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Dissipative processes and dust ion-acoustic shocks in a *Q* machine device

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A comparative analysis of the most important dissipative processes occurring during the excitation and propagation of dust ion-acoustic shocks in a *Q* machine device, among which are the charging of dust grains, the absorption of ions by grains, the transfer of the ion momentum to the grains, and Landau damping, is performed. The relative roles played by dissipative processes in different types of laboratory experiments with complex plasmas are estimated. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1885476]

At present, the problem of excitation and propagation of dust ion-acoustic (DIA) shocks occupies an important place in the physics of complex (dusty) plasma. Interest in this kind of research is associated primarily with the fact that the processes of dust grain charging are far from equilibrium precisely on ion-acoustic time scales, so that the anomalous dissipation, which, by its very nature, originates from the charging process, often plays a decisive role.[1] It is this anomalous dissipation mechanism that is responsible for the existence of a new kind of shock[2] that is "collisionless" in the sense that such shocks are almost completely insensitive to electron-ion collisions. However, in contrast to classical collisionless shocks, the anomalous dissipation involves interaction of electrons and ions with dust grains through microscopic electron and ion currents to the grain surface. DIA shocks related to this anomalous dissipation can have important applications in the description of natural phenomena such as those occurring in the interaction of the solar wind with dusty cometary comas[3] and also may find significant technological applications in, e.g., the so-called hypersonic aerodynamics.[4] DIA shock waves were observed in a *Q* machine device[5] and in a double plasma device[6] almost simultaneously. There are plans to carry out experiments on DIA shocks during the mission of the International Space Station (ISS).

DIA shocks can be described theoretically by solving a set of hydrodynamic equations that is specially derived for a complex plasma from the kinetic equations for electrons, ions, and dust grains.[7] These equations are the basis for the so-called hydrodynamic ionization source model which allows us to obtain[8,9] DIA shock structures in a *Q* machine device (for large enough dust densities) as a result of evolution of an initial perturbation and to explain the experimental value of the width of the shock wave front and the dependence of the perturbation front velocity on the dust density.

Of course, in the hydrodynamic derivation, such a purely kinetic effect as Landau damping is not taken into consideration. However, in some situations, Landau damping can play an important role. Thus, the fact that, in laboratory experiments in a *Q* machine device where $T_e \sim T_i$, DIA waves were not observed at sufficiently low dust densities was attributed precisely to this damping.[5] Here, $T_{e(i)}$ is the electron (ion) temperature.

There are different approaches to describing Landau damping in complex plasmas. First of all, we must mention the papers in which the corresponding damping rates were calculated without allowance for the grain charging (see, e.g., Ref. 10). As early as 1993,[1] it became clear that the charging of dust grains has a significant impact on the damping described at the kinetic level (which will be referred below to as kinetic damping), part of which is Landau damping. Consequently, dust grain charging should be taken into account in calculations. Nevertheless, theoretical studies are still often conducted based on the results of Ref. 10, in particular, because the expression for the kinetic damping rate of DIA waves that takes into account dust grain charging and could be used to analyze the results of complex plasma experiments has not yet been given in a compact form. As for the results that are presented in Refs. 1 and 11 and could be used to calculate the corresponding damping rates, they either have a complicated integro-operator form or refer to the limiting cases irrelevant to the present-day experiments. Moreover, in Refs. 1 and 11, the final formula for the dielectric function of a complex plasma, which is important for deriving the expression for the kinetic damping rate, involves inconsistencies. All this goes to show that it is necessary to

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refine the expression for the kinetic damping rate of DIA waves and to reduce it to a compact form, convenient for analyzing the experimental results.

Here, we classify dissipative processes during formation and propagation of DIA perturbation in a Q machine device and determine the ranges of plasma parameters in which some particular processes dominate. We compare also the relative roles played by dissipative processes in different types of laboratory experiments with complex plasmas.

