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Advantages of Spherical Dust Structure Experiments According to the Results of Detailed Theory of Dust Structure Equilibrium and Stability

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1.**Spherical cameras.**

Investigations of dusty plasmas in spherical chambers has many advantages not yet used in micro-gravity experiments [1]: a)the wall surface charges cannot create fields and drag grains to the walls, b)some devices can be used at the periphery to create plasma fluxes toward the center [2,3], c)in micro-gravity conditions a force free configuration can form coherent self-organized structures. Some examples of spherical camera are given on Fig. 1 together with general model for numerical investigations. **2. General role of plasma fluxes.** Linear theory [4] shows that homogeneous dusty plasma is unstable to form plasma fluxes which separate regions of enhanced dust density and regions with dust density rarefication. The rarefication can develop to dust voids and the enhanced dust density regions can develop to self-organized structures. The present theory provides the phase diagram of possible equilibrium states in the plane ionization power versus fluxes, distributions of the main parameters inside the equilibrium structures, global responses of structures for variation of external fluxes and ionization power, derivation of global modes and the structure stability. The present investigation is made in frame of new hydrodynamic approach. The equilibrium states correspond to hydrodynamic balance conditions. **3. Ideology and of new hydrodynamics**. Usual hydrodynamics based on thermal plasma particle distributions is not applicable since the new collisions related with dust are much more important than the binary plasma particle collisions, namely the scattering of ions by grains, absorption of plasma fluxes by grains and the ion-neutral collisions. Large values of dust charges $Z_d \gg 1$, $(-Z_d$ is the dust charge in units of electron charge) create two important features: a) the binary ion-ion/electrons collisions are negligible for $Z_d P \gg 1$ b) for $\beta \ll 1$ (β - the ratio of ion-grain potential energy to the ion mean thermal energy T_i at the

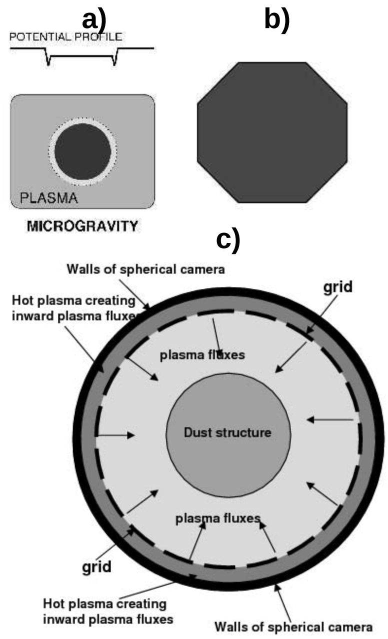

Figure 1: a)N.Sato device, b)One of U.Konopka devices c) Principal model for numerical investigations

Debye radius) the screening of grains becomes non-linear (in experiments cited in [1] $\beta \approx 30-50$). The new hydrodynamics is based on only the 3 new types of collisions with taking into account the non-linear grain screening. The straight forward way of it derivation is to use new collision integrals describing the interaction with variable charge grains [5] and to calculate the change of distribution function momenta by space inhomogeneities. Up to present the new dust-particle collision integrals have been found only for linear screening $\beta \ll 1$ and the ion drag forces for nonlinear screening have been investigated [6] only for small ion drift velocities $u \ll 1$ ($u \rightarrow u_i/\sqrt{2}v_{Ti}$). The new hydrodynamic avoids these restrictions. The results for drag force are generalized for moderate drifts using the drifting ion distributions in kinetic description with cross-sections of ion-dust scattering and ion dust absorption. The consideration is restricted to drift velocities much less than the ion sound velocity $u \ll u_s \approx \sqrt{1/\tau}, 1/\tau = T_e/T_i \gg 1$ where the changes of cross-section of ion-dust collisions by ion drift can be neglected and the drag force for nonlinear screening can be found by averaging with respect of drifting ion distribution. According to [7-9] the ion temperatures along the drift $T_{||}$ and perpendicular to the drift $T_\perp$, the $T = T_{||}/T_\perp$ could differ ($T \neq 1$) and this is taken into account in the asatz of the drifting distribution. The final result for distributions of drift velocity in the structures indeed indicate that $0 < u < u_s$.The ansatz is used for calculations of momenta of equations with cross-sections of grain-particle and ion-neutral interactions. For non-linear dust drag only the ion-dust scattering on large angles is important. The numerical calculations give the dependence of non-linear drag force on both nonlinearity in screening β and ion drift velocity u and is used in new hydrodynamics. The equation for ion drift takes into account both the addition friction related to dust drag (calculated from momentum conservation) and the ion-neutral non-linear friction. The con-

