Shell-void structures in complex plasmas

V.N.Tsytovich[1], S.V.Vladimirov [2] and G.E.Morfill [3]

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

[2] *University of Sydney, Australia*

[3] *Max Planck Institute for Extraterrestrial Physics, Arching, Germany*

1. Shell-void dust structures are defined as dust regions separated by dust voids. It is shown that depending on power of ionization all spherical shell-void structures can have either a compact dust structure in the central region or a compact dust void at the central region. Interchange of dust and void region with an increase of distance from central region (i.e. formation of dust-shells) is a general phenomenon in complex plasmas. Both voids and compact dust regions have finite radial size about (or larger than) the mean free path for ion grain collisions. The dust regions are supported by inwards dust fluxes and confine only finite number of dust particles (see sketch on Fig. 1). The plasma fluxes are self-created by shell structures and according to equilibrium conditions of structures require definite value of plasma external fluxes.

Theoretical investigations of dust-void shells in complex plasmas is based on numerical solutions of stationary master equation that describes both types of configurations of dust void structures and the distributions of dust, electron, ion densities, individual dust charges, electric fields and plasma fluxes inside the structures . The master equations take into account the equilibrium of electric and drag forces acting on dust grains, the equilibrium of ion forces that include the electric field force, ion pressure force and friction forces on neutrals and grains. The rate of change of plasma flux in structures is determined by balance of volume ionization and absorption on grains. The plasma fluxes consist of convective and diffusion parts and take into account both the ion-neutral and ion-dust collisions. Both the drag and diffusion coefficients are calculated numerically using the model [1,2] for non-linear grain screening and approximation of constant cross-section of ion-neutral collisions in neutral gas. It is shown that the necessary conditions for existence of equilibrium for all structures depend only on two global parameters - external plasma flux and power of volume ionization. In calculation instead of these two parameters other equivalent two parameters are used- the ion density at the center and the ionization coefficient (defined as ratio of ionization

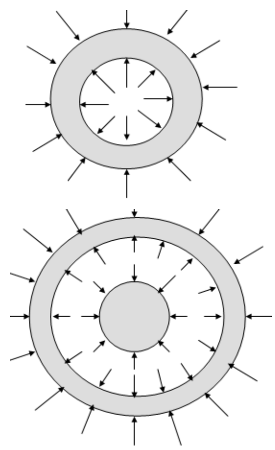

Figure 1: Sketch of dust void at the center surrounded by the first dust-void shell and sketch of compact dust structure at the center surrounded by a dust void and first dust-void shell

rate to electron density). It is shown that the equilibrium is possible in restricted range of phase space of these parameters. With an increase of ionization rate the range of existence of compact dust structures at the center is narrowed, the size of compact central structures and the number of confined grains are decreasing. For large ionization rates only structures with voids at their center are formed. For the non-linear grain screening the central voids are calculated numerically for the first time. Investigated are the dependence of the void size on degree of ionization and on boundary conditions at the void surface. It is found that void creation is a common phenomenon in complex plasmas. It is shown that voids should also always surround any compact dust structures. These voids are found to have finite size. It is found also that the spherical voids are surrounded by dust spherical shell of finite size. The general conclusion is that in complex plasma a shell like structures can be created with the sizes of the order or larger than the maximum of ion-neutral collision mean free path length and the dust charging length. This is new phenomenon predicted from the present approach. Structures with many dust shells can exist. These shells are of much larger size than that previously investigated for the case of small numbers of grains and are ruled by drag forces acting on grains and by forces acting on ions, the electric field forces, friction forces due to ion momentum transfer in process of dust drag and ion scattering, ion gradient pressure forces and ram pressure forces. The outer boundary of the voids separating the dust free region and the dust containing regions is calculated by concept of virtual voids. The virtual void surfaces correspond to balance of virtual electric field force and virtual drag force acting on grains and can correspond to either stable or unstable configuration (see Fig. 2). The existing experiments with injection of few probe grains in central dust free region support the concept of virtual voids. It is notices that the approach using non-linear grain screening model is the most appropriate for explanation of experiments with small number of grain on virtual surface and void structures with large number of grain surrounding the void region. The Fig. 3 gives an example of numerical calculations of parameters inside a stable virtual void for central void density $n = 10$ and ionization coefficient $\alpha_i = 0.1$ (notation see on caption of Fig. 3 and in [3]). On Fig. 3b,s,d $0 < r < R_v$. Fig. 3e indicates that the diffusion flux is contributing to the void structures only close to the void edge. The boundary conditions at the void surface are used to calculate the Havnes parameter P of the shell layer of finite thickness surrounding dust void at distances larger than the void surface. The necessary condition for existence of dust structure layer is used as $P > 0$ at the distance where the