The experiments[5] performed in a Q machine device (that was modified to allow the introduction of dust grains into the plasma) were performed with Cs^+ ions. The plasma parameters of the experiments were $T_e \approx T_i \approx 0.2$ eV, $n_{i0} \sim 10^6 - 10^7$ cm^{-3}, $a \sim 0.1 - 1$ μm. The parameter $\epsilon Z_{d0} \equiv n_{d0} Z_{d0}/n_{i0}$ was varied from 0 to 0.95. Here, n_i is the ion density, n_d is the dust density, $q_d = -Z_d e$ is the dust grain charge, $-e$ is the electron charge, a is the grain radius, and the subscript 0 stands for the unperturbed plasma parameters. The advantage of these experiments is the negligible role of neutral atoms in the dissipation processes which is caused by relatively low neutral atom densities.

An analysis of the dispersion properties of ion-acoustic waves on the basis of the set of equations of the hydrodynamic ionization source model[8,9] yields the following expression for the linear damping rate

$$\gamma_{\mathbf{k}} \approx -\Gamma \equiv -\frac{\nu_{\rm ch} + \tilde{\nu}}{2}, \tag{1}$$

where the rate $\nu_{\rm ch}$, at which the ions are absorbed by the dust grains, and the rate $\tilde{\nu}$, at which the ions lose their momentum as a result of their absorption on the grain surfaces and their Coulomb collisions with the grains, are equal, respectively, to

$$\nu_{\rm ch} = \nu_q \frac{Z_{d0} d}{1 + Z_{d0} d} \frac{(\tau + z_0)}{z_0(1 + \tau + z_0)}, \tag{2}$$

$$\tilde{\nu} = \nu_q \frac{Z_{d0} d}{(1 + Z_{d0} d) z_0 (1 + \tau + z_0)} \left(z_0 + \frac{4\tau}{3} + \frac{2 z_0^2}{3\tau} \Lambda \right). \tag{3}$$

Here, $\nu_q = \omega_{pi}^2 a (1 + z_0 + \tau)/\sqrt{2\pi} v_{T_i}$ is the grain charging rate, $\omega_{pi} = \sqrt{4\pi n_{i0} e^2 / m_i}$ is the ion plasma frequency, m_i is the ion mass, $d = n_{d0}/n_{e0}$, n_e is the electron density, $\tau = T_i/T_e$, $z = Z_d e^2 / a T_e$, $v_{Ti} = \sqrt{T_i/m_i}$ is the ion thermal velocity, $\Lambda = \ln(\lambda_{Di}/\max\{a, b\})$ is the Coulomb logarithm, $\lambda_{Di} = \omega_{pi}/v_{Ti}$ is the ion Debye length, and $b = Z_{d0} e^2 / T_i$. Equations (2) and (3) are valid in the range $v_i / c_s < 1$, where v_i is the ion velocity.

It is clear that, in terms of the hydrodynamic ionization source model, the dissipation in a complex plasma is governed by the processes of absorption of ions by dust grains and also by Coulomb collisions between ions and dust grains. All these processes are closely related to the mechanisms by which the grains are charged. In fact, on the one hand, we have $\Gamma \propto \nu_q$ and, on the other, we see that the absorbed ions participate directly in dust grain charging.

The hydrodynamic approach to describing DIA shocks is valid only if dissipative processes that are taken into account in the hydrodynamic equations turn out to be more important than kinetic (including Landau) damping. We have derived a dispersion relation and expressions for the kinetic damping rate of DIA waves on the basis of a standard, purely kinetic approach, with the use of the method developed in Ref. 11. We have obtained[9] the expression for the dielectric function of a complex plasma which coincides with the expression presented in Ref. 1. Note that, in a paper by Tsytovich and de Angelis,[11] the more general expression for $\varepsilon_{\mathbf{k},\omega}$ contains a misprint: the sign between the terms in the square brackets in the second row of formula (55) is incorrect. In particular, for dust grains with a zero velocity, formula (55) of Ref. 11 does not pass over to the formula that was obtained earlier in Ref. 1 for the dielectric function of a complex plasma.

