35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-5.131 (2008)

Non-linear equilibrium states of spherical self-organized dust structures

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The theory is developed and the numerical calculations are performed to find the range of parameters for non-linear equilibria of dust spherical structures. The processes included in computations are: non-linear dust screening, non-linear dust drag for large angle ion scattering [1,2] and ion absorption by dust, plasma flux damping due to dust drag, non-linear friction in neutral gas, effects causing deviations from local quasi-neutrality, ion ram pressure effects, ion and electron pressure forces, changes of plasma fluxes due to ion convection and diffusion in neutral gas, changes in dust charges due to plasma flux absorption on grains. It is found that the self-organized equilibrium spherical states exist and that the equilibrium is determined by a single parameter - total number of dust grains in the structure or either the total plasma flux on the surface of the structure or the size of the structure and the ion density at the center of the structure. All these parameters are found to be relates to each other and the equilibrium is established in the ranges of the parameters calculated numerically, the number of grain in the structure should be less than some the critical value. Non-linearity in dust screening and drag forces was previously [3] not considered and the local quasi-neutrality condition was used. The present more general treatment substantially increases the range of equilibria existence. For equilibria the ion density at the center of the structure (in dimensionless units $n(0) \rightarrow n_i(0)/n_{eff}; n_{eff} = T_i/4\pi e^2\lambda_{in}^2; \lambda_{in}$ being the mean free path for ion-neutral collisions) can vary in limits $n_{min} < n(0) < n_{max}$ where n_{min} and n_{max} depend on the grain size $a \rightarrow a/\lambda_{in}$, non-linearity in screening and ion to electron temperature ration $\tau = T_i/T_e$. For $\tau = 0.01, a = 0.01$ this range is approximately $0.5 < n(0) < 540$, i.e about 3 orders of magnitude. All other parameters at the center of the structures (the electron density, the dust charges, the derivative of the ion drift velocity with respect to distance etc. are calculated numerically as function of $n(0)$ for $0.01 < a < 0.1, 0.01 < \tau < 0.1$. Fig.1 gives the examples of the obtained results. The parameters at the center of the structure are used to calculate the dependencies of all parameters on the distance from the center. For that purpose the theory of non-linear dust drag was generalized for presence of moderate ion drift up to about 4 ion thermal velocities. Some results for these dependencies are given on Fig.2.

It is found that the ion drift velocity increases toward the edge of the structure and reaches about $1-3$ ion thermal velocity. It is found that all structures have finite size R_{str} of the the order or larger than the ion-neutral mean free path (decreasing with an decrease of the number of grains in the structure). The maximum number of grain in the structure is proportional to the ion-neutral mean free path λ_{in} and ion temperature T_i (or to τ/a where a is the grain size in units of λ_{in}). The structure self-consistently creates plasma fluxes toward their surface causing ram pressure for structure self-confinement. The computations are made scanning the possible number of grains in the structure in the range of existence of equilibria, the ratio of dust size to the ion-neutral mean free path from 0.01 up to 0.1, the ion to electron temperature ratio from 0.01 up to 0.1. Examples of the distributions of the parameters in the structures are given on Fig.3 for $a = 0.01, \tau = 0.01$, and for different values of the parameter $n(0)$, namely for $n(0) = 250$("large"structures), $n(0) = 100$ ("medium" structures) and $n(0) = 30$ ("small structures). The Figure 3 shows that the Havnes parameter $P = n_d Z_d/n_{eff}$ vanishes for finite distance from the center determining the size R_{str} of the structure (in units λ_{in}). It is found that $R_{str} = 0.908$ for large structure, $R = 0.686$ for medium structure and $R_{str} = 0.569$ for small structure.It is found that the structures are negatively charged with total structure charge $-eZ_{str}$ approximately determined by $z_{str} \equiv e^2 Z_{str}/R_{str} T_i$ vary-

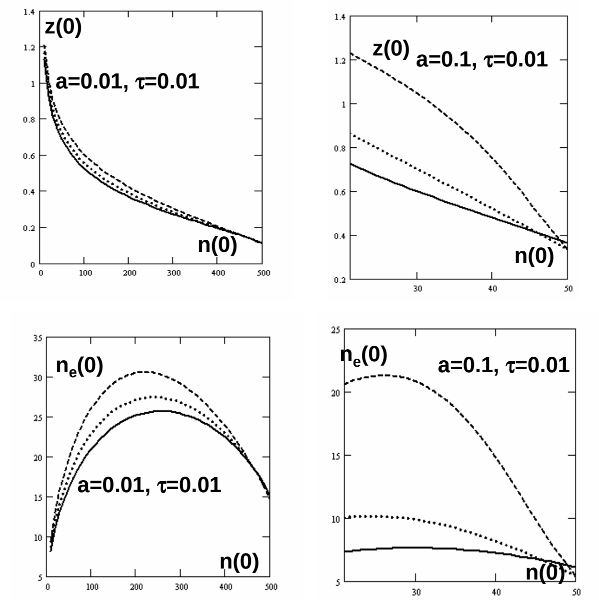

Fig.1

Figure 1: Dust charges $z = e^2 Z_d/aT_e$ and electron densities at the center of the structures in the range of existence of equilibrium

