Electric field influence on dust particle dynamics in dust vortices

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Abstract. We study dust vortices called dust devils and dynamics of dust in this structures. Dust devils are well formed relatively short-lived vortices that can appear over well heated surfaces like deserts and are clearly visible due to large amount of dust raised. Dust particles rotating in a flow bump and scrape each other and as a result particles obtain electric charges. Space separation of particles with opposite charges leads to generation of macroscopic electric field. We simulate dust dynamics with taking into account the electric field of the vortex.

1. Introduction
Dusty plasma can exist in various parts of the Solar System. For instance, charged dust grains are present in planetary magnetospheres and ionospheres, comet atmospheres, and the interstellar medium. During last tens of years we have been receiving a large amount of data from Mars. Martian atmosphere is 100 times less dense than the atmosphere of the Earth, the surface of the planet is arid, so dust plays a sufficient role there. Dust particles and particles of condensed water and carbon dioxide are present in a wide range of altitudes in the Martian atmosphere [1]. Mars has ionosphere and the Martian atmosphere is highly conductive even near the surface (the conductivity of the Martian atmosphere two orders of magnitude exceeds the conductivity of the atmosphere of the Earth). Taking into account the presence of electrons and ions at different altitudes and the photoelectric effect in the day time, we can conclude that dusty plasma systems appear in the Martian atmosphere.

The common charged dust phenomenon for the Earth and Mars is a possibility of formation of dust vortices—the so-called dust devils, which are a widespread event in the atmospheres of the Earth and Mars. Dust devils are strong, well-formed, and relatively long-lived whirlwinds, ranging from small (about a meter wide and a few meters tall) to large (more than 100 m wide and more than 1000 m tall) in the atmosphere of the Earth. Martian dust vortices can be up to fifty times as wide and ten times as high as terrestrial dust devils. The sizes of the Martian dust devils are large and the effect of them is more significant than that on the Earth. The dust devils raise large amount of dust from the surface which can influence thermal balance in rarefied Martian atmosphere. Tracks of dust vortices are well recognized in the photoimages of Martian surface and some parameters of Martian vortices were measured already by Viking missions in...
1970th [2]. Even small dust vortices can produce radio noise and electric fields greater than $10^4$ V/m. The question of possibility of lightning in the Martian dust events still remains.

2. Dynamics of vortices
Dust devils occur over hot surface where the temperature decreases with the altitude and conditions for convective instability are fulfilled. This situation frequently happens not only in the atmosphere of the Earth but also in the Martian atmosphere. It is accepted [3] that governing equations are common with those for internal gravity waves:

$$\frac{\partial \mathbf{V}}{\partial t} = -\frac{1}{\rho} \nabla P + \mathbf{g},$$

(1)

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \mathbf{V}) = 0,$$

(2)

$$\frac{\partial P}{\partial t} + (\mathbf{V} \cdot \nabla)P + \gamma P \text{div} \mathbf{V} = 0,$$

(3)

where $\mathbf{V}$ is the velocity, $P$ is the pressure, $\rho$ is the density of the gas, $\mathbf{g}$ is the gravity, and $\gamma$ is the ratio of specific heats. The first stage of vortex formation is generation of vertical motion in horizontal plane. Then toroidal motion with horizontal velocities appears. To describe vortical motion we use cylindrical reference frame. The density and the pressure are

$$\rho = \rho_0 + \tilde{\rho},$$

(4)

$$p = p_0 + \tilde{p},$$

(5)

respectively. Here, the density and pressure disturbances are small: $|\tilde{\rho}| \ll \rho_0, |\tilde{p}| \ll p_0$. For incompressible fluid in axisymmetric case, governing equations can be rewritten in the following way

$$\frac{\partial (\tilde{\Delta} \psi + \frac{1}{r} \frac{d \ln \rho_0}{dz} \frac{d \psi}{dz})}{\partial t} + \frac{1}{r} J\{\psi, \tilde{\Delta} \psi\} = -r \frac{d \chi}{dr} + \frac{r}{\rho_0} J(\tilde{\rho}, \tilde{p}) = 0,$$

(6)

$$r \frac{d \chi}{dt} - \omega_g \frac{d \psi}{dr} + J\{\psi, \chi\},$$

(7)

$$\frac{\partial \omega_z}{\partial t} + u_r \frac{\partial \omega_z}{\partial r} = \omega_z \frac{\partial u_z}{\partial z},$$

(8)

where

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

(9)

