Structurization of dusty plasmas in astrophysical conditions

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.**Introduction.** Structurization instability can develop in dusty plasmas with features similar to gravitational structurization instability but on much smaller scales [1]. The dusty plasma structurization is due to plasma flux absorption on dust particles creating effective forces which confine in some space regions both grains and plasma particles (ions and electrons). The effective length for dust structurization is similar to Jeans length in gravity but is much smaller than the latter and is of the order either the mean free path of plasma flux absorption on dust grains or the mean free path of ion - neutral atom collisions. At present the dusty plasma structurization is observed in several laboratory dusty plasma experiments and experiments on board of International Space Station (ISS) [1]. Different types of structures have been observed in conditions of micro-gravity including the dust compact structures, dust voids surrounded by dust layers and dust vortex structures. In laboratory Earth experiment the effect of structurization was discovered only recently [2].The structurization in laboratory experiments is fast as compared with observation time and at present only the non-linear stage of already formed stationary structures has been investigated. The theoretical result that homogeneous complex/dusty plasmas are universally unstable for structurization was first obtained in [3](see [1]). Subsequent efforts have been to describe theoretically the non-linear self-consistent structures as possible final state of structurization [4]. For small dust clouds where the attraction of grain can be caused by Lesage type of grain attraction the gravitation-like structurization instability was developed in [5] and the analogy with gravitational instability was mentioned. Investigations for sizes of dust clouds larger than the mean free path for charging [3,1] also pointed out this analogy. The difference between the laboratory and space conditions are found to be that: 1)the grain screening is simply Debye screening for space conditions and strongly non-linear screening for laboratory conditions, 2)the ratio of ion to electron temperatures is about 1 in space conditions and it is about 0.01 in laboratory experiments and experiments on board of ISS. The theoretical description for space conditions is simpler that for laboratory conditions since one can use good established process of dust drag by ion fluxes in the limit of linear Debye grain screening. But this has not been previously considered. We restrict ourselves here to result of investigations of simplest non-linear stage of dusty plasma structurization-possible formation of compact dust spherical structures similar to usual stars - called here as dust stars. In principle the non-linear stage of structurization dust instability can be more complicated and this should be taken into account in future applications for observations. Applications of dust structurization instability to problems of dust clouds recently observed close to stars in many space mission (in infrared frequency range) have been not yet considered (although many observations contradict the standard models). The aim of present paper is not to apply the results on dust structurisation instability to some existing astrophysical object but to make first estimate and to present the results for dust star formation in the form that they can be applied by researchers observing the structurization of dust in space dust clouds. We will be able to show that there exist necessary conditions when on non-linear stage the structurization can create equilibrium structures like dust stars, that contrary to usual stars the plasma wind (in dust stars - plasma flux created self-consistently by grains) is directed inwards and exists in limited ranges, that the size of the dust stars is larger than or of the order of the ion mean free path for dust charging or ion mean free path for ion-neutral collisions, that the balance of forces contrary to usual stars (where the main forces are the gravity and pressure), include also the dust drag by ion flux, friction of ions on grains and flux absorption by grains. The temperature inside dust stars cannot be high allowing the dust grain to survive or even to grow, but it should be high enough if the dust charge Z_d (in units of electron charge) is large ($Z_d \gg 1$ as it often found in space dust clouds). 2.**Simplifying assumptions**. To point out the main new features we restrict consideration using assumptions: 1)All dust grains in the dust cloud have almost the same size a_0. This assumption is a rough approximation for complicated dust size distributions in space which often are rapidly decreasing with an increase of dust size as $1/a^{\nu}, \nu > 3.5$ and is limited from below by smallest grain with size about average size a_0 with number of grains for $a < a_0$ being almost zero. 2)The grain charge in units of electron charge is large $Z_d \gg 1$. Although there are space clouds (for example dust-molecular clouds) where this inequality is not valid the large grain charges are often met in space. 3)The main grain interaction of interest is that appearing at distances larger than Debye screening distance λ_D where the charging flux on one grain creates the drag force acting on other grains. This is natural assumption found also valid in most laboratory experiments since the charging distance is λ_D/a larger then λ_D. 4) In astrophysical plasmas the $\Lambda = \ln(\lambda_D/a_0)$ is very large number and we assume $\Lambda \gg 1$. 5)The gravity forces can be neglected. This is certainly the case far from the stars and this assumption is made only to consider pure dust structurization not being mixed with gravity or gravitational instability. The distance R where the gravity of central star does nor influence the dust structurization can be estimated comparing the gravity force with drag force for ion drift velocity of the order of ion thermal velocity $a_0/1\mu\text{m} < 0.5(M_\odot/M_{star})(R/3\times10^{15}\text{cm})^2(z/2.5)^2(n_i/10\text{cm}^{-3})(T/2eV)(2\text{gr/cm}^3/\rho_d)(\Lambda/10)$ where $z =$