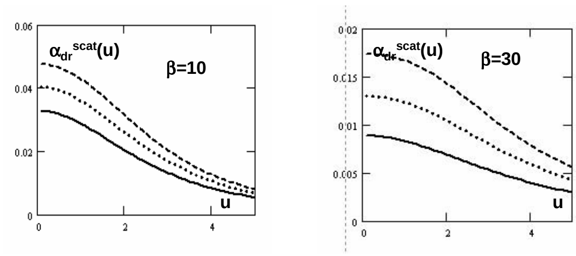

Fig.2

Figure 2: Examples of calculated dependencies od scattering drag coefficient α_{dr}^{scat} on the normalized ion drift velocity $u \rightarrow u_i/\sqrt{2}v_{Ti}$ the screening of grains is non-linear (ion screening charge $\rho_i \propto \phi^\nu$, solid line corresponds to $\nu = 0.9$ the dotted line correspond to $\nu = 0.5$ and the dashed line corresponds to $\nu = 0.1$; $\beta = a\sqrt{n}/\tau$

ing from 2.375, 2.026 to 1.243 for large, medium and small structures respectively.

Influence of absorption drag on the distributions in structures are found to be weak although the results depend on degree of non-linearity in screening ν (see Fig. 4). The Fig. 4 contains the results of computations of total flux and convective flux together with electric field for medium size structure where the absorption drag was neglected -the solid line, $\nu = 0.1$ or taken into account -the dotted line $\nu = 0.1$. The dashed line correspond to the total drag for $\nu 0.5$ and the dash-doted line corresponds to the total drag and $\nu = 0.9$. One can see form Fig.4 that the absorption flux mainly influences the distribution of electric fields in the structure. The role of gas pressure is illustrated by Fig. 5 where $a = 0.1 \tau = 0.01$ since $a \rightarrow a/\lambda_{in}$ is proportional to the density of neutral gas. The role of temperature ratio τ is illustrate by Fig.6 where $a = 0.1, \tau = 0.1$. Applications to the future experiments in spherical gas chambers [4,5] are discussed.

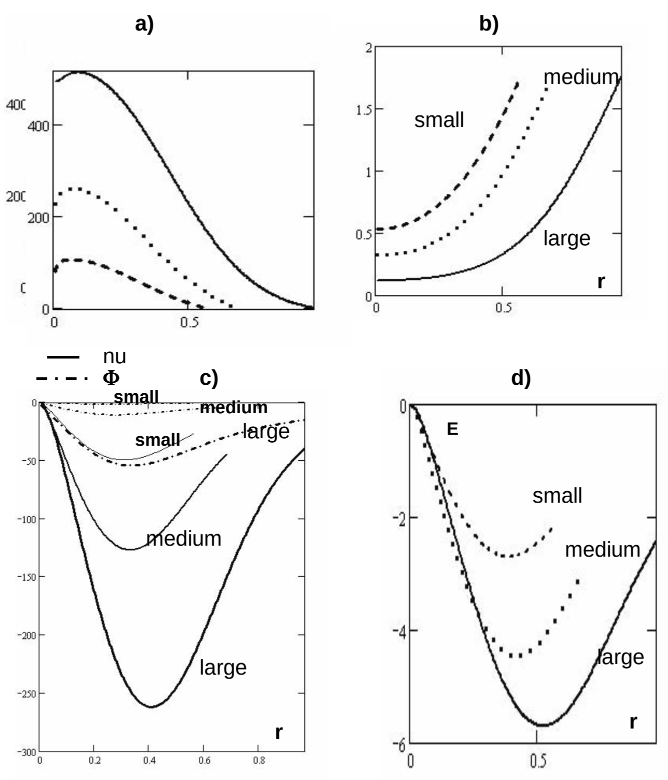

Fig.3

Figure 3: Results of distributions of parameters inside structure for $a = 0.01, \tau = 0.01$, a- distribution of Havnes parameter , b- distributions of dust charges, c-distributions of the total flux Φ and the convective flux nu, d-distribution of s the electric fields E; distance r is in units λ_{in}; solid line corresponds to $\nu = 0.9$ the dotted line correspond to $\nu = 0.5$ and the dashed line corresponds to $\nu = 0.1$; $\beta = a\sqrt{n}/\tau$

Thus we found theoretically that for self-organized dissipative structures in dusty plasma there exist a broad range of equilibrium states, regulated by a single parameter which can be found experimentally simply by counting all grain in the structure. The spherical structures can be investigated using spherical chambers. Such experiment that keep the spherical symmetry can be fulfilled in the conditions of micro-gravity.

