Dissipative Processes in Evolution of Dust Ion Acoustic Nonlinear Perturbations

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Dust ion acoustic (DIA) perturbations can propagate in cosmic plasma environments, dusty plasma of Earth’s mesosphere. They have a relevance to low–frequency noise in the F–ring of Saturn [1]. Bow shock in interaction of Solar wind with dusty cometary coma for large dust densities is a DIA shock [2]. In laboratory complex (dusty) plasmas nonlinear DIA perturbations have been observed [3, 4, 5]. Here we study the role of the following dissipative processes for DIA nonlinear shocks and solitons: 1) dust particle charging; 2) absorption of ions on dust grains; 3) a loss in ion momentum due to recombination on dust particles and Coulomb elastic collisions between ions and dust; 4) Landau damping. This study is important for understanding of origin and properties of shocks and solitons, and also for the parameter choice for future experiments on ground-based experimental installations and onboard the International Space Station (ISS).

We start the study with the Landau damping of DIA waves. It can prevent the formation of the shocks. Strong Landau damping prevents also the existence of the solitons. The basic equations for the description of Landau damping are the kinetic equations for electrons, ions, and dust grains (which are considered to be immobile because of the consideration of the ion acoustic time scales) [6, 7]. We separate regular and fluctuating parts of the distribution functions, use the Fourier transform, and find linear (in the electric field $E$) responses of the distribution functions. Using them and Poisson’s equation we obtain the expression for the dielectric function $\varepsilon_k^w$.

$$\varepsilon_k^w = \frac{\omega_p^2 \varepsilon_{||}}{2 \pi n_e z} \frac{(t + z)}{(1 + t + z) (1 + k^2 \lambda_D^2)}.$$

where $c_s = \sqrt{T_e/m_i}$ is the ion acoustic speed, $\lambda_D$ is the electron Debye length, $m_{e(i)}$ is the electron (ion) mass, $T = T_i/T_e$, $T_{e(i)}$ is the electron (ion) temperature, $n_e$, $n_i$, and $n_d$ are the densities of electrons, ions, and the dust particles, respectively, $\varepsilon_q = \omega_p^2 a (1 + z + t) / \sqrt{2 \pi} v_{Ti}$ is the dust grain charging rate, $\omega_p$ is the ion plasma frequency,
The second term in $\gamma_k^2$, proportional to $v_q$, is associated with the dust particle charging processes. It is not taken into account in [10]. Nevertheless, in many real situations this second term (we denote it as $\gamma_q^2/(1+k^2\lambda^2_{De})$) is dominant in Landau damping.

Because the consideration of the nonlinear processes in complex plasmas on the basis of the kinetic equations is very complicated problem, the hydrodynamical models are often used. When studying DIA shocks and solitons a good agreement between theory and experiments is provided by the so–called ionization source model developed in [11]. The evolution equations of this model are derived from the kinetic equations for plasma particles. This assumes, in particular, finding of the ionization frequency, which increases exponentially with $T_e$. Linearization of the equations of the ionization is constant [9]. For the case of the double plasma and Q-machine devices the source $S_i$ describing the ionization is constant [9]. For the case of the dc glow discharge and rf discharge laboratory installations which are used usually to study complex plasmas (see, e.g., [14, 15]) the ionization source corresponds to the standard electron impact ionization and is equal to $S_i = v_i n_e$, where $v_i$ is the plasma ionization frequency, which increases exponentially with $T_e$ and also depends on the atomic parameters of the neutral gas [16]. Linearization of the equations of the ionization source model and the use of Fourier transform allow us to find the linear dispersion law $\omega_k = \omega_k^0 + i\gamma_k$, where $\gamma_k$ depends on the modification of the model. For the first case ($S_i = \text{const}$) we obtain from the equations [9, 12] $\gamma_k \approx -\Gamma \equiv -(v_{ch} + \tilde{v})/2$. For the second case we get from the set of equations [11] $\gamma_k \approx -\Gamma + v_i/2(1 + |k|^2\lambda^2_{De})$.