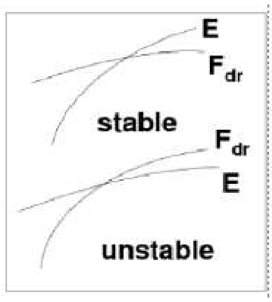

Figure 2: Intersection of $E(r)$ and $F_{dr}(r)$ correspond to the location of the surface of stable or unstable dust virtual dust void.

dust shell structure is joining the virtual void surface. The results of calculations of P at this distance are different for the case where the diffusion is neglected in master equation and for the case where it is taken into account. In the first case the calculated values of P is negative indicating that formation of finite size void-shell structure for small diffusion is not possible, while in the second case for the results shown on Fig. 3 the calculated value of P is positive (about 2) which is an indication that the diffusion is important in the dust shell surrounding the void at least in its region close to the void surface. Therefore the spherical dust layer surrounding the void should be calculated using the system of master equations that take into account the diffusion both the to ion-neutral collisions and ion-dust collisions. The values of ion density, electron density, ion drift velocity and plasma flux at the void surface are taken as starting values for calculations the dust spherical shell surrounding the void. The results are presented on Fig. 4. The value of Havnes parameter P, the value of ion density n and the value of coupling constant Γ have a maximum at the middle of the dust shell, the ion drift velocity u, the flux Φ and the electric field strength E are changing their directions at the middle of the dust shell. It is compressed from both sides by plasma fluxes that include the convective and diffusion fluxes, diffusion is sufficiently large on both size of the shell. The Fig. 4 was calculated using the numerical results for full diffusion coefficient in master equation that take into account the balance of electric field and drag force acting on grains, balance of ram pressure, thermal pressure forces, electric field force and friction force due both collisions of ions with neutrals and non-linearly screened grains. Investigated have been made for the case where compact dust structure is located at the center being surrounded by a void structure and subsequent dust shell. These type of shell structures are quite different from that known previously [4](see also [5]) for small number of grains

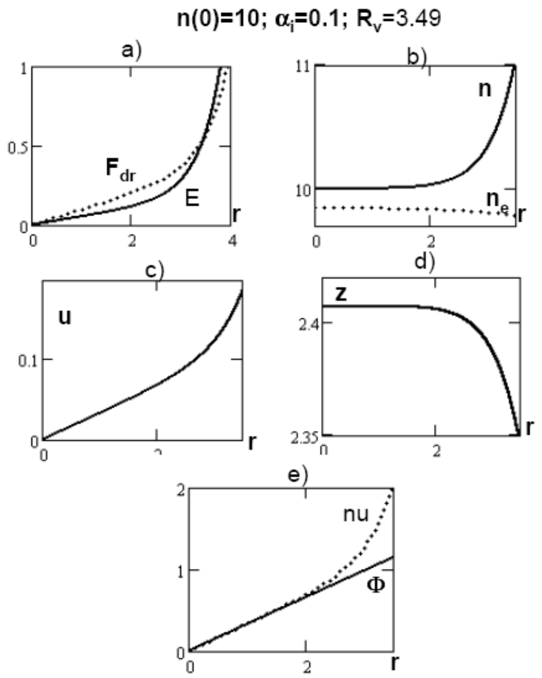

Figure 3: Numerical results of calculation of void structure for $n(0) = 10, \alpha_{ion} = 0.1$ $a = 0.01, \tau = 0.01$ gas Argon. The distance of the crossing point of curves $E(r)$ and $F_{dr}(r)$ correspond to the radial size of the virtual void $R_v = 3.49$, $n, n_e, Z_d n_d \to P$ are in units of $n_{eff} = T_i/4\pi e^2\lambda^2$; distance from the center r ,dust size a and void size R_v are in units of λ (the mean free path for ion-neutral collisions), $z = Z_d e^2/a\lambda T_e$: $\tau = T_i/T_e; u = u_i/\sqrt{2}v_{Ti}$, u_i is the ion drift velocity, the flux Φ is in units $\sqrt{2}v_{Ti}n_{eff}$ and the convective flux Φ_{conv} is nu

