The Influence of Aerosol's Size Dispersion on Dissipative Instability of Aerosol Flow in Planetary Atmospheres' Plasma

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Dusty (aerosol or complex) plasma:

neutrals, electrons and ions

+

large charged particles of micron/submicron size (dust/aerosols).

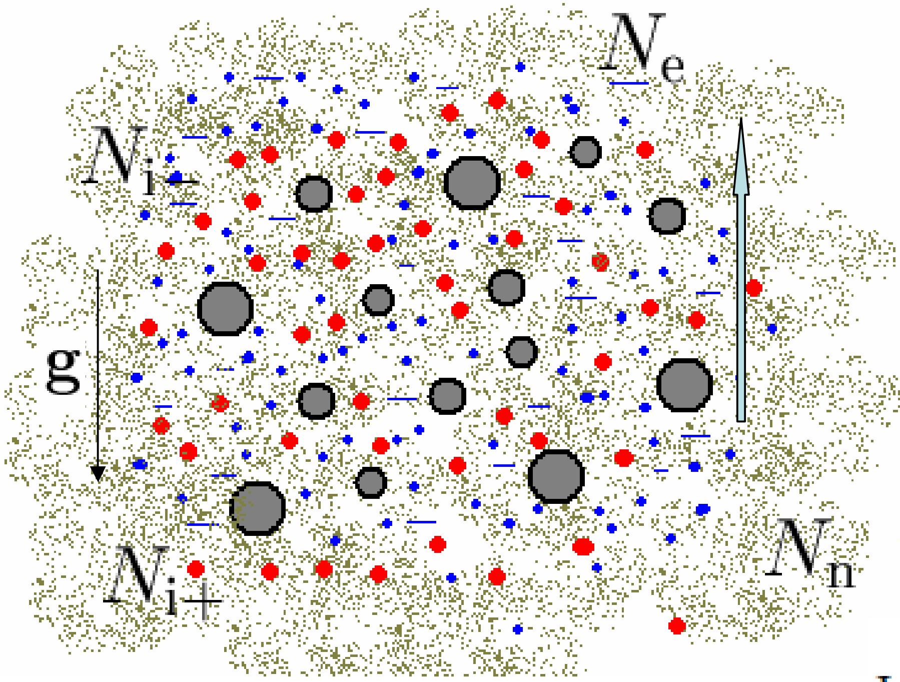
Charging of the large particles is an additional non-stationary process.

Dusty plasma can be found in space, different regions of planet atmospheres, is studied in laboratories.

The presence of dust causes phenomena with new spatial and time scales, including dust-acoustic wave (DAW). The development of DAW instability can generate fine structures in electron density/space charge/electric field in dusty plasma.

In the Earth's atmosphere such fine structures can be found in thunderclouds (~10 m), or in mesopause region (~ 5 cm-5 m, causing Polar Mesospheric Summer Echoes).

Aerosol (dust) particles in weakly-ionized collisional plasma:



Low temperatures T~300 K; thermal dispersion of velocities is negligible.

Aerosol flow is caused by gravity, velocity is determined by friction force:

$$V = \frac{g}{\nu}; \quad \nu = \frac{2\sqrt{2\pi}}{\pi}\gamma_F \frac{1}{\rho_a R}\frac{N_n T_n}{V_{T_n}} = \nu^* \frac{a}{R};$$

$$V = V^* \frac{R}{a} \qquad \nu^* \equiv \nu(R = a),$$

$$V^* \equiv V(R = a)$$

$$: \; Q_d(R)\mathbf{E}; \quad M(R)\mathbf{g}; \quad \mathbf{F}_{fr}$$

$Q_d(R)$ и $M(R)$ – charge and mass of a particle with radii R.