In the second case the expression for $\gamma_k$ includes the positive term $v_i/2(1 + |k|^2\lambda^2_{De})$ which is related to the ionization instability. In both cases the dissipation is determined by the term $\Gamma$. Thus the dissipation in the ionization source model is determined by the frequencies characterizing the ion recombination on dust particles and a loss in ion momentum due to recombination on dust particles and Coulomb elastic collisions between ions and dust. These processes are closely connected with the dust particle charging. Indeed, $\Gamma \propto v_q$ and the absorbed ions participate in the dust particle charging.

Shocks and solitons obtained in the hydrodynamical description [9, 12] exist only if Landau damping is not dominant. Let us compare the damping rates in the hydrodynamical description with the Landau damping rate. We emphasize that it is the situation
FIGURE 1. Profiles of equal magnitudes of the ratio $\gamma^{L-q}/\Gamma$ for the parameters of the experiments [4] (a) and [3] (b). The dark circle (a) corresponds to the plasma parameters of the experiment [4] and $\varepsilon Z_d = 0.75$, while the dark triangle (b) fits the plasma parameters of the experiment [3] and $\varepsilon Z_d = 0.5$. Solid lines correspond to the profile $\gamma^{L-q} = \Gamma$. The region $\gamma^{L-q} < \Gamma$ is above these lines.

of dominance of the term containing $\gamma^{L-q}$ in Landau damping rate that takes place in the experiments [3, 4, 5]. To evaluate the ratio of the second term to the first one in the expression (1) for $\gamma^{L-q}$ one has to use Fourier transform of shock or soliton profile. This allows us to obtain the typical wave vector. For example, for the data [9] used to model the experiments [4] the typical wave vector corresponding to $\varepsilon Z_d \equiv Z_d n_d/n_i = 0.75$ is $|k| \approx 0.12 \text{ cm}^{-1}$. For this value of $|k|$ the term in $\gamma^{L-q}$ associated with the dust particle charging is one order of magnitude larger than the first one.

Thus we compare the parameters $\gamma^{L-q}$ and $\Gamma$ for the data of four different installations: the Q–machine ($T_e = T_i = 0.2 \text{ eV}, n_i = 1.024 \cdot 10^7 \text{ cm}^{-3}, \text{Cs}^+ \text{ ions}, a = 0.1 \text{ \mu m}$) [4, 9]; the double plasma device ($T_e = 1.5 \text{ eV}, T_i < 0.1 \text{ eV}, n_i = 2.3 \cdot 10^8 \text{ cm}^{-3}, \text{Ar}^+ \text{ ions}, a = 4.4 \text{ \mu m}$) [3, 5, 9]; rf plasma discharge installation onboard the ISS ($T_e \approx 1 \text{ eV}, T_i \approx 0.03 \text{ eV}, n_i \approx 2 \cdot 10^9 \text{ cm}^{-3}, \text{Ar}^+ \text{ ions}, a = 3.4 \text{ \mu m}$) [15]; dc glow plasma discharge installation ($T_e \approx 3 \text{ eV}, T_i \approx 0.03 \text{ eV}, n_e \approx 10^9 \text{ cm}^{-3}, \text{Ne}^+ \text{ ions}, a \approx 4 \text{ \mu m}$) [14]. The results are presented in Figs. 1 and 2. We see that in the experiments on DIA shocks and solitons on the double plasma device and Q–machine [3, 4, 5] Landau damping is not significant and the nonlinear structures can be described within the ionization source models. For the parameters of the experiments [14, 15] the regions of the plasma parameters where Landau damping of DIA waves is negligible are very narrow. This means the dissipation in the rf discharge or dc glow discharge plasmas both on ground–based experimental installations and onboard the ISS is too large. In this case DIA shocks and solitons (if they will be observed) will have new origin. In particular, DIA shocks could be formed
FIGURE 2. Profiles of equal magnitudes of the ratio $\gamma^{L,q}/\Gamma$ for the parameters of the experiments [15] (a) and [14] (b). Solid lines correspond to the profile $\gamma^{L,q} = \Gamma$. The region $\gamma^{L,q} < \Gamma$ is above these lines.

as a result of the competition of the effects of dissipation related to Landau damping (which includes the effects of the dust particle charging) and nonlinearity.

This work was supported by INTAS (grant no. 01–0391) and RFBR (grants no. 03-02-16664-a and no. 03-05-64813-a).

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