Dust particle dynamics in convective vortices near the surface of the Earth: comparison with Mars

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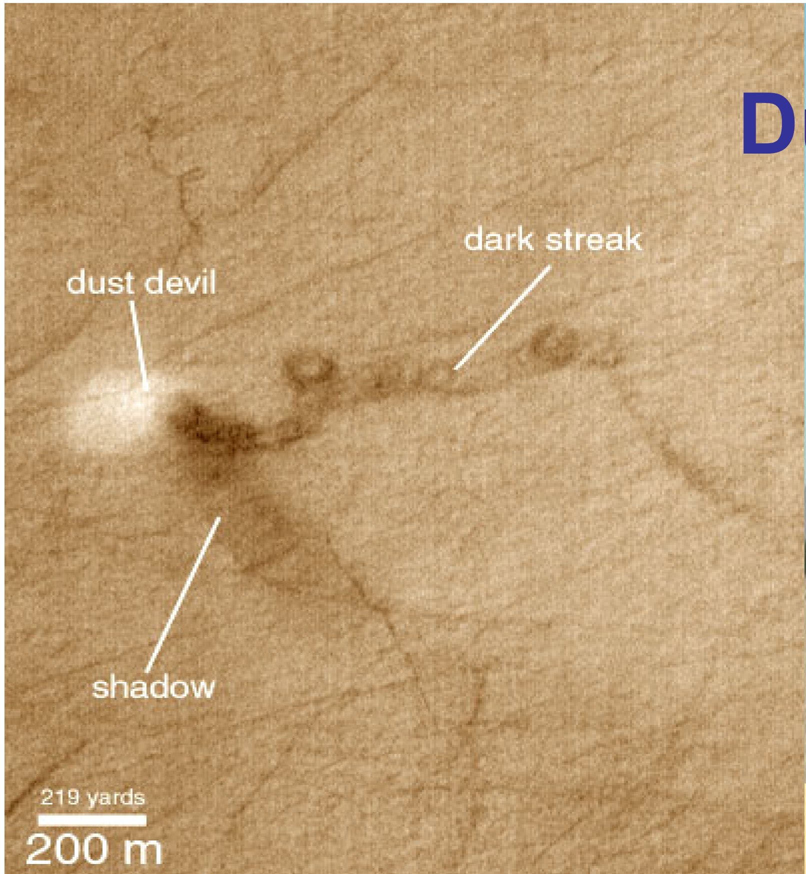
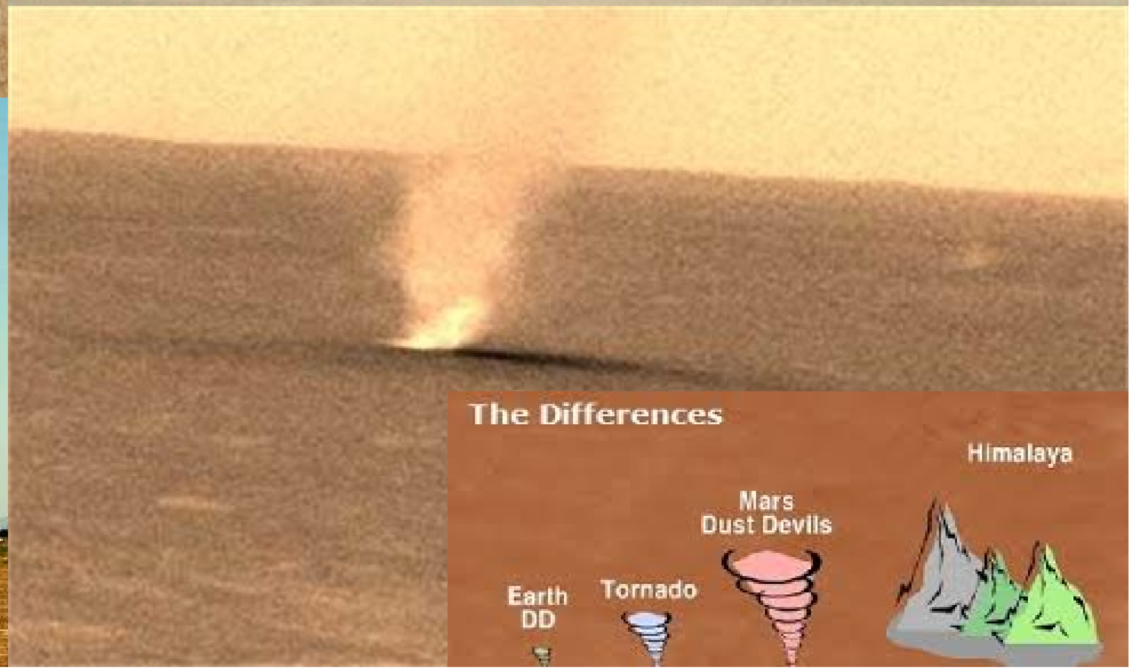
Dust devils


dark streak
dust devil
shadow
219 yards
200 m


The Differences
Himalaya
Mars
Dust Devils
Earth
DD
Tornado

Data available on dust devils

Earth	Mars
-	Orbital observations
Sizes, velocities	Sizes, velocities
Vertical velocities, structure	-
T, P	T, P (Viking, Pathfinder, InSight)
Electric fields	-

Observations and measurements

TABLE 8. Summary of Observation of Martian Dust Devils[a]

Study Reference	Data Source	N	H, km	D, m
	Direct Imaging Methods[b]			
Thomas and Gierasch [1985]	Viking (orbiter)	~100	1 to 2.5	70 to 1000
Wennmacher et al. [1996]	Viking (orbiter)	~30	mean ~1.3	~100
Edgett and Malin [2000]	MOC WA (orbiter)	NA	≤6	NA
Metzger et al. [1999]	MPF IMP (lander)	5	0.05 to 0.25	15 to 80
Biener et al. [2002]	MOC WA (orbiter)	NA	0.4 to 2.6	<1750
Ferri et al. [2003]	MPF IMP (lander)	14	NA	15 to 550
Fisher et al. [2005]	MOC NA (orbiter)	≥20	0.17 to 1.8	28 to 509
Fisher et al. [2005]	MOC WA (orbiter)	≥14	3.8 to 8.5	NA
	Indirect Methods[c]			
Ferri et al. [2003]	MPF ASI/MET	19	NA	mean ~200[d]
Ryan and Lucich [1983]	Viking 1 Lander Met	40	NA	10 to 700
Ryan and Lucich [1983]	Viking 2 Lander Met	78	NA	10 to 950
Ringrose et al. [2003]	Viking 2 Lander Met	8	NA	20 to 450[e]