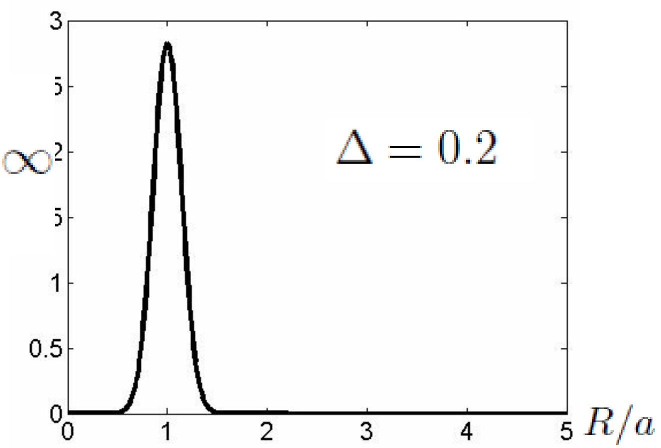
ν – effective frequency of aerosol collisions with neutral gas

Aerosol's size dispersion (model distributions):

Monodispersed ensemble: $f_R = \delta(R-a), \quad 0 < R < \infty$

Gaussian distribution:

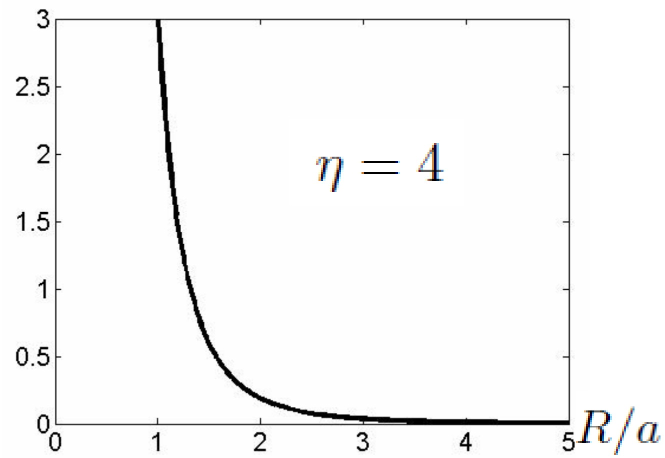
$$f_R = \frac{a}{\delta a\sqrt{\pi}} \exp\left[-\left(\frac{R-a}{\delta a}\right)^2\right], \quad 0 < R < \infty$$



Radii should be positive and finite: $\Delta = \frac{\delta a}{a} < 0.5$

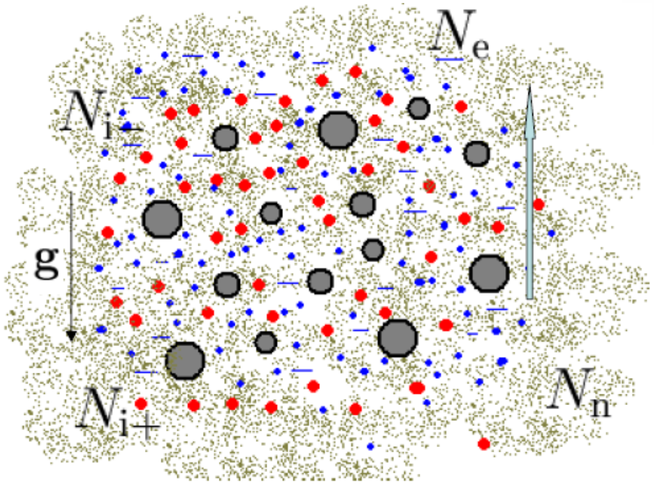
Power distribution:

$$f_R = \frac{\eta - 1}{a}\left(\frac{R}{a}\right)^{-\eta}, \quad a < R < \infty.$$



Flow integrals converge: $\eta > 3$

Charging of Aerosols
(due to collisions with ions and electrons, limited orbit model):



$$Q_d = Q_d^* \frac{R}{a}$$

$$\frac{dQ_d}{dt} = eR^2\sqrt{8\pi}[n_i V_{T_i}(1 - \frac{eQ_d}{RT_i}) - n_e V_{T_e} \exp\frac{eQ_d}{RT_e}]$$

Charging by high-energy electrons:

$n_h \ll n_e < n_i, T_h \gg T_e \quad n_h \ll n_i \quad I_h > I_e$

$$\frac{dQ_d}{dt} = eR^2\sqrt{8\pi} n_i V_{T_i}(1 - \frac{eQ_d}{RT_i}) - I_h$$

Ions and electrons: hydrodynamic, collisions with neutrals+electric field.