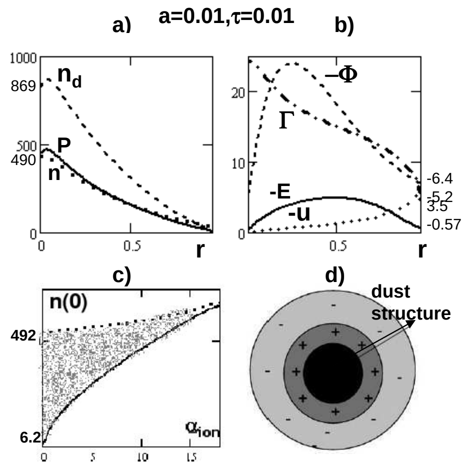

Figure 2: a)numbers at the left show the values at the center,$n_d \rightarrow 4\pi(\lambda_{in}^{eff})^3 a/\tau$ b)numbers at the right show the values at the surface (flux is minus 6.4,grift velocity is minus 5.2,coupling constant times $1/10000$ is 3.49,electric field is minus 0.569 corresponding to the structure charge $Z_{str}e^2/\lambda_{in}T_i = 0.509$), c)shadowed is the region of equilibrium, d)negative dust structure charge is screened by polarization charge at distances larger than the structure size; the distance of change of the sign of polarization charge is larger then the screening distance corresponding -effect of over-screening