TABLE 4. In Situ Wind Speed Measurements in Dust Devils[a]

Study Reference	N	V_{mean}, m s^{-1}	V_{max}, m s^{-1}	$V_{h\ mean}$, m s^{-1}	$V_{h\ max}$, m s^{-1}	W_{mean}, m s^{-1}	W_{max}, m s^{-1}
Sinclair [1964]	4	-	-	9.3	13	-	-
Ryan and Carroll [1970]	80	4.2	9.5	-	-	0.7	2
Fitzjarrald [1973]	11	7.3	11.5	-	-	1.3	4.25
Sinclair [1973]	3	10.8	11.5	-	-	13.3	15
Metzger [1999]	5	13.6	22	-	-	5.2	7
Balme et al. [2003a]	10	-	-	17.0	25	-	-
Tratt et al. [2003]	3			8.8	11.0	3.3	3.5

[a]Each measurement represents the largest value measured from that component within each dust devil. All measurements are taken at ~2 m height above surface except those of *Tratt et al.* [2003], which are made at ~3.5 m. N is the number of dust devils sampled, V is the peak tangential component of the wind speed, V_h is the peak total horizontal wind speed, and W is the peak vertical wind speed. Subscript "mean" represents the average value for the whole study; subscript "max" represents the greatest measurement in the study.

M. Balme, R. Greeley. Rev. Geophys., 2006

Basic equations

perturbations

Initial conditions

$$T = T_0 + T'$$

$$\rho = \rho_0 + \rho'$$

$$p = p_0 + p'$$

$$p_0 = -\rho_0 g z$$

$$\rho' = \left(\frac{\partial \rho}{\partial T}\right)_p T' = -\rho_0 \beta T'$$

Continuity equation $$div\,\mathbf{v} = 0$$

Motion equation $$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\nabla)\mathbf{v} = -\frac{\nabla p'}{\rho_0} - \mathbf{g}\beta T' + \nu\,\Delta\mathbf{v}$$

Heat equation $$\frac{\partial T'}{\partial t} + (\mathbf{v}\nabla)T' = \chi \Delta T' + \frac{2\nu}{c_p} D_{ij} D_{ij}$$

strain rate tensor → $$D_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$$

χ thermal diffusivity

c_p heat capacity

ν viscosity

Similarity theory

$$a = f\left(a_1, a_2, \dots a_n\right)$$

k
independent dimentions

Buckingham π theorem

$$\Pi_a = f\left(\Pi_1, \Pi_2, \dots \Pi_{n-k}\right)$$

dimensionless parameters

Convection

inertial forces >> viscosity forces

$$\mathbf{v} = \frac{\chi}{l} f\left(\frac{\mathbf{x}}{l}, \mathrm{Gr} \cdot \mathrm{Pr}^2 \right)$$

dimensionless parameters

$$\mathrm{Gr} = \frac{g l^3 \beta \Delta T}{\nu^2} \qquad \mathrm{Pr} = \frac{\nu}{\chi}$$

Earth and Mars

Similarity

$$\frac{\left(\mathrm{Gr}\cdot\mathrm{Pr}^2\right)_E}{\left(\mathrm{Gr}\cdot\mathrm{Pr}^2\right)_M}=1 \qquad \frac{\mathbf{v}_E l_E}{\chi_E}=\frac{\mathbf{v}_M l_M}{\chi_M}$$

$$\frac{g_E}{g_M}=2.65,$$

$$\frac{\beta_E}{\beta_M}\approx 1,$$

$$\frac{T_M^3}{T_E^3}\approx\left(\frac{200}{300}\right)^3\approx 0.3,$$

$$\frac{P_E^2}{P_M^2}\approx 10000,$$

$$\frac{m_E}{m_M}=\frac{29}{44}\approx 0.66$$

$l_M \approx 17 l_E$ scales

$v_M \approx 2.6 v_E$ velocities

Equations for modeling

$$\frac{\partial}{\partial t}\left(\tilde{\Delta}\psi + \frac{d\ln\rho_0}{dz}\frac{d\psi}{dz}\right) + \frac{1}{r}J\left\{\psi,\tilde{\Delta}\psi\right\} = -r\frac{d\chi}{dr} + \frac{r}{\rho_0^2}J\left\{\tilde{\rho},\tilde{p}\right\} \qquad (1)$$

$$r\frac{\partial\chi}{\partial t} - \omega_g^2\frac{\partial\psi}{\partial r} + J\left\{\psi,\chi\right\} = 0 \qquad (2)$$

$$\tilde{\Delta} = r\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}$$

$$\frac{\partial\omega_z}{\partial t} + u_r\frac{\partial\omega_z}{\partial r} = \omega_z\frac{\partial u_z}{\partial z} \qquad (3)$$

ψ stream function for poloidal motion

ω_g Brunt-Vaiisala frequency

$$J\left\{A,B\right\} = \frac{\partial A}{\partial x}\frac{\partial B}{\partial y} - \frac{\partial A}{\partial y}\frac{\partial B}{\partial x}$$

$$u_r = -\frac{1}{r}\frac{\partial\psi}{\partial z} \qquad u_z = \frac{1}{r}\frac{\partial\psi}{\partial r}$$

$\rho = \rho_0 + \tilde{\rho}$ density $\quad |\tilde{\rho}| << \rho_0$

$p = p_0 + \tilde{p}$ pressure $\quad |\tilde{p}| << p_0$

ω_z Toroidal vorticity

$$\chi = g\,\tilde{\rho}/\rho_0$$

[O.G. Onishchenko, W. Horton, O.A. Pokhotelov, L. Stenflo, Phys. Scripta, 89 (7), 075606, 2014.]

Stream-lines

Partial solution (1), (2) и (3)