In the case $\omega_{\mathbf{k}}^s \gg \nu_q$ the kinetic damping rate of DIA waves takes the form

$$\gamma_{\mathbf{k}}^L = \gamma_{\mathbf{k}}^{L,R} + \gamma_{\mathbf{k}}^{L,q}, \tag{4}$$

$$\gamma_{\mathbf{k}}^{L,R} \approx -\sqrt{\frac{\pi}{8} \frac{m_e}{m_i} \frac{n_{i0}}{n_{e0}}} \frac{\omega_{\mathbf{k}}^s}{(1 + |\mathbf{k}|^2 \lambda_{De}^2)^{3/2}} \times \left(1 + \frac{n_{i0}}{n_{e0}} \sqrt{\frac{T_e^3}{T_i^3}} \sqrt{\frac{m_i}{m_e}} \exp\left[-\frac{T_e n_{i0}}{2 T_i n_{e0} (1 + |\mathbf{k}|^2 \lambda_{De}^2)} \right] \right), \tag{5}$$

$$\gamma_{\mathbf{k}}^{L,q} = -\nu_q \sqrt{\frac{\pi}{2}} \frac{Z_{d0} d}{z_0} \frac{(\tau + z_0)}{(1 + \tau + z_0)(1 + |\mathbf{k}|^2 \lambda_{De}^2)}, \tag{6}$$

where m_e is the electron mass, $\lambda_{De} = \sqrt{T_e / 4\pi n_{e0} e^2}$ is the electron Debye length, $\mathbf{k}$ is a wave number, and

$$\omega_{\mathbf{k}}^s \approx \frac{|\mathbf{k}| c_s \sqrt{n_{i0}/n_{e0}}}{\sqrt{1 + |\mathbf{k}|^2 \lambda_{De}^2}} \tag{7}$$

is the linear dispersion relation for DIA waves. The case $\omega_{\mathbf{k}}^s \gg \nu_q$ is of primary interest for the description of DIA perturbations because the main contribution to their spectrum comes, as a rule, from modes with frequencies $\omega_{\mathbf{k}}^s \gg \nu_q$.

The first term $\gamma_{\mathbf{k}}^{L,R}$ on the right-hand side of Eq. (4) describes ordinary Landau damping on electrons and ions, and the second term $\gamma_{\mathbf{k}}^{L,q}$ describes damping due to the interaction of electrons and ions with dust grains. The rates of these two damping processes are both referred to as the kinetic damping rate. The introduction of the common term is justified because, in a complex plasma, these processes are inseparable. This is most strikingly exemplified in Ref. 1, in which the damping of DIA waves was considered in the case $\omega_{\mathbf{k}}^s \ll \nu_q$, opposite to the case treated here. It follows from this example that, even when the resonant denominators describing the damping in the dielectric response functions of the electrons and ions correspond to conventional Landau poles, a new kind of collisionless damping arises that differs from ordinary Landau damping and is associated with the dust grain charging processes.

In some situations typical of present-day experiments with complex plasmas, the second term $\gamma_{\mathbf{k}}^{L,q}$ predominates over the first term $\gamma_{\mathbf{k}}^{L,R}$. In fact, for the data of the experiments[5] on DIA shocks, cesium vapor plasma with $T_e = T_i = 0.2$ eV, $a = 0.1$ μm, and the characteristic wave vector

$|\mathbf{k}| \sim 2\pi/\Delta\xi \sim \nu_q/Mc_s$ corresponding to the characteristic width $\Delta\xi$ of the front of the shock wave associated with anomalous dissipation[8,9] (and to the experimental data of Ref. 5), the second term (with ν_q) in Eq. (4) is larger than the first term under the condition $\epsilon Z_{d0} > 0.6$. To obtain this condition we take into account the experimental dependence of the Mach number M on ϵZ_{d0} (see Fig. 5 in Ref. 5). DIA shock (front steepening) is observed in a Q machine device for $\epsilon Z_{d0} > 0.75$ when the condition $\epsilon Z_{d0} > 0.6$ is also satisfied. We thus arrive at the conclusion that dust grain charging processes can substantially modify the rate of kinetic damping of DIA perturbations; moreover, in many situations, it is these charging processes that dominate the kinetic damping mechanism.

