



HAL
open science

Study of nonlinear phenomena in four component dusty plasma

Iglika Spassovska, Paulo Sakanaka, Padma Shukla

► **To cite this version:**

Iglika Spassovska, Paulo Sakanaka, Padma Shukla. Study of nonlinear phenomena in four component dusty plasma. 2004. hal-00002003v1

HAL Id: hal-00002003

<https://hal.science/hal-00002003v1>

Preprint submitted on 12 Nov 2004 (v1), last revised 18 Nov 2004 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Study of nonlinear phenomena in four component dusty plasma

I. Spassovska¹, P.H. Sakanaka¹, P.K. Shukla²

¹Instituto de Física “Gleb Wataghin”, Universidade Estadual de Campinas, Campinas, SP, Brazil.

²Institute für Theoretische Physik IV, Ruhr-Universität Bochum, Bochum, Germany

The presence of a positive dust component in four component dusty plasma, as it was shown [1], gives rise to such novel features of the nonlinear structures as double-layers, which otherwise are absent. It is shown that stationary solutions of the fluid equations combined with Poisson’s equation can be expressed in terms of the energy integral of a classical particle with a modified Sagdeev potential. The parametric regions of solitons and double layers are given. In particular, we have applied the theory in the laboratory plasma reported by Oohara et al. [2], and we can predict that a double layer might be possible to be launched if small quantity of ions was introduced in their experiment. The case with negative charge fluctuation was studied when the time charging is of order of the characteristic time of formation of soliton and double-layer. The effect of the charge fluctuation is the attenuation of the dust acoustic waves.

KeyWords: Dusty Plasma; Nonlinear Dust Acoustic Waves; Charge Fluctuations

PACS: 52.27.Lw; 52.35.35.Mw

1. INTRODUCTION

Since the discovery of the dust acoustic wave (DAW) there been a great interest in investigating numerous collective processes in dusty plasmas. Recently, it has been suggested that positively and negatively charged dust grains can co-exist in space [3]-[5] and laboratory [6] plasmas. Therefore, it is desirable to investigate the linear and nonlinear properties of dust-acoustic waves in four-component plasma that consists electrons, ions and positively and negatively charged dust grains.

Here we present the governing equations for the DAW when both the negative and positive dust components are simultaneously present (see [1]) and define parameters that are relevant for the analysis of the nonlinear DAW. Stationary solutions of the governing nonlinear equations for arbitrary large amplitudes are discussed. Here, we derive the energy integral with a modified Sagdeev potential. The latter is analyzed both analytically and numerically to obtain the parameter regimes where soliton and DA double-layers are possible. Finally, a possible application of our investigation in laboratory plasmas is given.

The study of negative charge fluctuation is presented. Its linearized equation shows that the dusty-acoustic waves are damped.

2. THEORY

We consider unmagnified dusty plasma consisting of the electrons, the ions, negatively and positively charged massive dust particles, with similar masses.

The quasi-neutrality at equilibrium is written

$$N_{e0} + Z_n N_{n0} = N_{i0} + Z_p N_{p0}, \quad (1)$$

where, N_{e0} and N_{i0} are the average electron and average ion number densities, Z_n and Z_p are the negative and positive dust particle charge, N_{n0} and N_{p0} are the average dust particles number density, respectively.

The number densities of electrons and ions can be given by the Boltzmann distribution, respectively,

$$N_e = N_{e0} e^{e\Phi/T_e} \quad \text{and} \quad N_i = N_{i0} e^{-e\Phi/T_i}, \quad (2)$$

where, Φ is the electrostatic potential and e is the magnitude of the electron charge.

The dynamics of charged dust grains are governed by the equations of the continuity and the momentum, which are, respectively,

$$\frac{\partial N_j}{\partial t} + \frac{\partial(N_j V_j)}{\partial x} = 0, \quad \frac{\partial V_j}{\partial t} + V_j \frac{\partial V_j}{\partial x} = \mp \frac{Z_j e}{M_j} \frac{\partial \Phi}{\partial x} \quad (3)$$

Where $j = \{p, n\}$. Here V_j and M_j are the fluid velocities and mass of the charged dust grains, respectively. We are assuming cold dust particles, so no pressure term is present. The system of equations is closed with the Poisson's equation

$$\frac{\partial^2 \Phi}{\partial x^2} = 4\pi e (N_e - N_i + Z_n N_n - Z_p N_p) \quad (4)$$

