New physical effects in formation of non-linear equilibrium of dust structures in complex plasmas

V.N.Tsytovich [1],and G.E.Morfill [2]

[1] *General Physics Institute, Moscow, Russia*

[2] *Max Planck Institute for Extraterrestrial Physics, Garching, Germany*

1.**History remarks.** The result that homogeneous complex/dusty plasmas are universally unstable for structurization was first obtained in [1,2]. Subsequent efforts have been to describe the non-linear self-consistent structures as possible final state of structurization [3]. These theoretical efforts have been based on simplified description of processes responsible for confinement of all components in structures (such as linear screening, quasi-neutrality, negligible diffusion etc.). The further developments of experiments indicate the necessity to create compact dust structures for observing plasma crystals in pure boundary free conditions. For large dust charges necessary for crystal formation the dust screening is strongly nonlinear which substantially modifies the ion drag force being crucial for structure formation. The present report gives the main physical and computational results taking into account three new effects: non-linear screening, ion diffusion due to high rate of collisions with non-linearly screened grains and neutrals, nonlinear ion pressure force due to ion-grain and ion-neutral collisions. All 3 effects have been investigated for the first time. They strongly depend on dust density (that is high inside the dust structures) and on parameter of non-linear screening $\beta = Z_d e^2/\lambda_D T_i$ (λ_D being the Debye radius Z_d the dust charge and T_i the ion temperature) which is about 30 in laboratory experiment. The results of numerical investigations predict existence of equilibrium and stable structures for parameters of planned experiments. 2.**Physics of dust and ion/electron confinement in the structures**. Numerical investigations of dust structures was accompanied with calculations that have been devoted to clarify the physics of confinement of dusty plasmas components in the structures. They are the following: the grain drag force by plasma flux is directed inward the structure; to balance the drag an electric field force is excited which is for grains directed outwards and since the grains are charged negatively the electric field is directed inwards and drive ions inwards; the ions have a potential well at the structure center that substantially exceeds their temperature and the electrons are adiabatically following the potential distribution to compensate partially the charge separation created by drag force. This picture is not possible in absence of dust where the polarization forces can create Coulomb explosion. The degree of quasi-neutrality inside the dust structure is regulated by the strength of the drag force but not by polarization due to diffusion. In the described picture the maximum of ion and dust densities are located at the center of structure although the distributions can be complicated with several higher maxima inside the structures. For certain large distance which can be named as structure size the dust density vanishes and the for larger distances in some range the balance is absent. Such structures are surrounded by dust voids. 3.**Nonlinear drag force**. The new numerical calculations of grain non-linear screening have been made using exact expressions for screening [4]. It was found that the total screening of a grain charge occurs at about $10\lambda_D$ and the cross-section of ion scattering on large angles on grain potential can exceed about 4 times the previously known cross-sections both for approximate non-linear screening [5] and for linear screening [6]. These cross-sections nave been found numerically as functions of normalized velocity of impact ion $y = v_i/\sqrt{2}v_{Ti}$ and non-linear parameter β in the range $0.05 < y < 6; 3 < \beta < 90$ both by the backscattering model and directly by integrating on impact parameters taking into account the potential barriers. The drag force $F_{dr} = Z_d f_{dr} u$ was calculated with these cross-sections (normalized with respect to $T_i/\lambda_{i,n}$,$\lambda_{i,n}$ being mean free path for ion-neutral collisions) and depends both on normalized ion drift velocity $u = u_i/\sqrt{2}v_{Ti}$ and on $\beta = za\sqrt{n}/\tau$. We use through this presentation the notations $n = n_i/n_{eff}$; $n_{eff} = T_i/4\pi e^2\lambda_{in}^2$; $z = Z_d e^2/\lambda_{in} a T_e; a \to a/\lambda_{in}; r \to r/\lambda_{in}; \tau = T_i/T_e; n_e \to n_e/n_{eff}; P = Z_d n_d/n_{eff}$ (a is normalized grain size and r is the distance from the structure center). It is shown that with an increase of β the drag coefficient $\alpha_{dr} = f_{dr}/\beta$ is decreasing with u much slower and is $3-4$ times larger than that previously calculated by using simplifying assumptions. 4.**Nonlinear diffusion coefficient**. The total flux Φ is considered as sum of convective flux and diffusion flux $\Phi = nu - Ddn/dr$. In high dust densities regions of structures the ion dust collisions dominate. The diffusion coefficient is calculated numerically taking into account both the ion-neutral collisions (with constant cross-section) and ion-dust collisions (with non-linear cross-sections) in the ranges of its 3 parameters $0 < u < 4; 3 < \beta < 90, 0 < p = P/2\sqrt{n} < 20$. Fig. 2a gives illustration of the results obtained for D as functions of its 3 parameters. **5. Nonlinear ion pressure force**. Both ion-neutral and ion dust collisions contribute