$$u_z = Az\left(1-\frac{r^2}{r_0^2}\right)\exp\left(-\frac{r^2}{r_0^2}\right)$$

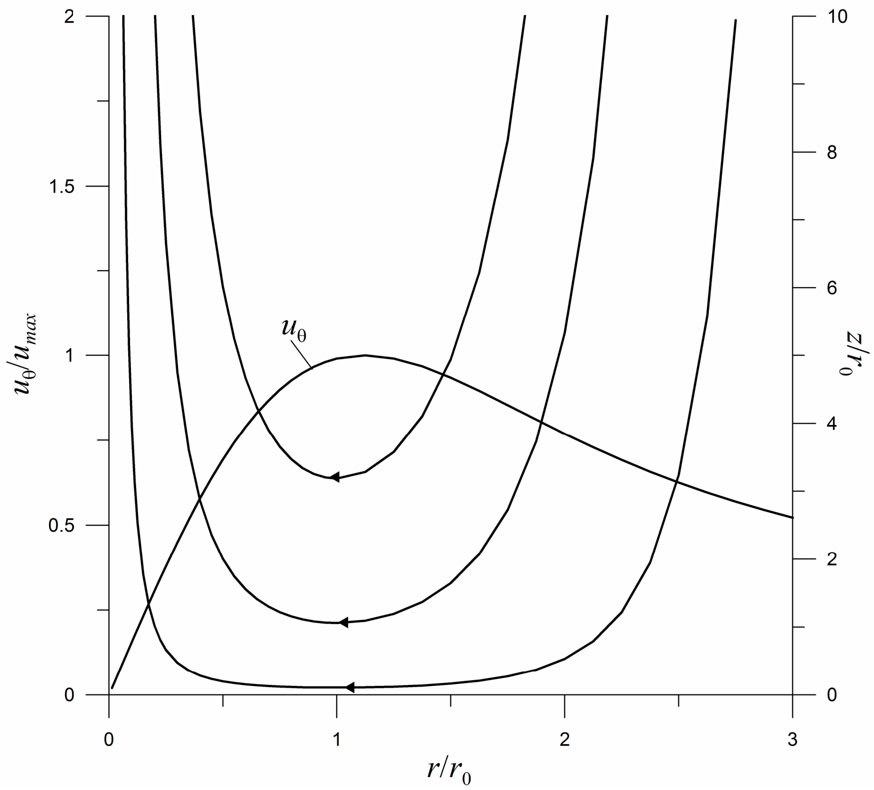
$$u_r = -\frac{Ar}{2}\exp\left(-\frac{r^2}{r_0^2}\right)$$

Toroidal vorticity

$$u_\theta = \frac{B}{r}\left(1-\exp\left(-\frac{r^2}{r_0^2}\right)\right)$$

$$\mathbf{u} = (u_r, u_\theta, u_z)$$

$$\omega_z = \frac{du_\theta}{dr} + \frac{u_\theta}{r}$$



Poloidal stream-lines and toroidal velocity depending on the distance from the center of the vortex

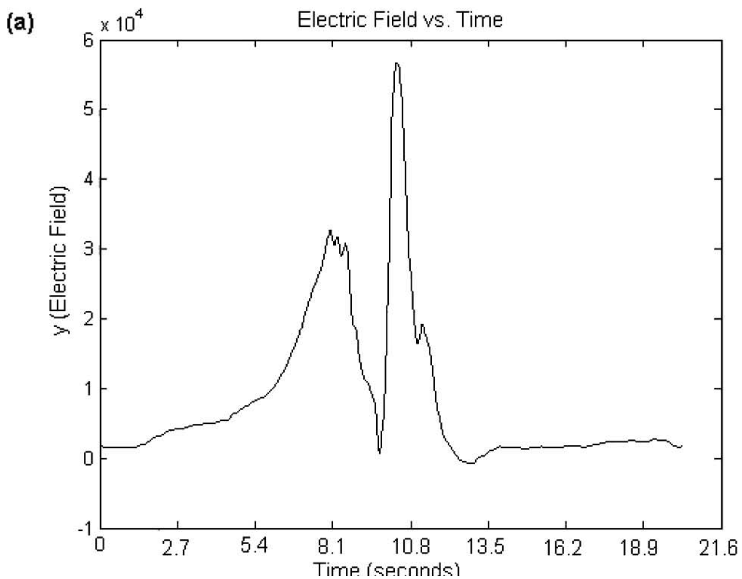
Measurements in dust devils on the Earth

- Electric fields 40 V/m – 100 kV/m (1-3)
- Electric moment 0,01 - 55 C m (1)
- Charge density ~10^6 e/cm^3 (1-2)
- Magnetic fields

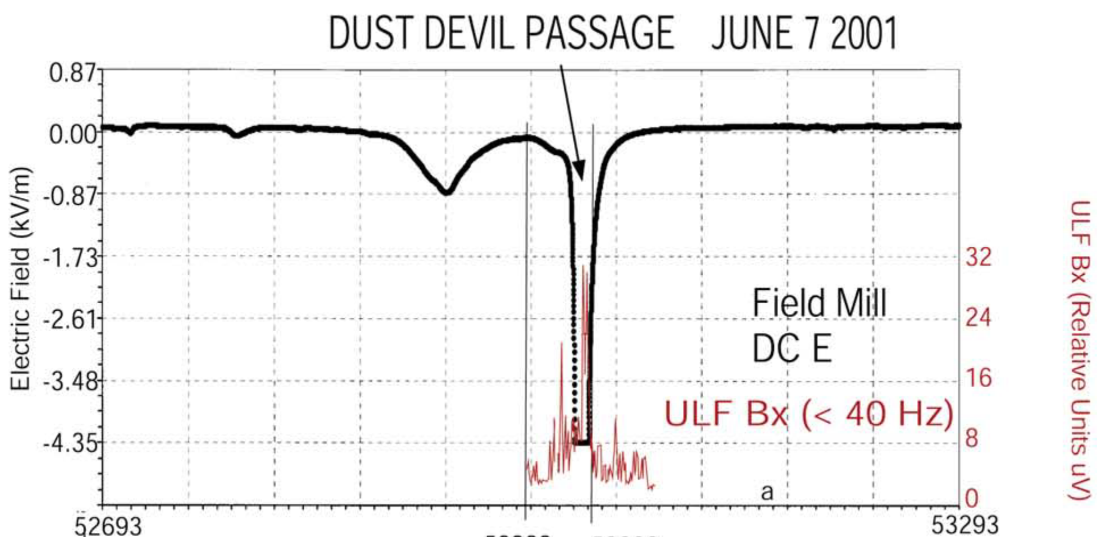
(1) Crozier, W. D. (1970), Dust devil properties, J. Geophys. Res., 75(24), 4583–4585.

(2) Farrell, W. M., et al. (2004), Electric and magnetic signatures of dust devils from the 2000–2001 MATADOR desert tests, J. Geophys. Res., 109, E03004.

(3) Jackson, T.L., Farrell, W.M., 2006. Electrostatic fields in dust devils: An analog to Mars. IEEE Trans. Geosci. Remote Sens. 44, 2942–2949.



