DUSTY PLASMA VOIDS IN A STRATIFIED DC GLOW DISCHARGE

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What is a dusty plasma?

**Dusty plasma** is quasineutral medium, containing:

- Electrons
- Ions
- Neutral atoms and molecules
- Solid micron-sized particles (dust)

=> Weakly-ionized, low-temperature plasma

**Charging of microparticles**

\[
I_e(\varphi_s) = I_i(\varphi_s)
\]

\[
Z_d = \frac{\varphi_s}{e\varepsilon_0 a} < 0
\]

\[
Z_d \sim 10^3 - 10^5
\]
Where the dusty plasma can be found?

a) interstellar medium, b) comet Halley 1986.03.12 c) Saturnian ring system

• **Space** – in interstellar medium, in cometary environment, in planetary rings, in planetary magnetospheres, in the upper atmosphere (80-95 km), etc.

• **Industrial and technological applications**, thermonuclear reactors, plasma chemical reactors for thing film deposition, fusion plasmas, etc.

• **Laboratory conditions** in RF and DC discharges.
  I. Langmuir, C. G. Found, and A. F. Detmer, *Science* 60, 392-394 (1924) - observation of droplets or globules of tungsten vapour in an arc discharge in argon (2-4 Torr, particles ~ 100 μm, $V_d$ ~ 10-30 cm/s)
Dusty plasma in laboratory conditions

\begin{align*}
\text{Ar-SiH}_4 & \quad \text{RF-discharge, 13.56 MHz} \\
\end{align*}


In reactive plasmas (PECVD-method) dust particles:
- are polydispersed particulates with radii in the nano- or micrometre range;
- are produced from the plasma itself by the coagulation of smaller clusters or polymerization of gas dissociation products;
- form a cloud that levitates above the wafer and contaminates it falling on it when the applied voltage on the wafer is turned off → leads to “killing defects”.


In laboratory conditions dusty plasmas are intensively investigated in the positive column of a DC glow discharge in noble gases at low gas density.

Electrons and ions densities are $n_i \approx n_e \sim 10^7-10^9 \text{cm}^{-3}$;
dust particles density is $N_d \sim (10^0-10^8) \text{ cm}^{-3}$;
and dust particles charge is $eZ_d = (10^3-10^5)e$. 
Voids formation in RF discharges in microgravity conditions

Voids formation in DC discharges in microgravity conditions

IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 38, NO. 4, 857 (2010)
Recent Complex Plasma Experiments in a DC Discharge

Fig. 1. Laboratory unit at MPE.

Fig. 3. Typical image with an exposure time of 8 ms of the microparticles drifting in the electrical field of the dc discharge [1].
Voids formation in DC discharges in microgravity conditions

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Recent Complex Plasma Experiments in a DC Discharge

**PK-4 experiments (2014-2018 onboard ISS)**

**Fig. 1.** Laboratory unit at MPE.

**Fig. 3.** Typical image with an exposure time of 8 ms of the microparticles drifting in the electrical field of the dc discharge [1].
Voids formation in combined RF+DC discharge

S. Mitic, B. A. Klumov, S. A. Khrapak, and G. E. Morfill
Three dimensional complex plasma structures in a combined radio frequency and direct current discharge
Physics of Plasmas, 20, 043701 (2013)
Voids formation in striations of DC discharges in gravity conditions

FIG. 1. (Color online) Sketch of the experimental setup.

FIG. 3. (Color online) Sketch of the dust particles cloud and the forces acting on it.

\[ I_d = 4 \text{ mA} \]

\[ I_d = 8 \text{ mA} \]

\[ I_d = 10.4 \text{ mA} \]

\[ I_d = 13.4 \text{ mA} \]
Boltzmann Equation for EEDF (Radial Geometry)

A non-stationary Boltzmann equation for isotropic part of EEDF $f_0(r;U,t)$:

\[
\sqrt{\frac{m_e}{2}} \frac{1}{\sqrt{U}} \frac{\partial f_0}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[ rU \left( \frac{\partial f_0}{\partial r} - eE_r \frac{\partial f_0}{\partial U} \right) \right] + \frac{\partial}{\partial U} \left[ \frac{U}{3H} \left( -eE_r \frac{\partial f_0}{\partial r} + e^2 (E_r^2 + E_z^2) \frac{\partial f_0}{\partial U} \right) \right] \\
+ \frac{\partial}{\partial U} \left[ (Uf_0) - G(U)f_0 + S(f_0) + S_{ion}(f_0) - S_d(f_0) \right]
\]  

\[ (1) \]

$E_r(r)$ is the radial and $E_z$ is the axial component of electric field.

Coefficients $C$, $G$, $S$ correspond to the collision terms and describe elastic and inelastic collisions.