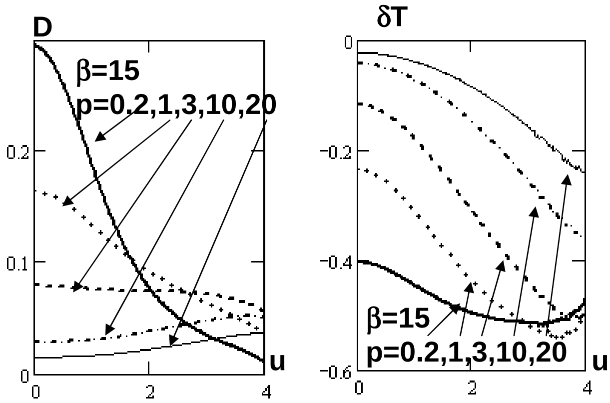

Figure 1: a-Dependence of diffusion coefficient on its parameters , b- Dependence of nonlinear ion effective temperature on its parameters

to the effective ion pressure force $F_{pr} = (1 + \delta T(u, \beta, p)(1/n)dn/dr$. Fig. 2b gives illustration of the results obtained for D as functions of its 3 parameters. For electrons the equality of electron and ion fluxes is gives $\delta T_e = 9/4\pi$.

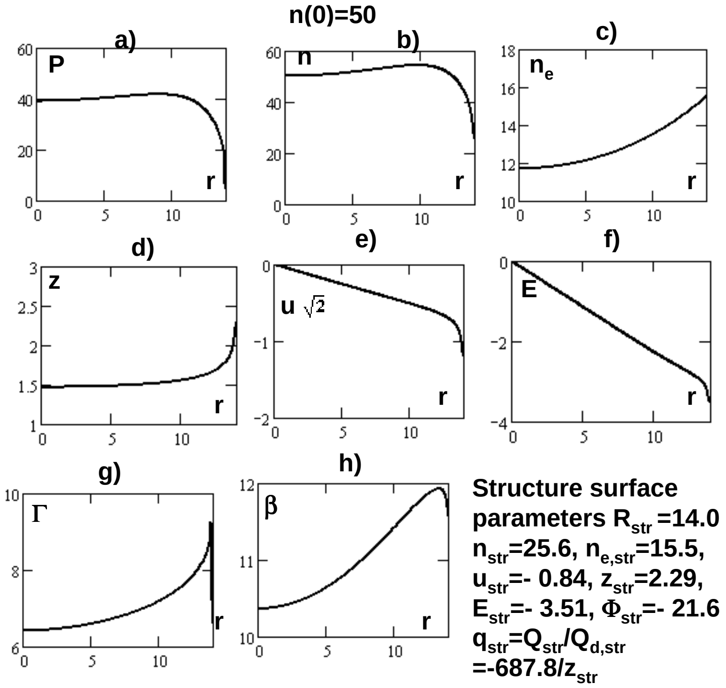

Figure 2: Dependence of parameters $P, n, n_e, z, u\sqrt{2}, \Gamma = P^{1/3}z^{5/3}$ on the distance from the center r for structure with $n(0) = 50$.

6.**Master equations for equilibrium state of dust structures**. To describe the equilibrium state we take into account 1)for dust particles the balance of electric field force and drag force, 2)for ion drift velocity the balance of ram pressure, electric field, friction on dust due to drag, fiction on neutral and nonlinear pressure force, 3) for ion density the diffusion equation. 4) for electron density the electric field force and electron pressure force with enhancement factor δT_e, 5)for flux the absorption on grains. Asymptotic of these equations in the center of the structures $r = 0$ with condition that a void is absent at the center and $P(0) > 0$ gives that the deriva-