and are much thicker. Their thickness is about or larger than the mean free path for ion-neutral or charging collisions. The compat dust structures at the center for shell void structures have similar properties with dust shells sorrounding central void. Starting from some critical value of $n(0)$ at the center the compact dust structures at the center have peaks in dust density and ion density distribition. An increase of the ionization rate for fixed $n(0)$ decreases the size of central dust structures and convert them to the peaked dust structures for smaller $n(0)$. In the case where the dust-shell structures has a void at the center the computations show that for fixed $n(0)$ the size of the void is decreasing with an increase of the ionization rate and the shell can have several peaks for dust and for ion densities. The maximum value of the Havnes parameter in the dust shell is substantially increased with an increase of ionization rate. Computation show that for example for $n(0) = 10, \alpha_i = 0.1$ the maximum value of Havnes parameter in the shell is $P \approx 11$ while for the same value of $n(0)$ but larger $\alpha_i = 1$ this maximum value of P is $P \approx 26$. Distances shown on Fig's are in units of ion-neutral atom mean free path. Also cylindrical and flat void-shell structures have been investigated.

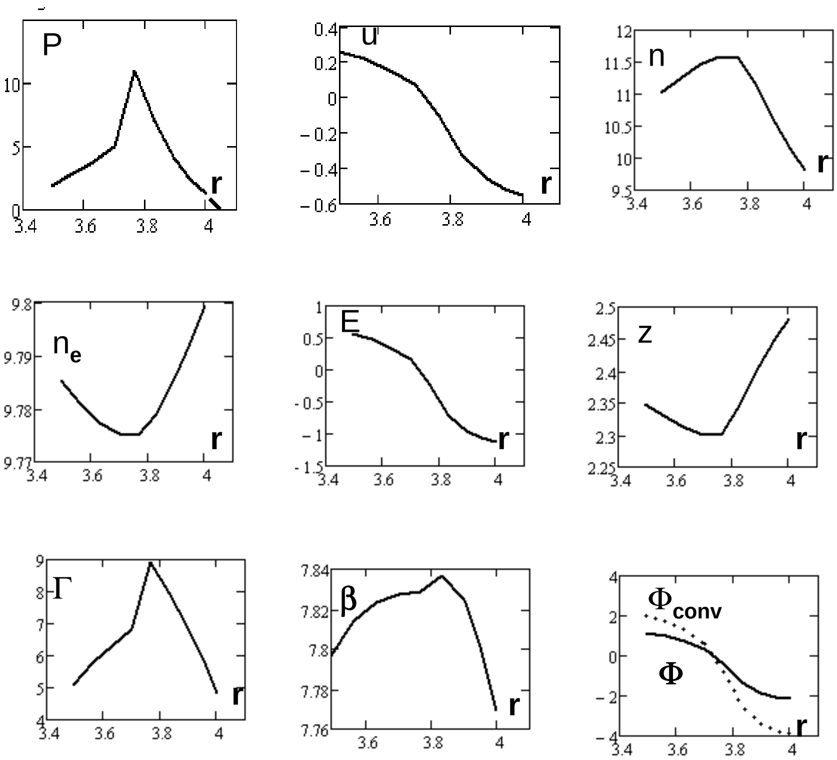

Figure 4: Distrubution of the parameters $P, u, n, n_e, E, z, \Gamma = z^{5/3}P^{1/3}, \beta = za\sqrt{n}/\tau, \tau = T_i/T_e \ll 1$ total flux Φ and convection flux nu inside the shell sorrounding the void of the parameters shown on Fig. 3

References [1] Ja. Alpert, A. Gurevich and L. Pitaevsky, *Space Physics with Artificial Satellites*, (Consutant Bureuat) , London,N.Y. (1965). [2] J. Lafranbose and L. Parker *Phys.Fluids*, **16**, 629 (1973); [3] V. Tsytovich G. Morfill "General feature and master equations for Dust structures". Proceedings this conference Contributer papers; [4] A. Melzer, M. Klidworf and A. Piel *Phys Rev.Lett*, **87**, 115002/1-4 ; [5] V. Tsytovich, G. Morfill, S. Vladimirov, H. Thomas, *Elementary Physics of Complex Plasmas*, Springer Verlag (Heidelberg, London, N.Y.) (2009).