Ionization balance is determined by the processes of direct electron impact ionization $S_{ion}(f_0)$, recombination of electrons and ions with energies higher than the particle potential $|e\varphi_d(r_0)| \sim Z d e^2/r_0$ on the dust particle surface $S_d(f_0) = N_d \nu \sigma_{cap}(\varepsilon) f_0(\varepsilon)$, and recombination on the wall of discharge tube (radial current $I_z$).

\[
I_z(t) = 2\pi e_0^2 E_z \sqrt{\frac{2}{m_e}} \int_0^{R_w} \int_0^\infty \frac{U}{3H(U)} \frac{\partial f_0(U,r,t)}{\partial U} dU r dr - \text{ normalization to the discharge current } I_z.
\]

\[
n_e(r,t) = \int_0^\infty f_0(U,r,t) \sqrt{U} dU - \text{ the electron density } n_e(r,t).
\]

\[
H(U) = N_g(\sum_k Q_k^{in}(U) + Q^{el}(U)) + N_d \pi r_0^2 (1 - |e\varphi_d|/U) \text{ momentum losses in elastic and inelastic collisions including collisions with dust particles}
\]
Drift-diffusion equation for $n_i(r,t)$ and Poisson equation for $\varphi(r,t)$

Non-stationary drift-diffusion equation for radial distribution of ion density $n_i(r,t)$:

$$\frac{\partial n_i(r,t)}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left[ r \left( \mu_i n_i(r,t) E_r - D_i \frac{\partial n_i(r,t)}{\partial r} \right) \right] = v_i(r,t) N_g - v_d(r,t) N_d$$  \hspace{1cm} (2)

$\mu_i$ is ion mobility coefficient, $D_i$ is ion diffusion coefficient, $v_i(r,t)$ is ionization frequency radial distribution calculated from Boltzmann equation (1), $v_d(r,t)$ is radial distribution of frequency of electrons and ions absorption on dust particle surface calculated from Boltzmann equation (1).

**Steady state drift-diffusion equation for radial distribution of dust particles density $N_d(r,t)$:**

$$\frac{1}{r} \frac{\partial}{\partial r} \left[ r \left( \mu_D N_d(r) F_d(r) - D_D \frac{\partial N_d(r)}{\partial r} \right) \right] = 0$$  \hspace{1cm} (3)

$\mu_D$ is dust particles mobility coefficient, $D_D$ is dust particles diffusion coefficient.

**Poisson equation for radial distribution of electric potential $\varphi(r,t)$:**

$$\frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial \varphi(r,t)}{\partial r} \right] = 4\pi \varepsilon \left[ n_i(r,t) - n_e(r,t) - N_d(r) Z_d(r,t) \right]$$  \hspace{1cm} (4)

$n_i(r,t)$ is ion density radial distribution, $n_e(r,t)$ is electron density radial distribution, $N_d(r)$ dust particles density radial distribution is a given function, $Z_d(r,t)$ was calculated with the help of OML model (OML model)
Dust particles density radial distributions

\[ F_{tot} = F_E + F_{id} + F_{dd} \]
\[ F_E = -eZ_d(r)E_r(r) \]
\[ F_{id} \sim j_{ir}(r) \]

\[ |F_{id}(r)/F_E(r)| \sim n_i(r)Z_d(r)/p_{He} \]
FIG. 5. (Color online) Radial distributions of charged particles densities: ions $n_i(r)$ (solid line), electrons $n_e(r)$ (dashed line), charge density of dust particles $N_d(r)Z_d(r)$ (dotted line), bulk charge $\Delta N(r)$ (dash-dotted line). (a) $I_d = 8$ mA, (b) $I_d = 10.4$ mA, (c) $I_d = 13.4$ mA.

FIG. 6. (Color online) Radial distribution of forces acting on dust particles. The solid line is the ion drag force $F_{id}N_d$, the dashed line is the electrostatic force $F_{E}N_d$, the dashed dotted line is the inter-particle repulsive force $F_{dd}N_d$. (a) $I_d = 8$ mA, (b) $I_d = 10.4$ mA, (c) $I_d = 13.4$ mA.
Radial and axial electric fields

FIG. 7. (Color online) (a) Electric potential radial distributions. (b) Electric field radial distributions. Solid lines for $I_d = 8$ mA, dashed lines for $I_d = 10.4$ mA, dashed dotted lines for $I_z = 13.4$ mA.
Conclusions

• In the work, probably the first experimental observations of dust-free regions (voids) formation in a dc glow discharge in gravity conditions are presented. With the increase of a discharge current, the voids were formed in the center of dust particles clouds (i.e. at the axis of the discharge tube).

• A numerical model was developed based on the solution of a non-local Boltzmann equation for the electron energy distribution function, drift-diffusion equations for ions and dust particles, and the Poisson equation for a self-consistent electric field. It was shown that it is the ion drag force radial component that leads to the formation of the voids. Both experimental and calculated results show that the higher the discharge current, the wider dust-free region (void) is formed. The calculations also show that more pronounced voids are formed for dust particles with larger radii and under lower gas pressures.

• The developed model and obtained experimental and numerical results can be important for the understanding of the void formation in complex plasma and for description of dusty plasma parameters, e.g. in "Plasmakristall-4" setup [Thoma, M. H., et al. (2010). "Recent Complex Plasma Experiments in a DC Discharge." Plasma Science, IEEE Transactions on 38(4): 857-860.]