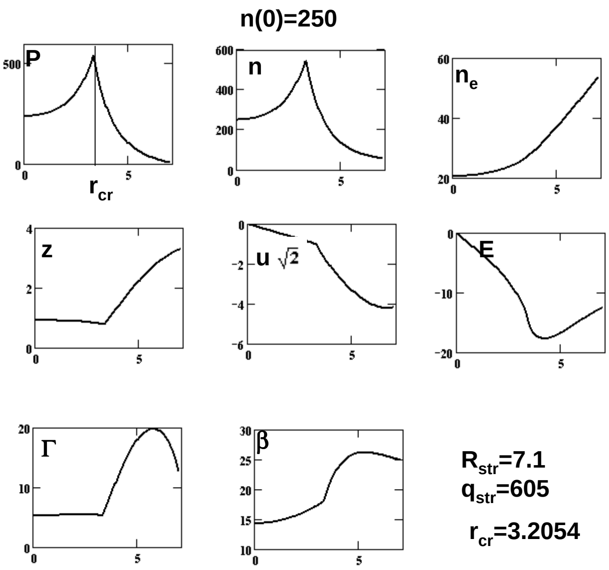

Figure 3: Dependence of structure parameters inside the structure with $n(0) = 250$ on the distance from the center r.

tive of ion drift velocity u_0' is negative (the flux is directed inwards) and the ion density at the center $n(0)$ ranges $n_{min} < n(0) < n_{max}$, $n_{min} = 8\sqrt{n(0)}/3f_{dr}(0)\sqrt{\pi}$, $P(0) = (n(0) - n_{min})n_{max}/n_-$, $u_0' = -2(n(0) - n_{min})/3\sqrt{\pi}n_-$, $n_e(0) = n_{min}(n_{max} - n(0))/n_-$; $n_- = n_{max} - n_{min}$. These relations can be substituted in the dust charging equation to find the dust charge at the center as function of $n(0)$, to find then $\beta(0), f_{dr}(0)$ and express all other parameters at the center through single parameter $n(0)$ which is related to the total flux at the surface of the structure. 7.**Solutions of Master equations inside the dust structures**. Using the data at the center one can scan distributions in all possible equilibrium structure states. The results of numerical calculations show that for $a = 0.01, \tau = 0.01$ the possible range is $2.6 < n(0) < 400$, that for $n(0) < 50$ the dust and ion density continuously decrease up to the surface of the structure which corresponds to $R_{str} \approx 14$, that for larger $n(0)$ several dust density maxima can occur inside the structure, and they look like "shell type" structure. After the dust density vanishes ($P = 0$) the structures is usually surrounded by voids followed by second spherical layer,i.e the "shell-type" structure where the voids separate different shells. Criteria of dust crystallization is first violated at the center, than at the surface and finally at some distance inside the structure. The total number of grains confined by the structure decreases with $n(0)$ and one shell does not contain more then 3×10^5 grains. The nonlinear diffusion and nonlinear ion pressure are the most important at the density peaks. Fig.'s 3, 4 illustrate the distributions of parameters in the structures for $n(0) = 50$ and $n(0) = 250$. **8. Discussions**. The ion dust collisions decrease the diffusion resulting of its small values except the density peaks where they determine the width of the peak. The nonlinear pressure force are always negative and decreases the total ion pressure force, but mostly in the regions where it is small as compared to ion-neutral friction force. In the case of presence of volume ionization the voids can be created at the center of the structure with surviving the general shell type features. It is natural therefore that in the first micro-gravity experiments [1] the dust crystallization was found only in the shell surrounding a big void. The present investigations shows the necessary conditions and the possibility to obtain crystallization in compact dust structures without voids at the center.**References**

[1]V.Tsytovich, G.Morfill, S.Vladimirov, H.Thomas, *Elementary Physics of Complex Plasmas*, Springer Verlag (Heidelberg, London, N.Y.(2008); [2]G.Morfill and V.Tsytovich *Plasma Physics Reports*, **26**, 727, (2000);[3]V.N.Tsytovich ,*Plasma Physics Reports*,**26**,668-681 (2000),**31**,133-146 (2005),**35**,1-22 (2009),[4]Ja. Alpert, A. Gurevich and L. Pitaevsky, *Space Physics with Artificial Satellites*,(Consutant Bureuat),London,N.Y.(1965) [5]V. Tsytovich, U. de Angelis, A.Ivlev, G.Morfill and S.Khrapak, *Physics of Plasmas*,**12**, 112311,(2005);[6]S.A.Khrapak et all *Phys.Rev.Lett.*, **90**, 226005(2003)