A simple criterion for determining whether the hydrodynamic ionization source model is applicable to nonlinear DIA structures is the condition $\Gamma > \gamma_{\mathbf{k}}^{L}$. The validity of this condition means that the dissipative processes that are taken into account in the hydrodynamic equations are more important than the kinetic damping. For cesium vapor plasma with $T_e = T_i = 0.2$ eV, $a = 0.1$ μm, $n_{i0} = 1.024 \times 10^7$ cm^{-3}, and the characteristic wave vector $|\mathbf{k}| \sim 2\pi/\Delta\xi \sim \nu_q/Mc_s$, the condition $\Gamma > \gamma_{\mathbf{k}}^{L}$ is valid if $\epsilon Z_{d0} > 0.07$. We see that for a wide range of the plasma and dust grain parameters in a Q machine device the hydrodynamic ionization source model is applicable for the description of DIA nonlinear structures.

The dissipation related to the processes of momentum loss by ions as a result of their absorption on the grain surfaces and their Coulomb collisions with the grains forbids the existence of stationary shocks. There is no external source of ion momentum which is able to compensate for this momentum loss. This statement is valid independently whether we use hydrodynamic or kinetic approach to nonlinear dust ion-acoustic waves. In the dust ion-acoustic nonstationary shocks a balance between nonlinearity and dissipation is possible in the vicinity of their front, which results in the formation of the shock front during the time $\tau \sim \nu_q^{-1}$ much shorter than the characteristic time of shock propagation. But the amplitude of such shocks decreases. This statement is in accordance with the experimental data.[5] Such a decrease in the shock amplitude is accompanied by an attenuation of the ion flux as the ions pass through the region of the dust.

For $T_e \sim T_i$, Landau damping is the most significant dissipation process for small ϵZ_{d0} (in our case for $\epsilon Z_{d0} \lesssim 0.07$). The significant role of Landau damping in this case means that it can make a contribution to a spreading out of the pulse as it propagates down the plasma column. The increase in the parameter ϵZ_{d0} leads to the diminution of the role of Landau damping, while the processes of the charging of dust grains, of the absorption of ions by grains, and of the transfer of the ion momentum to the grains become more important. This is consistent with the data of the experiments[12] performed in a Q machine device which have established that the presence of negatively charged dust greatly reduces the strength of Landau damping of DIA waves, even in a plasma with $T_i = T_e$.

We emphasize that in other installations used for the investigation of complex plasmas such as a double plasma device,[6] devices based on glow discharges (see, e.g., Ref. 13) and rf discharges (see, e.g., Ref. 14), the inequality $T_i \ll T_e$ is usually fulfilled. This means that Landau damping on ions [the term containing exponent in Eq. (5)] is negligibly small. In this case the term $\gamma_{\mathbf{k}}^{L,q}$ is approximately $\sqrt{m_i/m_e}$ times larger than the term $\gamma_{\mathbf{k}}^{L,R}$.