$Z_d e^2/a_0 T$ is dimensionless dust charge, n_i is the ion density, T is the temperature and ρ_d is the dust material mass density. 3. **Dust drag by plasma fluxes and flux absorption by grains**. For $\Lambda \gg 1$ the dust drag force F_{dr} by plasma flux ions is created by Coulomb scattering of ions on grains (see[1]) $F_{dr} = Z_d z a n_i e^2 (u_i/v_{Ti})(4\sqrt{2\pi}\Lambda/3)$. The flux created by one grain acts on other grains existing around each grain at distances about either the charging distance λ_D^2/a or the mean free path for ion-neutral collisions λ_{in} (in low degree ionized dusty plasmas). In space dust clouds the volumes of such size contain usually large number of grains. For $Z_d \gg 1$ the only force on grains that can compensate the drag is the electric field force. In equilibrium an electric field is created by spatial differences of fluxes (similarly as the Ohm law creates an electric field by difference of voltages). The drag creates also a friction force for ions which is $Z_d n_d/n_i$ less than the electric field force acting on ions. The rate of absorption of plasma flux on grains is Λ times less than scattering rate and describes the plasma flux sink. The presence of collective plasma flux is usually inevitable due to it self-consistent creation by dust charging. 4.**Balance of forces at the center of equilibrium dust star**. It is useful to introduce the dimensionless parameters and dimensionless distances from the center of the star: the ion density $n = n_i/n_{eff}$, the electron density $n_e \to n_e/n_{eff}$, the Havnes parameter $P = Z_d n_d/n_{eff}$, the plasma flux $\Phi \to \Phi/n_{eff}\sqrt{2}v_{Ti}$, the ion drift velocity $u = u_i/\sqrt{2}v_{Ti}$ and the distance from the center $r \to 2r/3\sqrt{\pi}\lambda_{in}$ with $n_{eff} = T/\pi e^2 a_0 \lambda_{in}\Lambda$. At the center $r \to 0$ the drift velocity, the flux and electric field vanishing being proportional to r. The three relations obtained from flux equation, ion drift velocity equation and the Poisson equation can be used to express all parameters at the center $P(0), n_e(0), u_0'$ through the ion density at the center $n(0)$.

$$P(0) = \frac{n(0)z(0)-1}{z(0)-1/\Lambda};\;\; n_e(0) = \frac{\Lambda - n(0)}{z(0)\Lambda - 1};\;\; ;\;\; u \to r u_0';\;\; u_0' = -\frac{n(0)z(0)-1}{z(0)\Lambda - 1}$$

(the dust charge at the center $z(0)$ is found from the dust charging equation $\exp(-z(0)) = \sqrt{m_e/m_i}z(0)(z(0)\Lambda - 1)/(\Lambda - n(0))$. This gives the necessary range for existence of equilibria in dust stars: from $P(0), n_e(0) > 0; u_0' < 0$ one finds $\frac{1}{z(0)} < n(0) < \Lambda$. 5.**Balance equations for equilibrium distributions inside the dust stars**. For ion drift velocity we use in equation for balance of electric field force, friction forces on grains and neutrals, ram and thermal pressure forces. For electrons we take into account the electron pressure force modified by plasma flux and the electric field force. For ion density we take into account the ion diffusion on neutrals. For flux we take into account the absorption on grains. The main balance equation than are:

$$\frac{dn}{dr} = (1 + 0.61u^2 + 0.17u^4)(nu - \Phi);\;\; \frac{dn_e}{dr} = -4.66 n_e n z u;\;\; \frac{du}{dr} = n n_e z - \sqrt{1 + 0.442u^2} -$$

$$-\frac{1 + 0.61u^2 + 0.17u^4}{2nu}(nu - \Phi);\;\; \frac{d\Phi}{dr} + \frac{2\Phi}{r} - \frac{3}{\sqrt{1 + \frac{4u^2}{\pi}}\Lambda} n(n - n_e)$$

with additional equation for dz/dr, obtained by differentiation of the grain charging equations. The numerical coefficient in these system of equations have been obtained ether by fitting the numerical results or by interpolating the analytical results between $u \ll 1$ and $u \gg 1$.

6.**Numerical results**. Numerical solutions of equilibrium equations have been investigated in the whole range of necessary conditions for equilibrium for hydrogen plasmas, i.e for $0.4 < n(0) < \Lambda$ starting with the asymptotic solutions for $r \to 0$. An example of the solutions for $n(0)$ close to lower limit $n(0) = 1$ and for $\Lambda = 30$ are given on the Figure. With an increase of $n(0)$ several maxima for P appear inside the dust stars with possible abrupt change P to zero. In these calculations the dust star confinement is produced by external plasma flux self-consistently adjusted according to equilibrium conditions. It the periphery the dust vortices can be excited due to azimuthal instability creating azimuthal of dust charge inhomogeneities. 7. **Discussions**. The future programm (partially started) is a generalization for presence volume ionization (especially ionization by ultraviolet radiation). Present numerical results show that the distributions depend substantially on the model for diffusion - for constant diffusion the stars have always a single maximum of P at the center. The models used have limits of applicability being based on assumptions of constant cross-sections for ion-neutral collisions and drifting ion distributions. To use the experimental cross-sections in presence of high flux and detailed ion distributions depending on charge-exchange collisions and dust charging requires special experiments probably on board of ISS. As the numerical results indicate the electric field at the surface of the dust stars is not zero which means that they are charged. In tern this means that the clusters of dust stars can be created forming the next step of hierarchy of dust structurizatiion process.

References. [1]V. Tsytovich, G. Morfill, S. Vladimirov, H. Thomas, *Elementary Physics of Complex Plasmas*, Springer Verlag (Heidelberg, London, N.Y. (2009); [2]J. Hendrich, S. Kim and R. Merlino *Physical Review E*, "Structurization instability in a DC glow discharge dusty plasma" in press (2010); [3]G. Morfill and V. Tsytovich *Plasma Physics Reports*, **26**, 727, (2000); [4]V. N. Tsytovich ,*Plasma Physics Reports*,**26**,668-681 (2000),**31**,133-146 (2005),**35**,1-22 (2009); [5]R. Bingham and V. Tsytovich *Astr.Astroph.Letters*, **376**, L43, (2001).

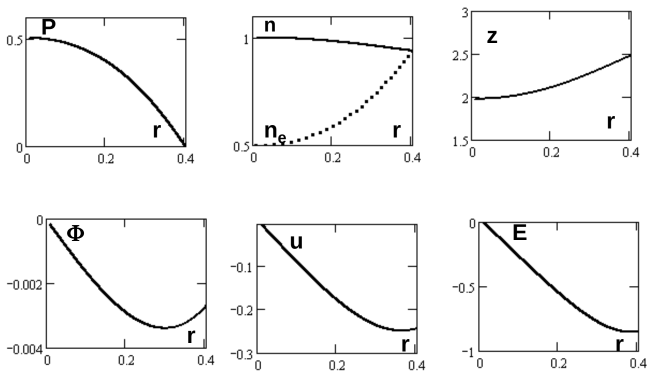

Figure 1: a-Dependence of P, n, n_e, Φ, u, E inside a dust star for $\Lambda = 30; n(0) = 1$