(3)



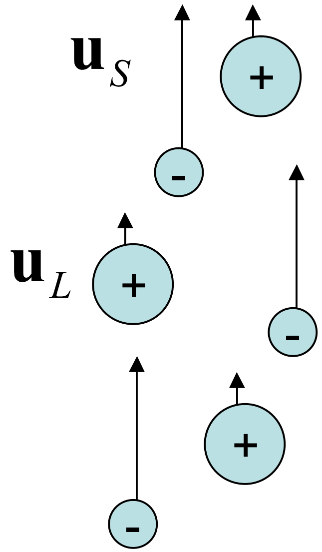
(2)

Charging of particles

$$\frac{dQ_L}{dt} + \frac{\sigma}{\varepsilon_0} Q_L = \nu \Delta q$$

Equlibrium charge

$$Q_L \to Q_{L\max}$$



$$\sigma = 2.8 \cdot 10^{-12}\ S/m$$ Electric conductivity of the atmosphere

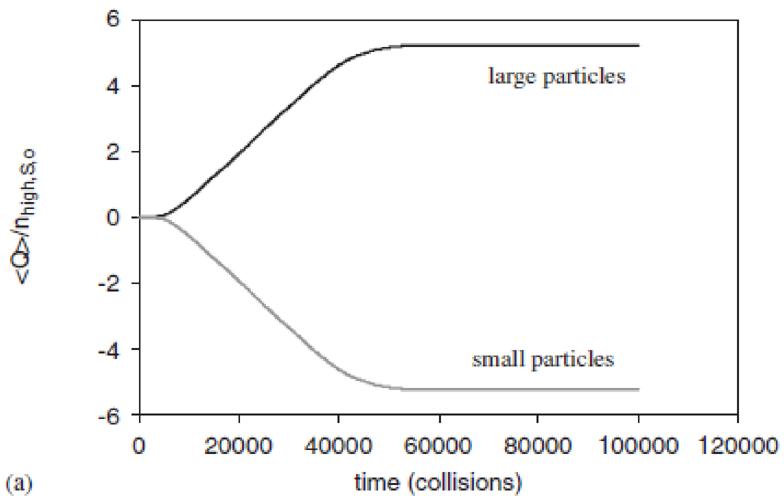
$$\nu = \pi r_L^2 n_S \Delta u$$ Collision frequency

Y.Zhai et. all, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, E01006, 2006

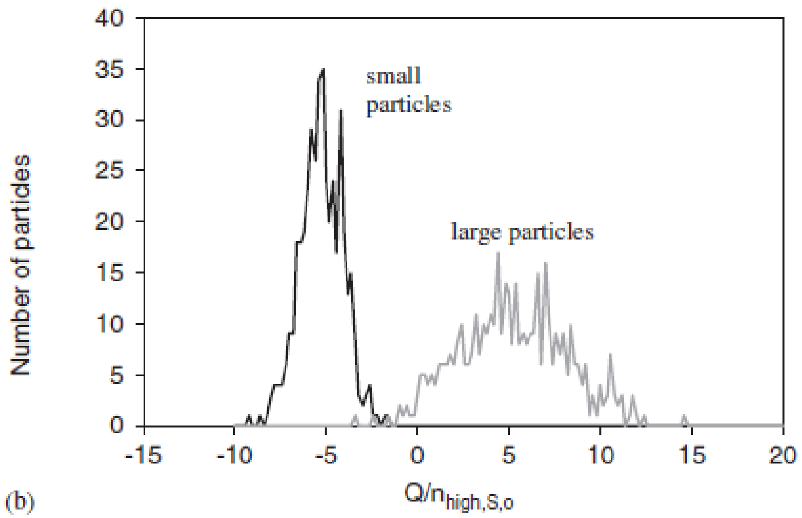
$$\Delta q = \alpha r_S \qquad \alpha = 10^{-15}\ C/\mu m$$

$$\frac{\partial \rho_q}{\partial t} = \frac{2 n_L \Delta Q_L \Delta u}{h}$$

$$n_L Q_L = -n_S Q_S$$



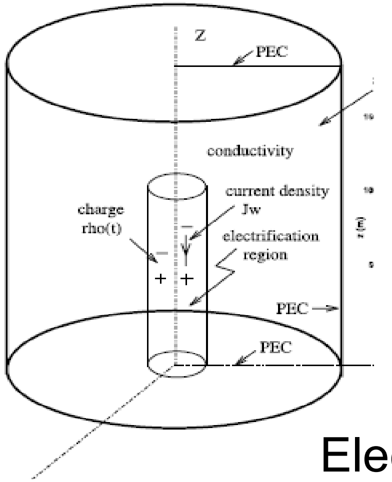
(a)



(b)