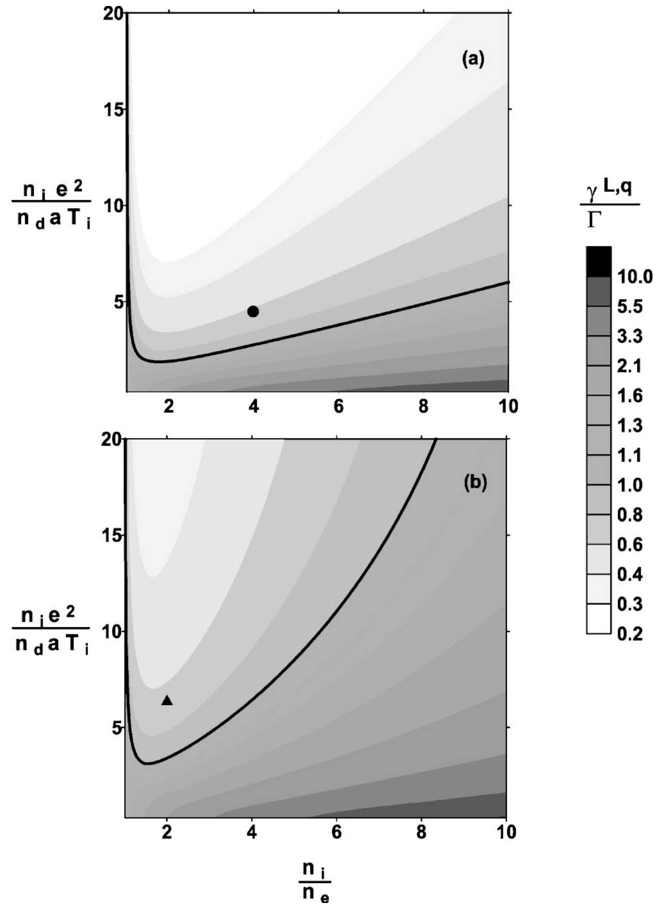

FIG. 1. Relief of the ratio $\gamma_{\mathbf{k}}^{L,q}/\Gamma$ on the plane $(n_i e^2/n_d a T_i, n_i/n_e)$ for the plasma parameters (a) in the experiments of Ref. 5 and (b) in the experiments of Ref. 6. The closed circle in plot (a) corresponds to $\epsilon Z_{d0} = 0.75$ and to the plasma parameters in the experiments of Ref. 5. The closed triangle in plot (b) corresponds to $\epsilon Z_{d0} = 0.5$ and to the plasma parameters in the experiments of Ref. 6. The heavy curves correspond to $\gamma_{\mathbf{k}}^{L,q} = \Gamma$.

Figures 1 and 2 present the relief of the ratio $\gamma_{\mathbf{k}}^{L,q}/\Gamma$ for the parameters of complex plasmas in the experiments in a Q machine device, a double plasma device, and devices based on glow discharges and on rf discharges. Figure 1(a) corresponds to the experimental conditions of Ref. 5 ($T_e = T_i = 0.2$ eV, $n_i = 1.024 \times 10^7$ cm^{-3}, Cs$^+$ ions, $a = 0.1$ μm). The closed circle in Fig. 1(a) corresponds to $\epsilon Z_{d0} = 0.75$. Figure 1(b) was drawn for the experimental conditions of Ref. 6 ($T_e = 1.5$ eV, $T_i < 0.1$ eV, $n_i = 2.3 \times 10^8$ cm^{-3}, Ar$^+$ ions, $a = 4.4$ μm). The closed triangle in Fig. 1(b) corresponds to $\epsilon Z_{d0} = 0.5$. It can be seen that the experimental parameters of Refs. 5 and 6 satisfy the inequality $\gamma_{\mathbf{k}}^{L,q}/\Gamma < 1$. This indicates that the hydrodynamic ionization source model is applicable to DIA shocks not only in a Q machine device (for $\epsilon Z_{d0} > 0.07$), but also in a double plasma device. Figure 2(a) refers to the plasma parameters of experiments carried out onboard the ISS (Ref. 14) ($T_e \approx 1$ eV, $T_i \approx 0.03$ eV, $n_i = 2$