We have introduced the effective number density N_0 , the temperature T_0 and the mass M_0 as

$$N_0 = N_{e0} + N_{i0}, \quad \frac{N_0}{T_0} = \frac{N_{e0}}{T_e} + \frac{N_{i0}}{T_i}, \quad \frac{N_0}{M_0} = \frac{Z_n^2 N_{n0}}{M_n} + \frac{Z_p^2 N_{p0}}{M_p}. \quad (5)$$

Moreover, we define, then

$$\phi = \frac{e\Phi}{T_0} \quad \text{and} \quad u(\phi) = \frac{U(\Phi)}{4\pi N_0 T_0}, \quad (6)$$

$$n_{e0} = \frac{N_{e0}}{N_0}, \quad n_{i0} = \frac{N_{i0}}{N_0}, \quad a_e = \frac{T_0}{T_e}, \quad a_i = \frac{T_0}{T_i} \quad (7)$$

$$n_n = \frac{Z_n N_{n0}}{N_0}, \quad n_p = \frac{Z_p N_{p0}}{N_0}, \quad a_n = \frac{Z_n T_0}{M_n V_0^2}, \quad a_p = \frac{Z_p T_0}{M_p V_0^2} \quad (8)$$

Thus, for the nonlinear dust acoustic wave parameters we have

$$n_{e0} + n_n = n_{i0} + n_p \quad (9)$$

$$n_{e0} + n_{i0} = 1 \quad (10)$$

$$n_{e0} a_e + n_{i0} a_i = 1 \quad (11)$$

$$n_n a_n + n_p a_p = \frac{1}{M^2} \quad (12)$$

For the arbitrary large amplitude solution of the nonlinear equations (2) to (4), using equations (5) and (6), we obtain

$$\frac{1}{2} \left(\frac{\partial \phi}{\partial \zeta} \right)^2 + u(\phi) = 0, \quad (13)$$

where the modified Sagdeev potential [1] for our purposes is

$$u(\phi) = - \left\{ \frac{n_{e0}}{a_e} (e^{a_e \phi} - 1) + \frac{n_{i0}}{a_i} (e^{-a_i \phi} - 1) + \frac{n_n}{a_n} (\sqrt{1 + 2a_n \phi} - 1) + \frac{n_p}{a_p} (\sqrt{1 - 2a_p \phi} - 1) \right\}, \quad (14)$$

with the conditions for the existence of soliton:

- (i) $u(\phi) = u'(\phi) = 0$ at $\phi = 0$,
- (ii) $u(\phi) = 0$ at $\phi = \phi_1 \neq 0$,
 $u'(\phi) < (>) 0$ for $\phi_1 < (>) 0$,
- (iii) $u(\phi) < 0$ for $0 < |\phi| < |\phi_1|$.

The conditions for the existence of double layers are:

- (i) $u(\phi) = u'(\phi) = 0$ at $\phi = 0$,
- (ii) $u(\phi) = u'(\phi) = 0$ at $\phi = \phi_1 \neq 0$,
- (iii) $u(\phi) < 0$ for $0 < |\phi| < |\phi_1|$.

Now the conditions in the item (ii) provide two relations

$$n_{e0}a_e + n_{i0}a_i - n_n a_n - n_p a_p = 0 \quad \text{and} \quad (17)$$

$$n_{e0}a_e^2 - n_{i0}a_i^2 + 3n_n a_n^2 - 3n_p a_p^2 = 0, \quad (18)$$

which are conditions under that double-layer exist.

3. NUMERICAL RESULTS

We proceed to obtain the parametric regions where conditions (15) for the solitons and (16) for the double layer are satisfied.

In figure 1 we show the regions of existence of solitons for different Mach number M : 4 – 0 for $M= 2.0$, 3 – 0 for $M= 1.5$, 2 – 0 for $M= 1.1$ and 1 – 0 for $M= 1.01$.

Starting with 9 parameters defined in (7)-(8) with the inclusion of 4 equations (9)-(12), we have a 5-parameter region. We introduce parameters α and β in substitution of a_i and a_n , $\alpha = a_e/a_i = T_i/T_e$ and $\beta = a_p/a_n = Z_p M_n/Z_n M_p$.