D. J. Lacks and A. Levandowsky, J. Electrostatics 65, 107 (2007).

Electric fields in dust devils

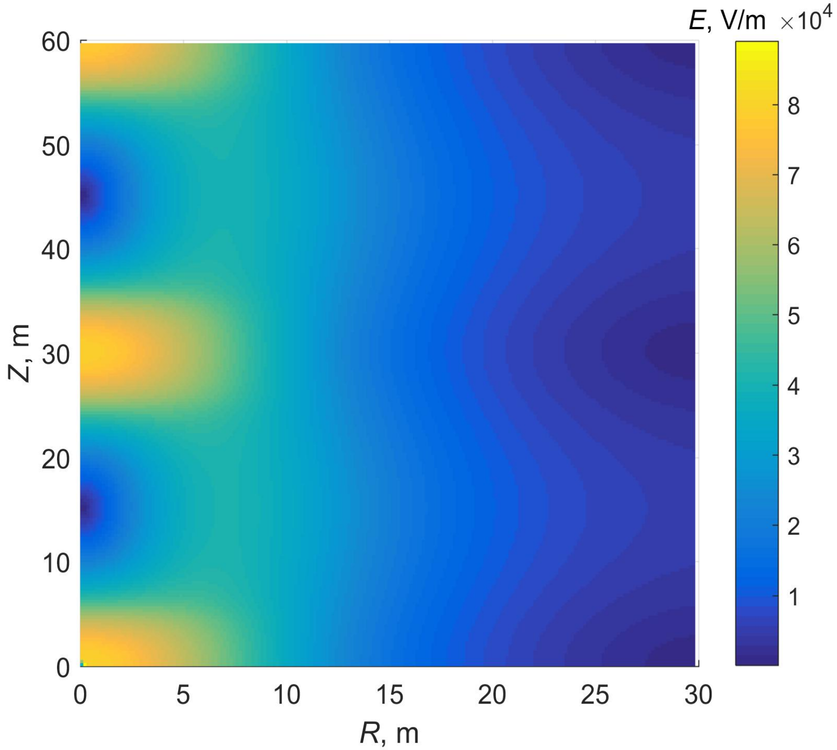


$$\Delta \varphi = -\frac{\rho_q}{\varepsilon_0}$$

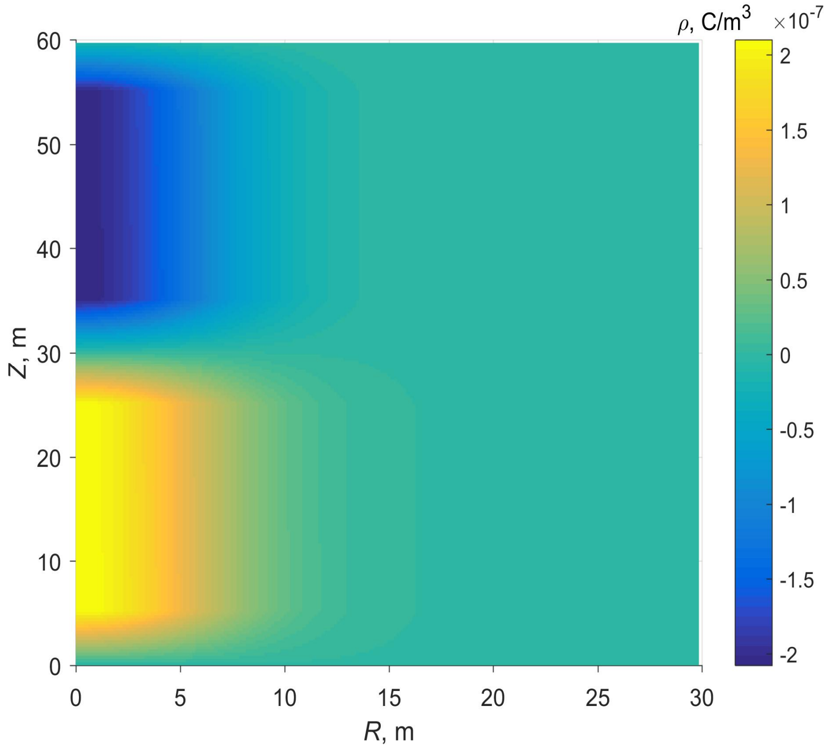
$$\frac{\partial \rho_q}{\partial t} + (\nabla \sigma) \cdot \mathbf{E} + \frac{\sigma \rho_q}{\varepsilon_0} = 0$$

