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Evolution of the Dust Ion–Acoustic Solitary Waves in Complex Plasmas

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The dust ion–acoustic solitons in complex plasmas have been studied in [1]. The approximation has been used when it is possible to neglect variations in dust particle charge and absorption of electrons and ions by dust particles. In a typical complex plasmas these processes can result in the anomalous dissipation. This means that the existence of completely steady–state nonlinear structures is impossible in complex plasmas. In reality, this note is truth for any real system. However, in complex plasmas it leads to qualitatively new results. The usual consideration of a soliton assumes that the electrons are not trapped by the potential well formed by the soliton. However, this assumption is violated when the inequality $\tau \gg L/v_{Te}$ (see, e.g., [2]) is valid, where τ is the characteristic time of the variation of the soliton field, L is the characteristic spatial scale of the soliton, and v_{Te} is the electron thermal velocity. In complex plasmas the characteristic time τ of soliton damping is determined by the realtionship $\tau^{-1} \sim \max\{\nu_{\rm ch},\ \tilde{\nu}\}$, 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 given by the following relationships (see, e.g., [3, 4])

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

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

Here $q_d = -Z_d e$ is the grain charge, $-e$ is the electron charge, $d = n_{d0}/n_{e0}$, n_d is the dust density, n_e is the electron density, the subscript 0 stands for the unperturbed plasma parameters, $\nu_q = \omega_{pi}^2 a\,(1+z_0+T_i/T_e)/\sqrt{2\pi} v_{Ti}$ is the grain charging rate, ω_{pi} is the ion plasma frequency, $T_{e(i)}$ is the electron (ion) temperature, a is the grain radius, $z = Z_d e^2/aT_e$, v_{Ti} is the ion thermal velocity, $\Lambda = \ln(\lambda_{Di}/\max\{a,b\})$ is the Coulomb logarithm, λ_{Di} is the ion Debye radius, and $b = Z_{d0}e^2/T_i$. The characteristic soliton width L is of the order of $10\lambda_{De}$, where λ_{De} is the electron Debye length. For such values of L the inequality $\tau \gg L/v_{Te}$ is fulfilled always for $Z_{d0} d \geq 1$. The latter inequality is the typical one for the most of dusty plasmas. Thus in the dusty plasmas it is necessary to take into account the effect of adiabatically trapped electrons.

This effect influences the spatial electron distribution. If the electrons are under the action of the soliton electric field corresponding to the *positive* electrostatic potential

φ (the potential well for the electrons), then their distribution is determined by the Gurevich's formula (see, e.g., [2])

$$n_e = n_{e0}\left\{\exp\left(\frac{e\varphi}{T_e}\right)\left[1-\mathrm{erf}\left(\sqrt{\frac{e\varphi}{T_e}}\right)\right]+2\sqrt{\frac{e\varphi}{\pi T_e}}\right\}. \tag{3}$$

The equations for the description of the dust ion–acoustic solitons with the positive electrostatic potential (compressive solitons) are analogous to those of the ionization source model (see Eqs. (3) – (5), (9), and (10) in [3]) with the following exception: instead of the Boltzmann distribution for the electrons (Eq. (3) in [3]) it is necessary to use the Gurevich's distribution (3). The form of the ionization source intensity S_i depends on the plasma parameters. In our calculations we use the parameters similar to those of the experiments on dust ion–acoustic soliton excitation [5]: the argon ion density $n_{i0} = 3\cdot 10^8$ cm^{-3}; the dust particle size $a = 4.4$ μm; the electron and ion temperatures $T_e = 1.5$ eV and $T_i = 0.1$ eV, respectively. The experiments [5] were performed on the same installation (double plasma device) as the experiments [6]. As it has been shown (see [4]), in this case it is possible to consider the source S_i as a constant.

We use the following normalization:

$$\frac{e\varphi}{T_e}\to\varphi,\quad \frac{v}{c_s}\to v,\quad \frac{n_{i,d}}{n_{e0}}\to n_{i,d},\quad \frac{tc_s}{\lambda_{De}}\to t,\ \text{ and }\ \frac{x}{\lambda_{De}}\to x, \tag{4}$$

where v is the velocity, $c_s = \sqrt{T_e/m_i}$ is the ion–acoustic speed, m_i is the ion mass, and n_i is the ion density.

We have performed the following investigations.

1) We have studied the steady–state compressed solitons, which propagate with a constant speed (Mach number) M and are the solutions of the set of equations consisting of Eq. (3) and the following equations given in Ref. [3]: Eqs. (9) – (10) (with the right–hand sides equal to zero) and Eq. (4). Here we neglect the dissipation processes related to the dust particle charging and absorption of plasma particles by dust grains (below we use the notion "steady–state soliton" for the solitons satisfying equations which do not take into account these dissipation processes). The solitons obey the equation

$$\partial_x^2\varphi = -d_\varphi V(\varphi), \tag{5}$$

where the subscript x (φ) denotes derivative with respect to x (φ), and the Sagdeev potential $V(\varphi)$ is given by

$$V(\varphi) = 1-\exp(\varphi)-\frac{2\sqrt{\varphi}}{\sqrt{\pi}}-\frac{4\varphi^{3/2}}{3\sqrt{\pi}}-\varphi Z_d d$$
$$+M(1+Z_d d)\left(M-\sqrt{M^2-2\varphi}\right)+\exp(\varphi)\mathrm{erf}(\sqrt{\varphi}). \tag{6}$$

2) We have considered the evolution of the initial steady–state soliton (from the previous item) in complex plasmas with taking into account the dissipation processes related to the dust particle charging and absorption of plasma particles on dust.