We obtained the curves where the double layer solutions are found. We have chosen $\alpha = 0.09$ and $\beta = 0.10$. For each given value of M , from 1.01 to 3.0, a curve is drawn on $n_{e0} \times n_p$ space where DL exists.

The same treatment was applied for the particular case of laboratory plasma reported by Oohara et al [2], for fullerene-ion plasma. For calculations we used main characteristics of the dusty plasma, i.e. $n_e / n_p \sim 10^6$, $n_e = 1.0$, $n_p = n_n \sim 10^6$ and $M_p = M_n$. Moreover, we introduce, on their experimental conditions, a small quantity of ions to fulfill conditions of the four component dusty plasma. Thus we have parameter $\alpha = 0.09$ and $\beta = 1.0$ that is different from the case discussed above. We calculated that the authors [2] have possibility to obtain a double layer in laboratory plasma.

CHARGE FLUCTUATION

Dust grains in plasma are not neutral, but are charged due to their interaction with electrons, ions, and background radiation.

The dust grains are mainly charged by the collection of electrons and light ions flowing onto their surfaces. Since ions are much heavier than electrons, initially the ion current, I_i is much smaller than the electron current, I_e , and the dust grain becomes negatively charged [7]. As electrons are depleted, the electron current decreases and the ion current increases until they reach equality $|I_i| = |I_e|$. This is the equilibrium operating point. If the charging time is comparable to the dust acoustic wave time, there will be effect of the charging on the dust acoustic waves. When energies of electrons or ions are sufficiently

high, they may pass through the dust grain material, and during their passage they may lose their energy partially or fully. A portion of the lost energy can go into exciting other electrons that, in turn, may escape from the dust grain. The emitted electrons are known as secondary electrons. The release of these secondary electrons from the dust grain tends to make the grain surface positive. On the other hand, when dust grains are within the radiative background, the incidence of radiation onto the dust grain surface causes photoemission of electrons from the dust grain surface. The dust grains, which emit photoelectrons, may become positively charged. The emitted electrons collide with other dust grains and are captured by some of these grains which may become negatively charged. There are, of course, a number of other dust grain charging mechanisms, namely thermionic emission, field emission, radioactivity, impact ionization, etc., which are significant only in some different special circumstances.

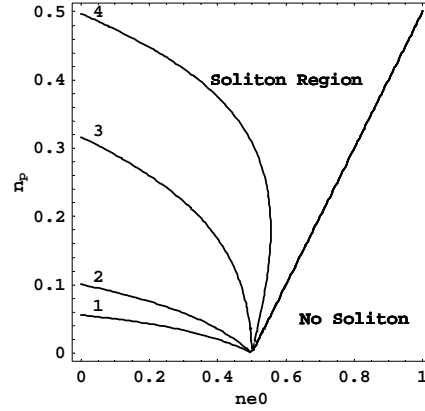


Figure 1. Contour plot of soliton solutions for different Mach numbers.

For this study we have considered only one charging mechanism, which is the charging of dust particle by attachments.

The currents to the particle can be described by the OML model first derived by Mott-Smith and Langmuir in 1926. It is assumed that electrons and ions arriving from infinity that hit the particle are captured by the dust particle.

The ion and electron OML currents are given by:

$$I_i = \pi a^2 n_i e \sqrt{\frac{8kT_i}{\pi m_i}} \left(1 - \frac{e\phi_p}{kT_i} \right) \quad \phi_p < 0$$

$$I_e = -\pi a^2 n_e e \sqrt{\frac{8kT_e}{\pi m_e}} \left(\frac{e\phi_p}{kT_e} \right) \quad \phi_p < 0$$

Where a is the dust particle radius, n_i, n_e are ion and electron densities, T_i, T_e the respective temperatures and m_i, m_e their masses. For positive particle potentials the currents are:

$$I_i = \pi a^2 n_i e \sqrt{\frac{8kT_i}{\pi m_i}} \left(-\frac{e\phi_p}{kT_i} \right) \quad \phi_p > 0$$

$$I_e = -\pi a^2 n_e e \sqrt{\frac{8kT_e}{\pi m_e}} \left(1 + \frac{e\phi_p}{kT_e} \right) \quad \phi_p > 0$$