Earth

Electric field, V/m



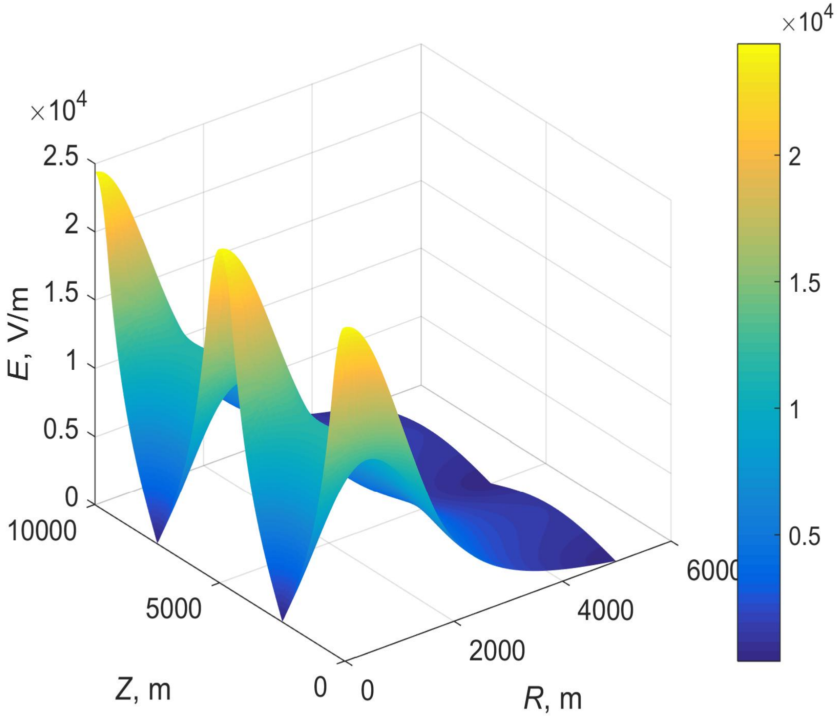
Charge density, C/m³



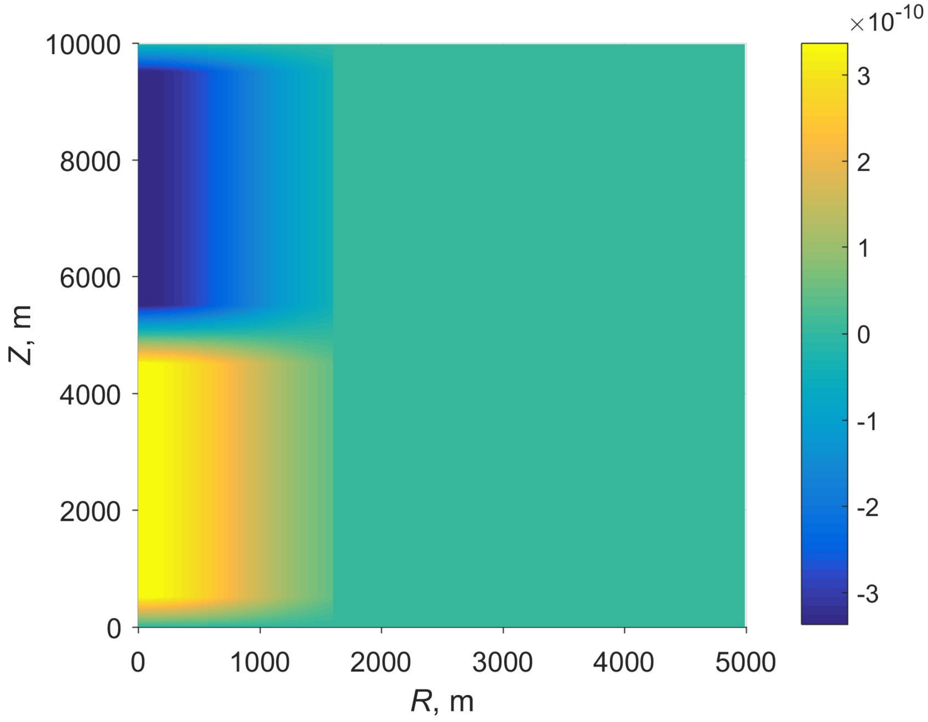
Electric fields in dust devils

Mars

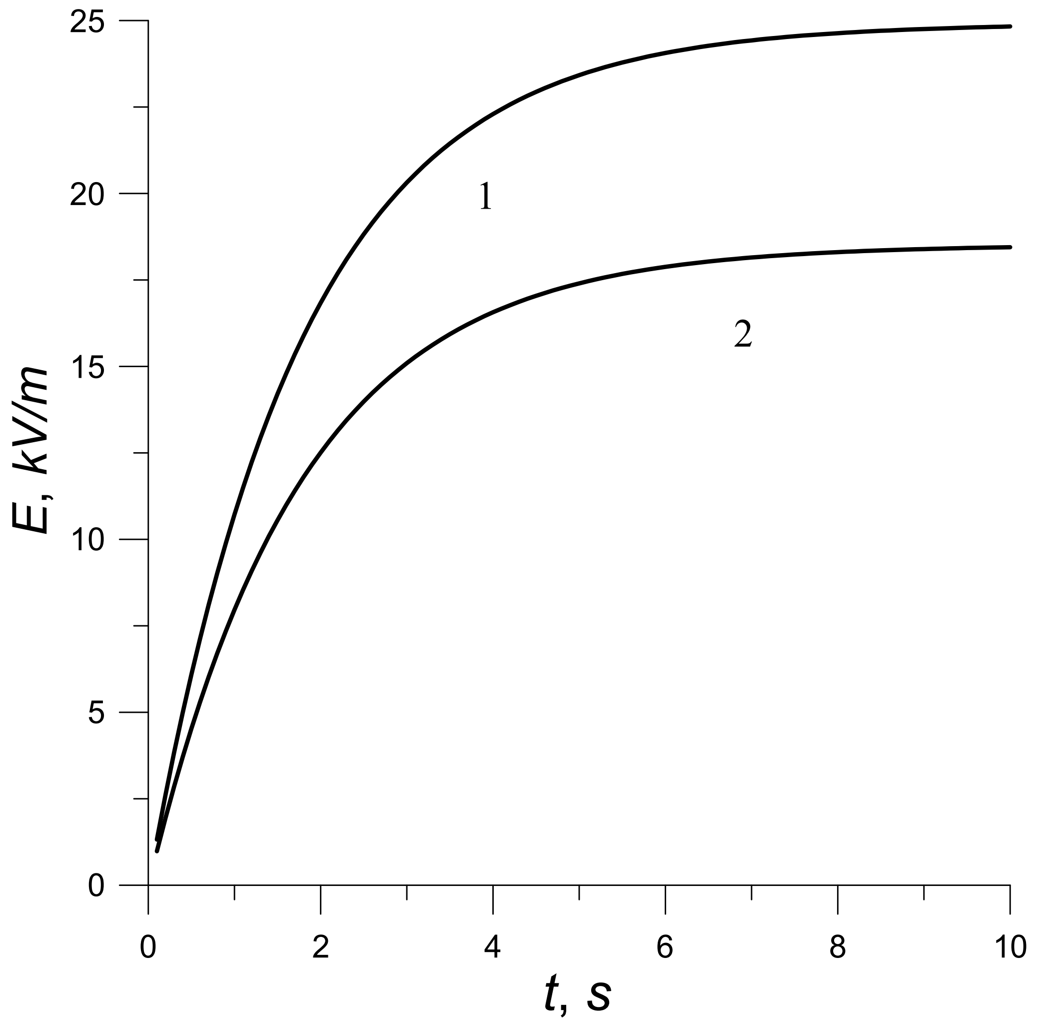
Electric field, V/m



Charge density, C/m³



Evolution of the maximum value of the electric field in the process of charge separation



(1) -

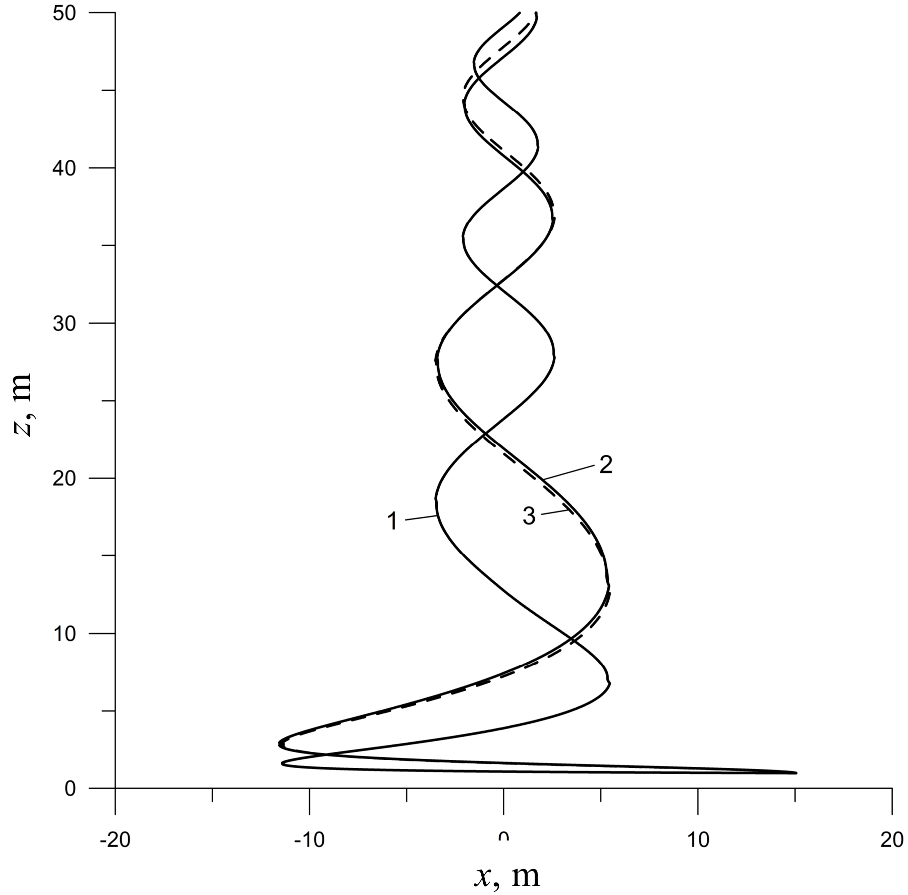
$$\partial\overline{\rho}_q / \partial t = 7.4 \cdot 10^{-11}\, C / \left(m^3 \cdot s\right)$$