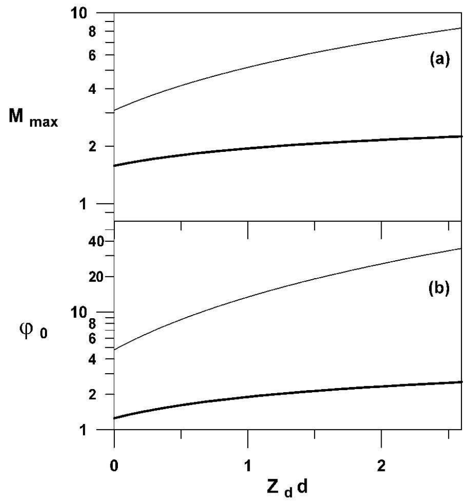

FIGURE 1. Dependencies of the maximum value of Mach number $M_{\max}$ (a) and the maximum soliton amplitude φ_0 (b) on $Z_d d$ for the compressive soliton with the trapped electrons (thin lines) and that with Boltzmann electrons (bold lines).

3) We have studied the interaction of two different compressive dust ion–acoustic solitons with the trapped electrons taking into account their damping due to the anomalous dissipation.

The main results of the investigation are the following.

1) The properties of the compressive solitons with the trapped electrons are very different from those with the 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 (see Figure 1). This shows the principal possibility to study experimentally the role of trapped electrons in the soliton formation.

2) The evolution of the initial perturbation in the form of the steady–state compressive soliton with the trapped electrons 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 (the Mach number M) decreases. However, at any time the form of the evolving perturbation is similar to that of the steady–state compressive soliton with the trapped electrons corresponding to the Mach number at this moment of time. This fact is related to small variations in the dust particles charges (less than several per cent from the equilibrium value).

3) After the interaction of two damped solitons (see Figure 2), 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 compressive solitons which are damped and slowed down, but their form corresponds to the soliton one for the running value of their speed. After their interaction they conserve the soliton form. The role of trapped electrons in such solitons is significant.

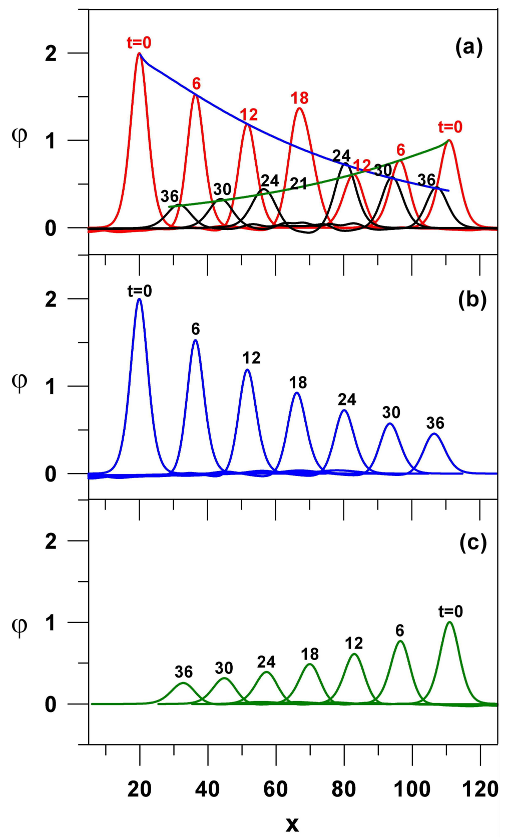

FIGURE 2. Time evolution of compressive solitons with the trapped electrons. The interaction (a) of two individual solitons (b) and (c). Red and black lines (a) correspond to the soliton profiles respectively before and after the interaction at t =0, 6, 12, 18, 21, 24, 30, 36; blue and green lines (a) are the envelopes of the solitons (b) and (c), respectively. At $t = 0$ all the perturbations have the form of the steady–state solitons. The initial ($t = 0$) amplitude of the left soliton (a) and the individual soliton (b) is $\varphi_0 = 2$, the Mach number is $M = 2.8$. The initial parameters of the steady–state right soliton (a) and the individual soliton (c) are $\varphi_0 = 1$ and $M = 2.435$. The remaining plasma parameters are as follows: the argon ion density $n_{i0} = 3 \cdot 10^8$ cm^{-3}, $a = 4.4$ μm, $T_e = 1.5$ eV, $T_i = 0.1$ eV, and $Z_d d = 2$.

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