Relative motion of charged components (aerosols and ions) in collisional plasma can cause a dissipative instability of Dust Acoustic Wave.

Dispersion equation:

(time evolution of quasi-static electric disturbances)

For processes $\sim \exp(-i\omega t + i\mathbf{k}\mathbf{r})$, $E_0=0$

$$1 - 4\pi N_{\mathrm{d}}^{0} \int \frac{Q_{\mathrm{d}}^{2} f_R \mathrm{d}R}{M\Delta_{\mathrm{d}}} + \frac{4\pi\sigma_{\mathrm{i}}}{\Delta_{\mathrm{i}}}\left[1 + iN_{\mathrm{d}}^{0}\int \frac{G_{\mathrm{i}}^{0} f_R \mathrm{d}R}{\omega - \mathbf{k}\mathbf{V}_{\mathrm{an}} + i\nu_{\mathrm{ch}}}\right] +$$

$$+\frac{4\pi\sigma_{\mathrm{e}}}{\Delta_{\mathrm{e}}}\left[1 + i\delta N_{\mathrm{d}}^{0}\int \frac{G_{\mathrm{i}}^{0} f_R \mathrm{d}R}{\omega - \mathbf{k}\mathbf{V}_{\mathrm{an}} + i\nu_{\mathrm{ch}}}\right] + 4\pi e N_{\mathrm{d}}^{0} n_{+}^{0}\left(\frac{1}{\Delta_{\mathrm{i}}} - \frac{1}{\Delta_{\mathrm{e}}}\right)\int \frac{G_{\mathrm{i}}^{0} Q_{\mathrm{d}} f_R \mathrm{d}R}{M\Delta_{\mathrm{d}}} = 0$$

here

$$\Delta_{\mathrm{d}} = (\omega - \mathbf{k}\mathbf{V}_{\mathrm{an}})(\omega - \mathbf{k}\mathbf{V}_{\mathrm{an}} + i\nu)$$

$$\Delta_{\mathrm{i}} = \omega + iD_{\mathrm{i}}k^2 + i\nu_R,\ \Delta_{\mathrm{e}} = \omega + iD_{\mathrm{e}}k^2 + i\delta\nu_R \qquad \delta = n_{+}^{0}/n_{-}^{0}$$

$\nu = g/V_{\mathrm{an}}$ - effective collision frequency

$D_{\mathrm{i}}, D_{\mathrm{e}}$ - diffusion coefficients

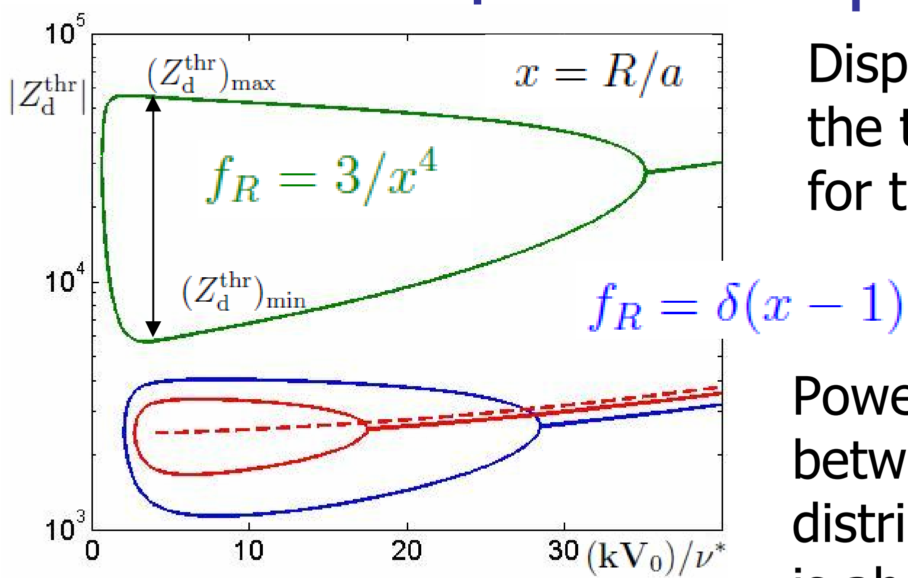
$\sigma_{\mathrm{i}}, \sigma_{\mathrm{e}}$ - conductivities