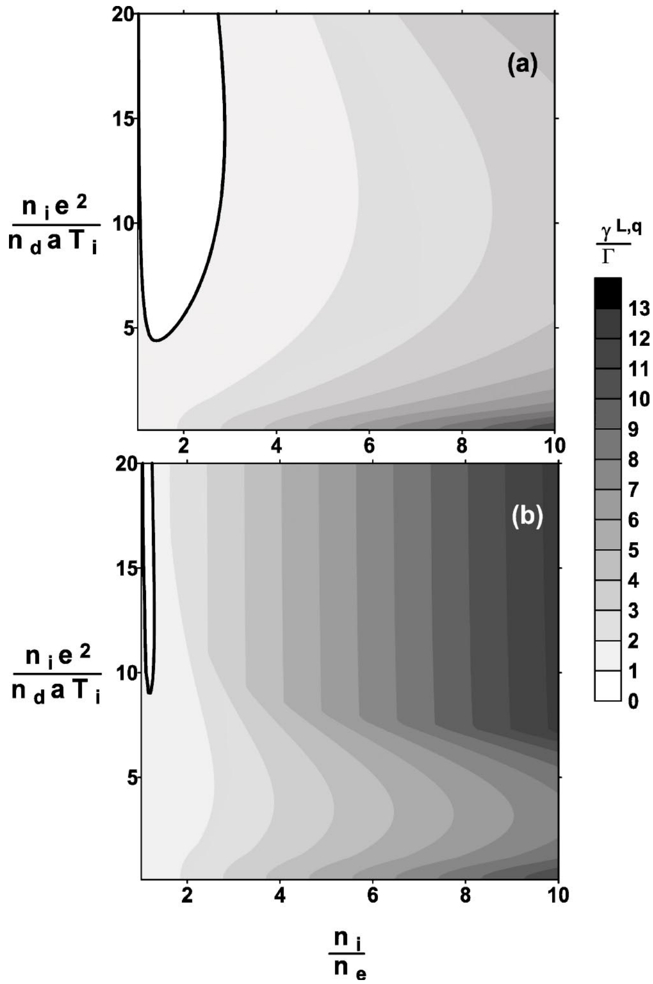

FIG. 2. Relief of the ratio $\gamma_{\mathbf{k}}^{L,q}/\Gamma$ on the plane $(n_i e^2/n_d a T_i, n_i/n_e)$ for the plasma parameters (a) in the experiments of Ref. 14 and (b) in the experiments of Ref. 13. The heavy curves correspond to $\gamma_{\mathbf{k}}^{L,q}=\Gamma$.

$\times 10^9$ cm^{-3}, Ar^+ ions, $a=3.4\mu$m). Figure 2(b) was obtained for the plasma parameters in experiments with glow discharges[13] ($T_e \approx 3$ eV, $T_i \approx 0.03$ eV, $n_e \approx 10^9$ cm^{-3}, Ne^+ ions, $a \approx 4$ μm). For $n_i/n_e = 1/(1-\epsilon Z_{d0}) > 3$ in experiments[14] and for $n_i/n_e = 1/(1-\epsilon Z_{d0}) > 1$ (i.e., always when dust is present) in the experiments of Ref. 13, the ratio $\gamma_{\mathbf{k}}^{L,q}/\Gamma$ is larger than unity. This means that, over fairly wide ranges of the dust grain parameters, DIA structures in typical experiments carried out with complex plasmas on devices based on glow and rf discharges should be described in terms of kinetic theory. In the regions of plasma parameters where Landau damping is negligible in comparison with the dissipative processes that are taken into account in the hydrodynamic equations, the condition $\gamma_{\mathbf{k}}^{L,q}/\Gamma > 1$ serves as a criterion for determining whether or not the kinetic effects are important during formation and propagation of DIA shocks.

Thus the above analysis has shown that the experiments[5] performed in a *Q* machine device allowed to observe two significant effects.

(a) A significant reduction of the strength of Landau damping of DIA perturbations, which is the dominant dissipation process for small dust densities, by the presence of negatively charged dust, even in a plasma with equal ion and electron temperatures.

(b) The formation and propagation of DIA shocks at sufficiently high dust densities such that $\epsilon Z_{d0} \geqslant 0.75$, the dissipation in such shocks being related to the charging of dust grains, the absorption of ions by grains, and the transfer of the ion momentum to the grains.

The experiments[5] enable to determine the role of each of dissipative processes and to classify them because of the negligible role of neutral atoms in the dissipation. This is an advantage of the experiments in a *Q* machine device on DIA shocks over those in other installations (a double plasma device and devices based on glow discharges and on rf discharges) where the role of neutral atoms is significant. Moreover, over fairly wide ranges of the dust grain parameters, DIA structures in typical experiments carried out with complex plasmas in devices based on glow and rf discharges should be described in terms of kinetic theory. This implies a significant modification of the properties of DIA shocks in such devices.

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