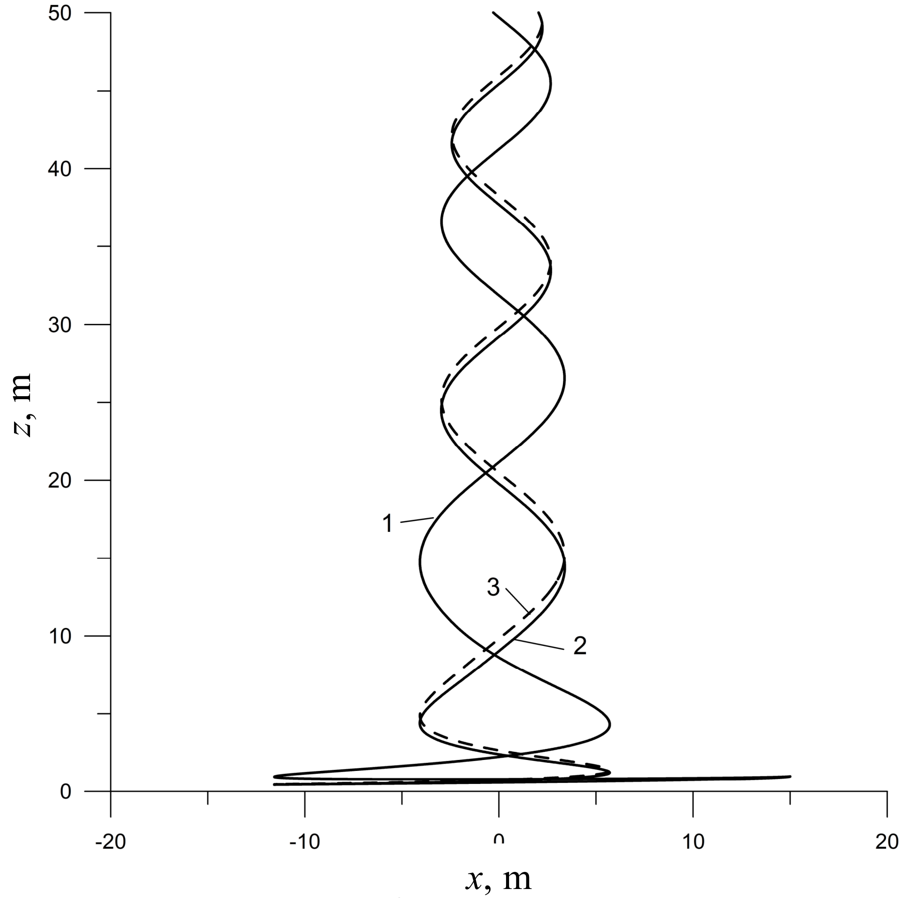
(2) –

$$\partial\overline{\rho}_q / \partial t = 5.5 \cdot 10^{-11}\, C / \left(m^3 \cdot s\right)$$

Mars

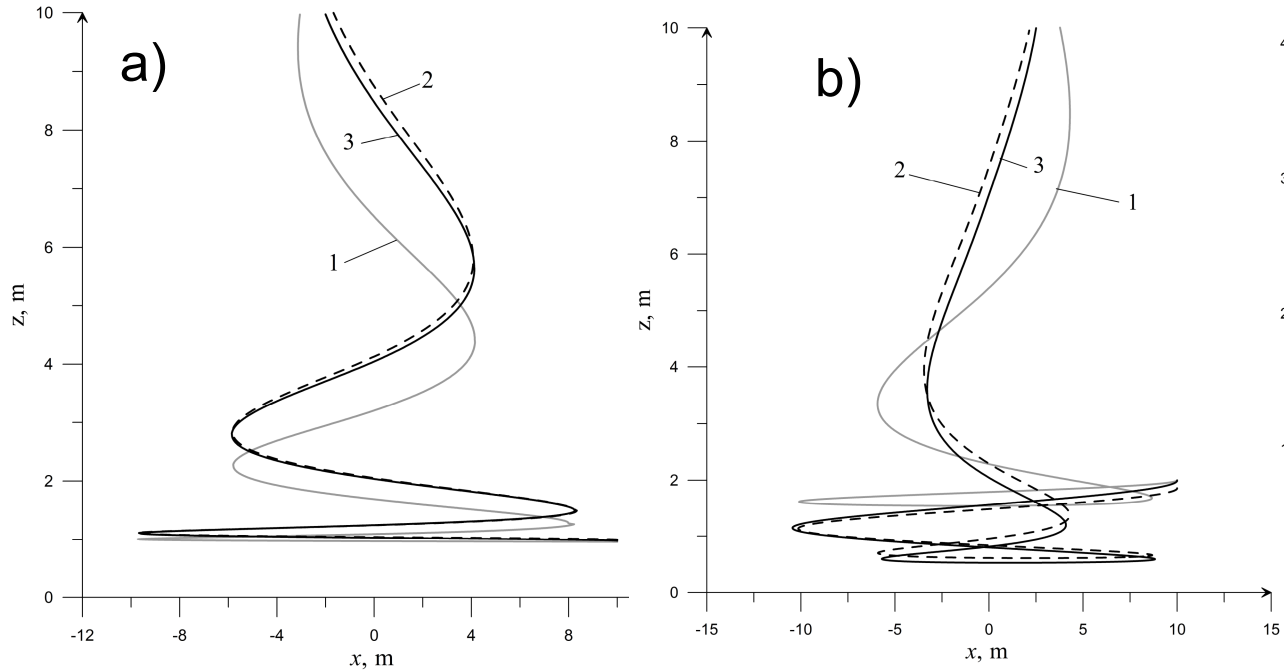
Dust particles trajectories in the 100 m Martian dust devil





Trajectories of (a) a grain with a diameter of 2 μm and charge $-8 \cdot 10^{-17}$ C and (b) a grain with a diameter of 10 μm and charge of $1.6 \cdot 10^{-16}$ C in a dust devil with a core radius of 100 m and height of 2 km for three cases: (*1*) without an electric field, (*2*) with the electric field, and (*3*) with the electric field of a point dipole.

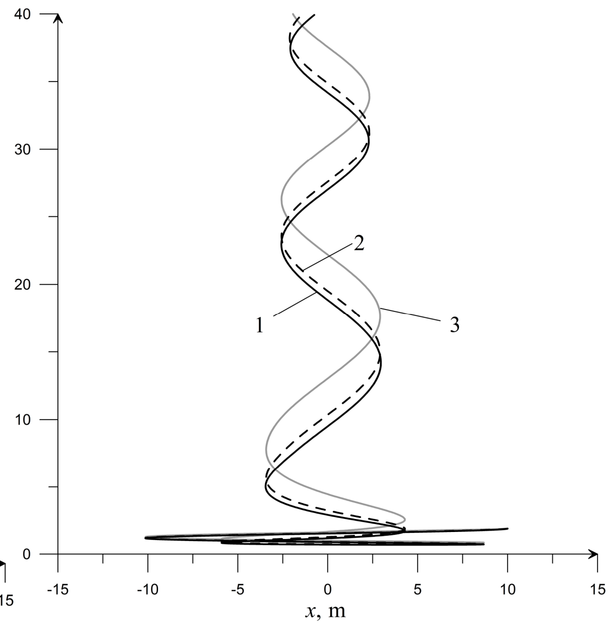
Dust particles trajectories in the 20 m dust devil



1- without electric field, 2 – with electric field,
3 – dipole field.

a) vertical projection of the trajectory of a negatively charged particle (Q = -16·10^{-17} C) with a size of 4 μm .

b) vertical projection of the trajectory of a charged particle of the size of 40 μm with a charge of Q = 8 · 10^{-15} C.