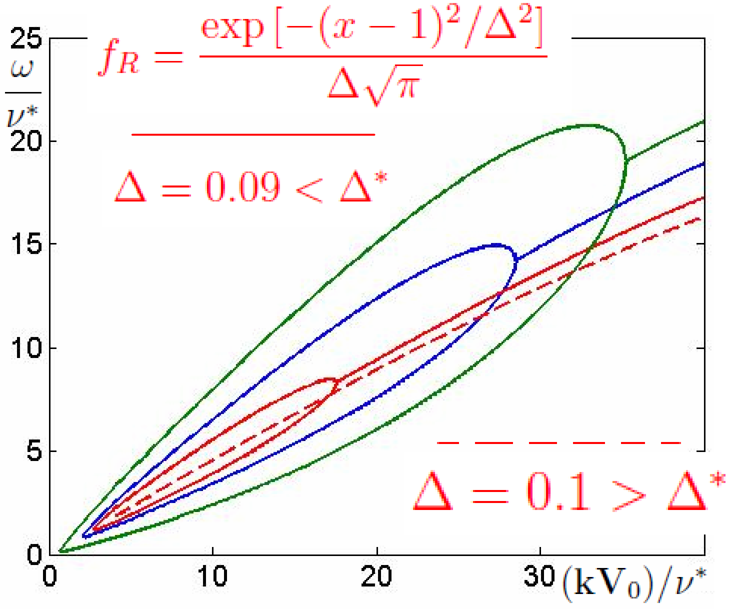
$\nu_{\mathrm{ch}} = \frac{\mathrm{d}}{\mathrm{d}Q_{\mathrm{d}}}(G_{\mathrm{e}}n_{\mathrm{e}} - G_{\mathrm{i}}n_{\mathrm{i}})|_{Q_{\mathrm{d}}=Q_D^0}$ - reverse charging time;

$G_{\mathrm{i}}n_{\mathrm{i}},\quad G_{\mathrm{e}}n_{\mathrm{e}}$ - ion/electron flows

ν_{R} - ion/electron collisions with dust

Instability Threshold (solution of the dispersion equation if Imω=0):





Dispersion equation has two solutions on the threshold, so the sufficient condition for the instability is:

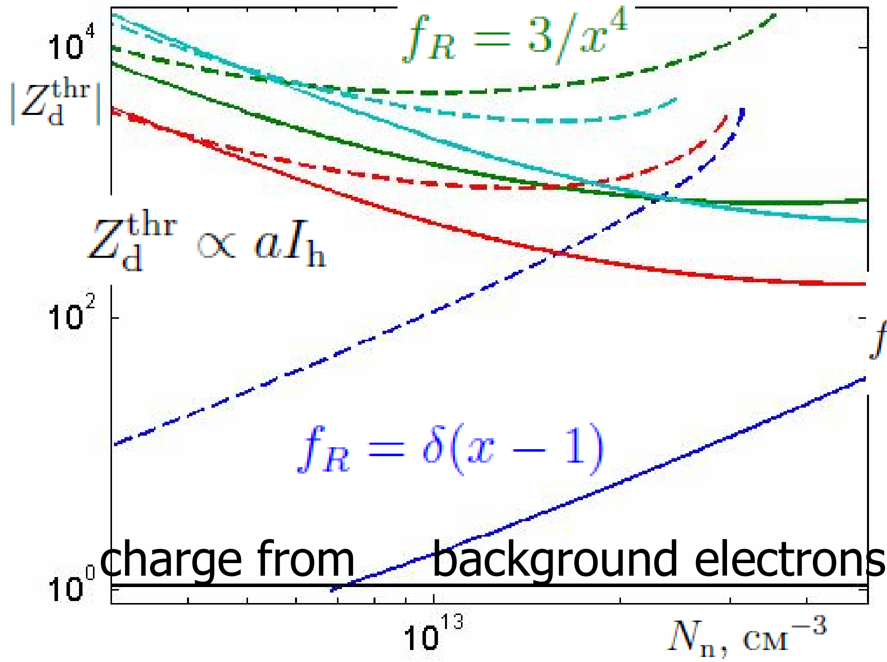
$$(Z_d^{thr})_{min} < Z_d < (Z_d^{thr})_{max}$$

