust charging frequency. The bow shock is similar, by its origin, to the shocks observed in [2,3] and those predicted theoretically in [1].

4. Dust ion acoustic nonlinear structures in active and laboratory experiments, which use generator of high-speed plasma jets

(1) The idea of the formation of shocks related to dust charging in active rocket experiments, which involve the

release of some gaseous substance in near-Earth space, was forwarded in [18]. 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. Nano- and micro- (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.
(2) The laboratory experiments modeling the active rocket experiments have been carried out at the Institute for Dynamics of Geospheres RAS. The main results are the following: clusters consisting of 10–1,000 atoms appear at the initial stage of jet expansion, significant part of substance is condensed (approximately 50 %); appearance of anomalous ionisation in the region in front of the propagating jet, that is characterized by irradiance in the environment of the jet; conservation of high ionisation degree for significant expansion of the jet; significant radiation from the region of the interaction of the jet and the ambient medium (the energy of the radiation reaches more than 60 % of the initial energy of the jet).

5. Melting dust acoustic shock in a 2D complex plasma

The experiments on shocks in a laboratory two-dimensional complex plasma which suggest the melting transition from "flat" plasma crystals to liquid (and possibly gaseous) phase were performed [7] in a setup using a capacitively coupled rf discharge. The discharge chamber had a lower disk electrode and an upper ring electrode. The upper electrode and the chamber were grounded. A rf power of 10 W was applied to the lower electrode. The working argon gas pressure was 1.8 Pa in the chamber. Monodisperse plastic microspheres of approximately 8.9 µm size were levitated in the sheath above the lower electrode forming a monolayer hexagonal lattice. They were confined radially in a bowl shaped potential formed by a rim on the outer edge of the electrode. A horizontal tungsten wire 0.1 mm in diameter was placed 4 mm below the particle layer and roughly half way between the center and the edge of the electrode. The wire was normally grounded so that it had little influence on the particles. A short negative pulse (–100 V, 50 ms applied to the wire at 0.07 s) pushed the particles away breaking the lattice above the wire and creating a pulsed one-dimensional compressional disturbance propagating horizontally perpendicular to the wire. The lattice also oscillated in the vertical direction with a small amplitude which caused a periodic change of brightness of the particles. The disturbance propagated to the other end of the crystal and melted it from the excitation edge to about the middle of the field of view. A time interval of about 1 min allowed the lattice to come to an equilibrium between the experimental runs and recrystallise.

The disturbance can be treated as a shock wave because:

(1) The dust grain kinetic temperature and the defect fraction have a jump at the shock front, there is the density compression; There is the mass transfer via the shock front. The mass transfer is described well by the first Hugoniot relationship $n_2\ (V - v_2) = n_1 V$, where V is the shock propagation velocity, m is the particle mass, n is the two dimensional particle number density, v is the component of the particle velocity normal to the shock front, the indices 1 and 2 denote the condition ahead and behind the shock respectively;
(2) The width of the shock front is determined by several mean free paths of dust grains in the region of the shock front. This is related to the fact that in this region the grains are in the "collisional regime".

The observed shock is related to the melting of the plasma crystal. The solid-to-liquid (and possibly gaseous) phase transition for a plasma crystal appears to develop via the growth of crystal defects, directed particle flows around crystalline islands (floes), enhanced vibrations associated with greater order and flow suspension, to a completely disordered state. The mechanism of the formation of the disordered state is the increase in the dust grain temperature (up to 300 eV) behind the shock front. For such a temperature the Coulomb coupling parameter becomes of order unity. This seems neither a straightforward first-order nor a classical second-order transition.

6. 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. The dust ion acoustic nonlinear structures are important in different real and artificial objects of geophysical and space plasmas. In particular, for rather dense dusty coma the bow shock formed as a result of the interaction of the solar wind with the coma is expected to be related to the anomalous dissipation due to the dust particle charging. Dust acoustic shock propagation in plasma crystal can lead to the melting of the latter.

This work was supported by INTAS (grant No. 2001-0391) and RFBR (grant No. 03-02-16664-a).

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