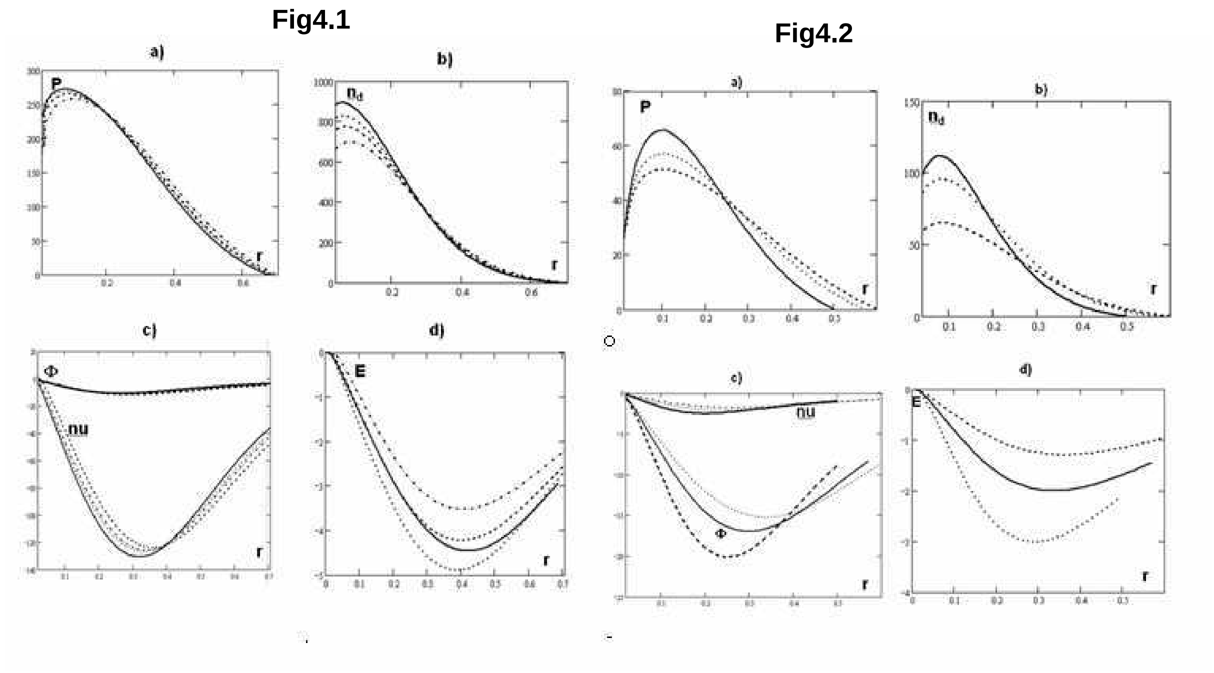

Figure 4: Figure 4.1:Results of distributions of parameters inside structure for $a = 0.01, \tau = 0.01$, a- distribution of Havnes parameter , b- distributions of dust densities P/z, c-distributions of the total flux Φ and convective flux *nu*, d-distributions of electric fields E; different lines correspond to the total or scattering flux and different value of non-linear parameter ν (solid line -to $\nu = 0.1$, dotted line -to $\nu = 0.5$ and dashed line to $\nu = 0.9$);Figure 4.2:Results of distributions of parameters inside structure for $a = 0.1, \tau = 0.01$ different lines correspond to different value of non-linear parameter ν

References

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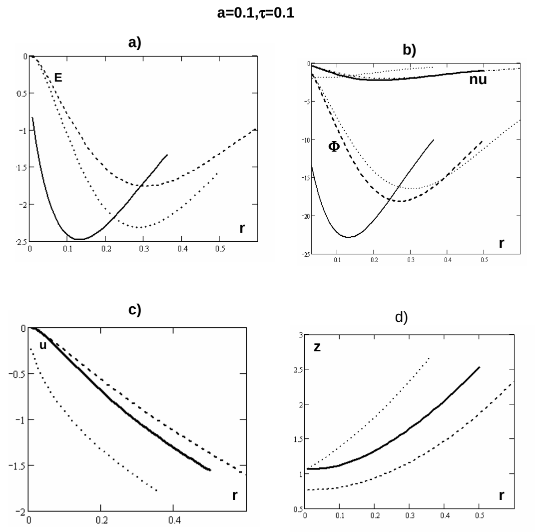

Fig.5

Figure 5: Same as on Fig.4.2 but for $a = 0.1, \tau = 0.1$