Power distribution increases interval between $(Z_d^{thr})_{min}$ и $(Z_d^{thr})_{max}$; Gaussian distribution decreases it. If $\Delta \geq \Delta^*$, instability is absent.

$$Z_d e = Q_d{}^*$$

Threshold value minimum over wavenumbers defines optimal scales.

Earth's mesosphere (heights 80-90 km):



Neutrals: N_2, T~120 K;
Ions: heavy clusters $H(H_20)_n$
Aerosols: ice, a=100 nm
g=9.8 m/c^2

$\Delta = 0.09$

$$f_R = \frac{\exp\left[-(x-1)^2/\Delta^2\right]}{\Delta\sqrt{\pi}}$$

$\Delta = 0.2$

------ $\rho_{\rm a} = 1\ {\rm g/cm^3},\ \delta = n_{\rm i}/n_{\rm e} = 10,\ \nu_{\rm i}/N_{\rm n} = 9\cdot 10^{-10}\ {\rm cm^3/c}$

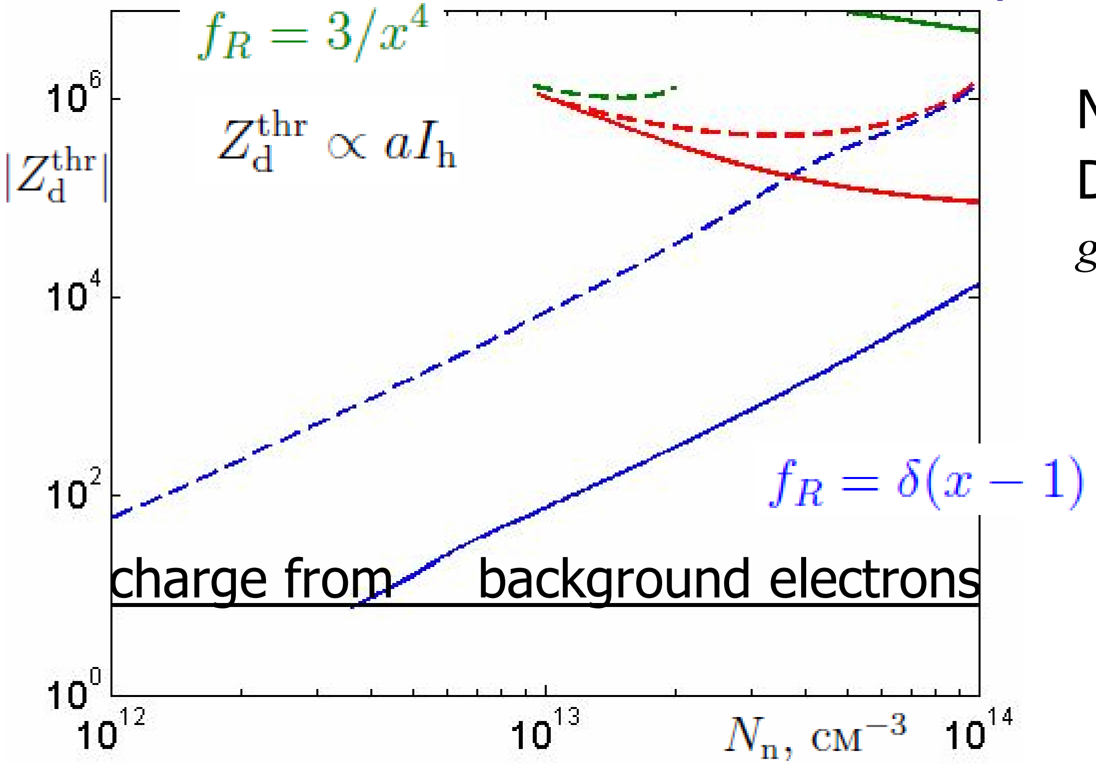
—— $\rho_{\rm a} = 2\ {\rm g/cm^3},\ \delta = n_{\rm i}/n_{\rm e} = 50,\ \nu_{\rm i}/N_{\rm n} = 27\cdot 10^{-10}\ {\rm cm^3/c}$