Vertical projection of the 40 μm particle trajectory (curve 1), modeled situation when electric field is swiched off at the altitude of 1.88 m (curve 2) and 1.78 m (curve 3).

Similarity for dust particles

particle motion equation

$$\frac{d\mathbf{V}_p}{dt} = \mathbf{g} + \frac{18\eta}{C_c \rho_p a^2}\mathbf{V}_{pr}$$

dimensionless variables

$$\frac{d\tilde{\mathbf{V}}_p}{dt} = \tilde{\mathbf{g}} + \frac{18\eta}{C_c \rho_p a^2}\frac{r_0}{V_0}\tilde{\mathbf{V}}_{pr}$$

similarity

Earth → $$\frac{\eta_E}{C_{cE}\rho_{pE}a_E^{\ 2}}\frac{r_{0E}}{V_{0E}} = \frac{\eta_M}{C_{cM}\rho_{pM}a_M^{\ 2}}\frac{r_{0M}}{V_{0M}}$$ ← Mars

$$a_M \approx a_E$$

C_c = 1+Kn (1.257 +0.4 exp(-1.1 /Kn))

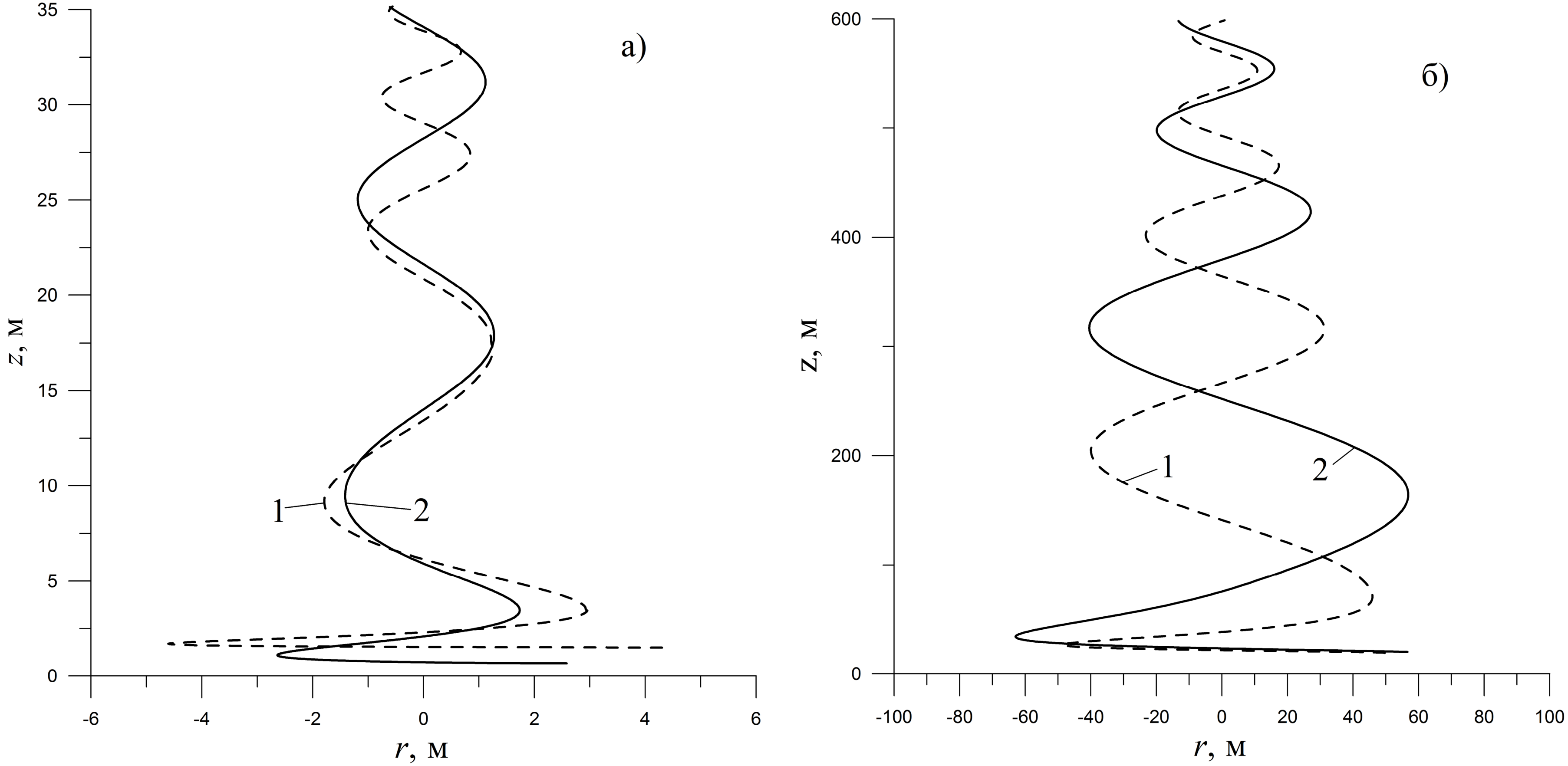
Dust particles trajectories

$$\frac{d\mathbf{V}_p}{dt} = \mathbf{g} + \frac{18\eta}{C_c \rho_p a^2}\mathbf{V}_{pr}$$

Earth

1 – 1μm, 2 – 10 μm

Mars



Conclusions

A similarity of the Earth's and Martian dust devils has been shown. The parametres of Martian vortex are obtained. It appeared that the trajectories of the dust particles of the same size in the vortices are similar for the Earth and Mars.

A model describing the dynamics of dust particles in dust devils is constructed. Calculations based on the model have shown that dust vortices are an important mechanism of dust uplift in the atmosphere of Mars.

The influence of an electric field on the dynamics of dust particles in a vortex is investigated. Near the surface (at altitudes less than a quarter of the vortex), the electric field affects the trajectory of the particle motion. Starting at a certain height in the vortex, the effect of the electric field on the trajectory is negligible.

When modeling the motion of particles far from the center of the vortex, the electric field can be approximated by the dipole field located at half the height of the vortex.

Thank you!