In case of negative dust particle charge fluctuation e OML model the charge equation is:

$$\frac{\partial Z_n}{\partial t} = \frac{1}{e} (I_e + I_i)$$

The dispersion relation for the linear wave becomes:

$$k_D^2 + \frac{c_4}{c_5 - i\omega} + k^2 \left(1 - \frac{\omega_D^2}{\omega^2} \right) = 0$$

Where k_D is the inverse of the dust Debye length, ω_D is the dust Debye frequency, c_4 and c_5 are constants which depends on charging constants. c_4 and c_5 introduces damping of the dust acoustic waves. In figure 2 we have shown the dispersion relation with and without the charge fluctuation for the case of $\omega_D = k_D = 1$, and $c_4 = 0.2$ and $c_5 = 0.5$.

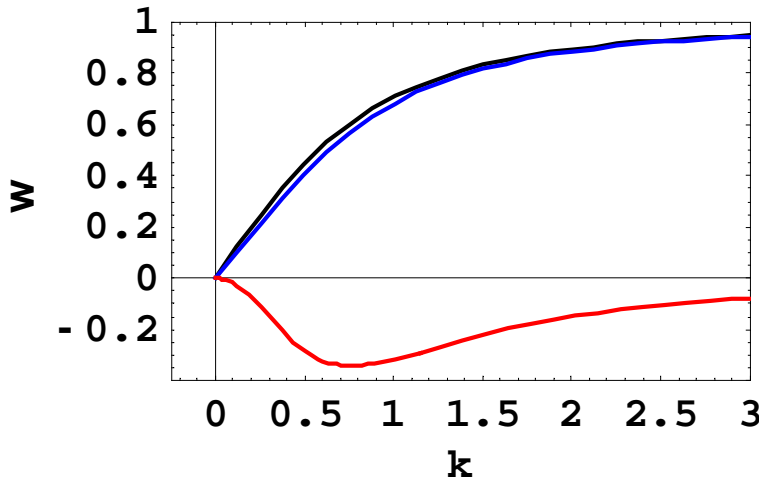


Figure 2 – Dispersion relation of dusty acoustic wave without considering the charge fluctuation, black line, and with fluctuation, blue line – frequency, and red line damping. $\omega_D = k_D = 1$, and $c_4 = 0.2$ and $c_5 = 0.5$.

Just as the linear dust acoustic wave is damped, a nonlinear wave, such as solitons are the charge fluctuation is put into account.

SUMMARY

The linear and nonlinear properties of dust-acoustic waves (DAW) were studied. We used the model of multi-component dusty plasma with inertialess electrons and ions as well as positively and negatively charged inertial dust grains. We found that in four component dusty plasma there are remarkable changes in the nonlinear properties of the DAW. The presence of positively charged dust grains produces double-layers in those parameter regimes. The theory was applied to the laboratory plasma reported by Oohara et al. We predict that a double-layer might be possible to be launched in their experiment if a trace ions component is added. Our parametric studies and double-layers should be useful in identifying coherent nonlinear structures in the Earth's mesosphere. Furthermore, non-stationary double-layers could be potential accelerators for dust particulates in space plasmas. We have also considered the dust charge fluctuation and found that it brings damping for both linear and nonlinear phenomena.

ACKNOWLEDGMENTS

The authors thank the financial support given by Fundação de Amparo à Pesquisa do Estado de São Paulo, Proc. 98/14711-4, and CAPES-Capacitação de Pessoal do Nível Superior.

REFERENCES

1. Sakanaka, P.H., and Shukla, P.K., *Phys. Scripta*, 84, 181 (2000)
2. W. Oohara, N. Tomioka, T. Hirata, R. Hatakeyama, and N. Sato, *Proceedings of the 2000 International Congress on Plasma Physics, Quebec, October, 2000.*, Vol 1, pag. 116-119 (2000).
3. Nakamura, Y., Odagiri, T., and Tsukabayashi, I., *Plasma Phys. Control. Fusion* 39, 105 (1997).
4. Watanabe, S., *J. Phys. Soc. Japan* 53, 950 (1984), Tajiri, M., and Tilda, M., *ibid.* 54,19 (1985).
5. Sheridan, T. E., *J. Plasma Phys.* 60,17 (1998).
6. Shukla, P. K., *Phys. Plasmas* 1, 1362 (1994).
7. Mamun, A. A. and Shukla P.K., *Phys. Plasmas*, 10, 1518 (2003).