$\lambda_{\rm opt} = 20 \div 45$ cm $\lambda_{\rm opt} = 60 \div 100$ cm $\lambda_{\rm opt} = 50 \div 150$ cm $\lambda_{\rm opt} = 80 \div 200$ cm

Size dispersion **increases** the instability threshold and optimal scales significantly and also changes threshold's dependence on some of the parameters. The influence of size dispersion is stronger under **bigger values of aerosol velocity** (lower values of density N_n) → it changes threshold's dependence on the parameters, defining aerosol velocity.

For monodispersed ensemble, threshold decreases with increasing of the aerosol velocity (decreasing of N_n, increasing of ρ_a); with the account of the dispersion, **threshold charge has a minimum over velocity**. The threshold increases with the ion diffusion coefficient.

Mars's atmosphere (heights 70-100 km):



Neutrals: CO_2, T~130 K,
Dust particles: a=1μk,
g=3.71 m/s^2

$$f_R = \frac{\exp\left[-(x-1)^2/\Delta^2\right]}{\Delta\sqrt{\pi}}$$

$$x = R/a \qquad \Delta = 0.05$$

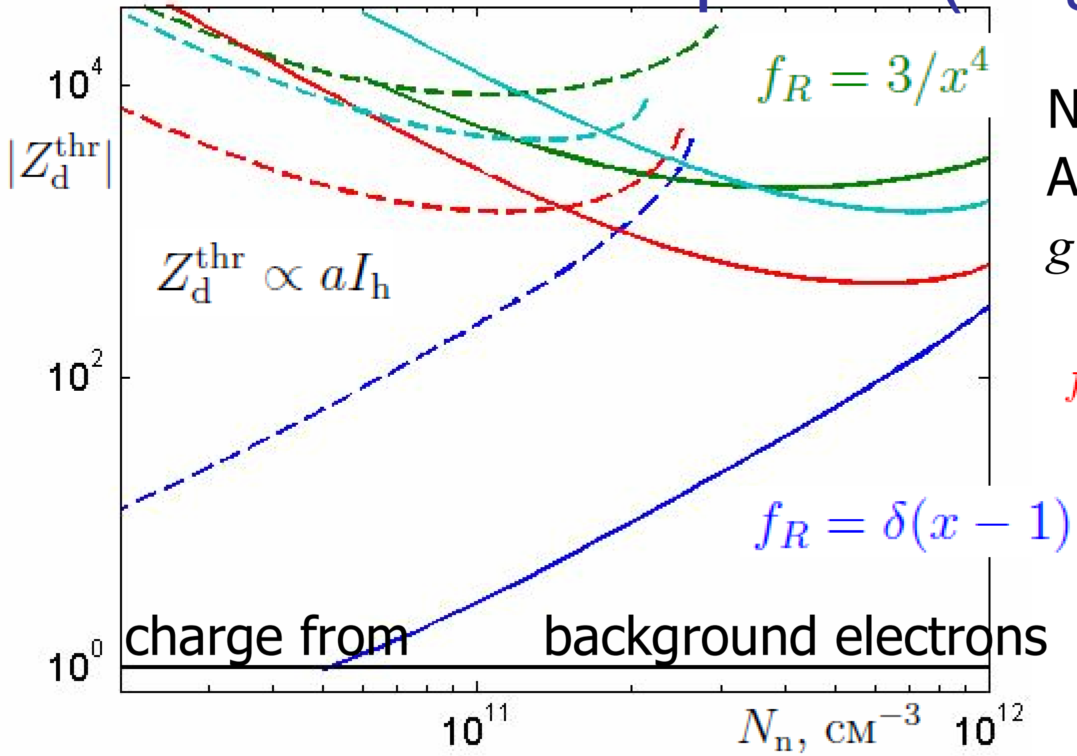
- - - - - - $\rho_a = 1 \text{ g/cm}^3,\ \delta = n_i/n_e = 10,\ \nu_i/N_n = 9\cdot 10^{-10}\ \text{cm}^3/\text{c}$