tribution of plasma flux absorption is dominated only in ion continuity equation. The drag forces are depending on individual dust charges $z \equiv Z_d e^2/aT_e$ and the equation for space dependence of z is used in new hydrodynamics. The ion flux Φ derivatives in space include both the ionization proportional to electron density and the absorption on grains. **4. Definition of new variables.** Non-standard normalization is used: ion density $n \equiv n_i/n_{eff}$, electron density $n_e \rightarrow n_e/n_{eff}$, Havnes parameter $P = n_d Z_d/n_{eff}$, ion flux $\Phi \rightarrow \Phi/n_{eff}\sqrt{2}v_{Ti}n_{eff}$. The normalization density is $n_{eff} = T_i/4\pi e^2 \lambda_{in}^{eff}$ where $\lambda_{in}^{eff} = (3\sqrt{\pi}/8)\lambda_{in}$ and $\lambda_{in} = 1/n_n\sigma_{in}$ is the ion-neutral collision mean free path. For the forces and electric fields $F \rightarrow F\lambda_{in}^{eff}/T_i; E \rightarrow eE\lambda_{in}^{eff}/T_i$. The grain size and distances are $a \rightarrow a/\lambda_{in}^{eff}, r \rightarrow r/\lambda_{in}^{eff}$. For typical laboratory parameters $n_{eff} = 2.3 \times 10^7 \mathrm{cm}^{-3}$ and the range $6 < n < 500$ (see phase diagram) is reachable in experiments. The factor $3\sqrt{\pi}/8$ is convenient to use for linear mobility in ion-neutral collisions to be $u = E$.**5. Perturbations by inhomogeneities.** The smallest is the ion-dust scattering mean free path but for large angle scattering the scattering does not contribute to the perturbations produced by inhomogeneities. Competing are the charging mean free path λ_{ch} and λ_{in}. The effect of charging collisions is small for $Pa \ll 4(1+u^2)$. Only in the inner part of the largest spherical structures with $P \approx 490; a \approx 0.01$ the charging absorption could be of order of ion-neutral collision, while in the outer part of the structures the ion-neutral collisions can dominate. For dominant ion-neutral collisions the flux has a new form $\Phi = nu - dD(u)n/dr$ (for constant cross-sections). The $D(u)$ was found analytically for $u \ll 1$ and numerically in the range $0 < u < 5$ with good fitting by $D(u) = \sqrt{(32/9\pi)^2 + 4u^2}$. The fitting of charging coefficient is $\alpha_{ch}(u) = 2/\sqrt{\pi + 4u^2}$. **6. Example of hydrodynamic equations for dominant ion-neutral collisions.** The equation for the flux, and ion drift velocity are $(1/r^2)d(r^2\Phi)/dr = \alpha_{ion}n_e - \alpha_{ch}(u)anP$; $F(u)du^2/dr = -(1+2u^2)(1/nD(u))(dnD(u))/dr + E(1-P/n) - u\sqrt{1+u^2}$ with a fitting expression $F(u) = (0.562 + 8u^2)/(D(u))^2$. Dust equilibrium does not depend on the dust state in the structure (gaseous, liquid or crystal) and has the form $E = F_{dr}, F_{dr} = \beta\sqrt{n}\alpha_{dr}(\beta,u)u$ with the drag coefficient $\alpha_{dr}(\beta,u), (\beta = az\sqrt{n}/\tau)$ calculated numerically. The other 3 equations are the adiabatic change in electron density, the equation for ion density (from the expression of plasma flux) and the equation for changes of grain charges. The rate of quasi-neutrality is found from Poisson equation the solution of which leads to an analytical expression for Havnes parameter as function of other variables. The nonlinear equations were found for the case of dominant charging collisions and for $T \neq 1$ **7. Physics of dust confinement in structures and collective electric field generation.** The fluxes are inevitable created self-consistently due to dust charging and the dust drag generates electric fields which in tern create fluxes. The ion fluxes are directed inwards and confine dust by ion drag, the electric fields being positive drives grains outwards both balancing the drag and creating the potential well for ions (calculations give the ion potential well $\approx (4-10)T_i$). In structures both dust and ions are concentrated at the center. Many numerical solutions of the obtained non-linear equations support this statement for different parameters a, τ and parameter of non-linear screening. An example of distribution of parameters in the structure are given on Fig. 2 together with the phase diagram for existing of equilibrium and a scheme of polarization charge over-screening in structure corona.

MAIN RESULTS. 1. Equilibrium structures have finite maximum size about $(2-6)\lambda_{in}^{eff}$ for ion-neutral collisions. This could be less than the camera size and for non focused external flux several structures can be created opening the possibility to investigate their interactions and over-screening of the polarization charge of a single structure **2**. Self-organized structure can confine finite number of grains, less than the $N_{d,max}$ calculated. The structures are determined only by three parameters: external flux Φ_{ext}, ionization power (coefficient α_{ion}) and total number of grains confined. The Φ_{ext} can be expressed through the ion density at the center n_0. Fig. 2 shows the region of existence of equilibrium structures. **3**. Responses of structures to modulation of flux and ionization power have been calculated taking into account dust friction in neutral gas and dust inertia. The dependence of responses on the frequency of modulation has resonances depending on ionization rate and indicating the existence of global structure modes. **4**. The theory of linear perturbations of the equilibrium states shows that the structures have large domain of stability for S-modes. **5**. The structures have large negative total charges $z_{str} \equiv Z_{str}e^2/\lambda_{in}T_i$ (numerically $0.5 < z_{str} < 50$). **6**.) Stable structures cane be regarded as super-grains and form super-structures (including super-crystals). The latter is inevitable in presence of ionization in large volume and is a consequence of both finite structure sizes and finite maximum values of fluxes that can be absorbed by single structure. **7**. The over-screening of the polarization field is the common phenomenon for single grains and structures. For single grains this effect gives the best explanation of plasma crystal formation while the experimental investigation of over-screening is simpler for structures.

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