——— $\rho_a = 2 \text{ g/cm}^3,\ \delta = n_i/n_e = 50,\ \nu_i/N_n = 27\cdot 10^{-10}\ \text{cm}^3/\text{c}$

Optimal scales:

$\lambda_{opt} = 30 \div 150$ cm $\lambda_{opt} = 10^3 \div 10^4$ cm $\lambda_{opt} = 50 \div 1000$ cm

Titan's ionosphere (heights 900-1200 km):



Neutrals: N_2, T~170 K;

Aerosols: ice HC_nN, a=50 nm

g=1.35 m/c^2

$$f_R = \frac{\exp\left[-(x-1)^2/\Delta^2\right]}{\Delta\sqrt{\pi}} \quad \Delta = 0.09$$

$$\Delta = 0.2$$

$$x = R/a$$

$\rho_a = 0.7$ г/см^3, $\nu_i/N_n = 7 \cdot 10^{-10}$ см^3/с

———

$\rho_a = 1.5$ г/см^3, $\nu_i/N_n = 21 \cdot 10^{-10}$ см^3/с

Optimal scales:

$\lambda_{opt} = 400 \div 2200$ cm $\quad \lambda_{opt} = (0.3 \div 3) \cdot 10^4$ cm

$\lambda_{opt} = (0.3 \div 10) \cdot 10^4$ cm $\quad \lambda_{opt} = (0.5 \div 10) \cdot 10^4$ cm

Summary:

1. Size dispersion increases the instability threshold and optimal scales significantly.
2. If size dispersion has Gaussian distribution, there is no instability under big dispersions.
3. Size dispersion changes threshold's dependence on some of the parameters (threshold charge has a minimum over parameters, defining respective velocity).
4. Strict requirements for the instability to develop: small size's dispersion and a flux of high-energy electrons.

Quantitative estimates:

	Earth	Mars	Titan
Dispersion	$(\lvert Z_{\mathrm{d}}^{\mathrm{thr}}\rvert)_{\mathrm{min}} \approx 100 \div 450$	$(\lvert Z_{\mathrm{d}}^{\mathrm{thr}}\rvert)_{\mathrm{min}} \approx (7 \div 30) \cdot 10^4$	$(\lvert Z_{\mathrm{d}}^{\mathrm{thr}}\rvert)_{\mathrm{min}} \approx (450 \div 1300)$
Monodispersed ensemble	$(\lvert Z_{\mathrm{d}}^{\mathrm{thr}}\rvert)_{\mathrm{min}} \approx 5$	$(\lvert Z_{\mathrm{d}}^{\mathrm{thr}}\rvert)_{\mathrm{min}} \approx 8$	$(\lvert Z_{\mathrm{d}}^{\mathrm{thr}}\rvert)_{\mathrm{min}} \approx 1$