$\psi$ is the stream function of poloidal motion, $\omega_g$ is the buoyancy frequency, $\chi = g \tilde{\rho}/\rho_0$ is the normalized density perturbation,

$$J\{a, b\} = \frac{\partial a}{\partial x} \frac{\partial b}{\partial y} - \frac{\partial a}{\partial y} \frac{\partial b}{\partial x},$$

(10)

$\omega_z$ is the toroidal vorticity. The poloidal components of the velocity $u_r$ and $u_z$ are determined by the stream function $\psi$ as follows

$$u_r = \frac{1}{r} \frac{\partial \psi}{\partial z},$$

(11)

$$u_z = \frac{1}{r} \frac{\partial \psi}{\partial r},$$

(12)
3. Electric field model

Electric field generated in dust devils on the Earth was repeatedly measured [4,5]. Tribocharging [6,7] is the main mechanism of charging of particles in dust vortices. Dust particles of the same material colliding in the air flux acquire charges with small particles being charged negatively and large particles being charged positively [8]. The mechanism of spatial charge separation is following. In uplifting flux negatively charged particles collect at the upper part of the vortex and large positively charged particles are gathered in the lower part with the result of generation of the electric field.

The conditions on Mars are different from that on Earth, but the main process of electrization remains the same. So the charges acquired by particles at the surface of the Martian atmosphere in the absence of a tribocharging amount to no more than 10–20 electron charges [9], while the triboeffect can lead to charges 2–3 orders of magnitude larger [10]. In this regard, in further calculations it is assumed that the main effect affecting the charging of dust particles is tribocharging. As a result of one collision small particle of the radius \( r_s \) acquires charge \( \Delta q \) [7]:

\[
\Delta q = \alpha r_s,
\]

where \( \alpha = 10^{-15} \text{ C}/\mu\text{m} \). Large particle got charge \( Q_L \), which can be found from an equation

\[
\frac{dQ}{dt} + \frac{\sigma}{\varepsilon_0} Q_L = \nu C \Delta q,
\]

with \( \sigma \) being the atmospheric conductivity, \( \nu C \) a frequency of collisions between small and large particles

\[
\nu C = \pi r_L^2 n_S \Delta V,
\]

here \( r_L \) is the large particle radius, \( n_S \) is the small particles density, and \( \Delta V \) is the difference in velocities of large and small particles.
Figure 2. Dust particle trajectories in the vortex with $r = 10$ m at (a) the Earth (the charge of the particle $4 \times 10^{-18}$ C) and (b) the Mars (the charge of the particle $4 \times 10^{-17}$ C). The size of the particle 1 $\mu$m. Solid lines are for calculations with electric field, dash lines are for calculations without electric field.

To find the picture of power lines of electric field $E$ we use equations

$$\nabla \cdot E = 4\pi \rho_q,$$  

$$\frac{d\rho_q}{dt} + (\nabla \sigma) \cdot E + 4\pi \sigma \rho_q = 0,$$  

with $\rho_q$ being the charge density. The result of calculation of the electric field for vortex of 10 m is shown in figure 1.

4. Dust trajectories

We calculate the dynamics of a charged grain in a dust vortex taking into account forces of various natures, such as gravity force, the electrostatic force and the hydrodynamic force acting from the vortex. The motion of the particle is described by the following equation

$$m \frac{dV}{dt} = QE + mg + \frac{3\pi \mu a}{C_c}(U - V),$$  

where $Q$ is the charge of the particle, $V$ is the particle velocity, $U$ is gas velocity in a Burgers like vortex which is partial solution of the set of equations (6)–(8), $mg$ is gravity force, $\mu$ is viscosity of gas, $a$ is the particle diameter, $C_c$ is Cunningham correction factor for small particles [1]. Electric field $E$ of dust devil is calculated by method described above.

The horizontal sizes of terrestrial and Martian vortices are taken to be 10 m. The trajectories of dust of 1 m size (charge $4 \times 10^{-18}$ C) in the Earth vortex are shown in figure 2(a) and for the Martian conditions (charge $4 \times 10^{-17}$ C) in figure 2(b). One can see that electric field influences the dynamics of the particle.

5. Conclusions

The dust vortices in the atmospheres of the Earth and Mars are studied. The gas dynamics of the vortices is described. Charging dust particles leads to electric field generation as a result
of spatial charge separation. The electrical field of the vortex is calculated. The behavior of the dust in the vortex with taking into account the electrical field of the vortex is studied. One can conclude that dust vortices can lift dust grains from the near-surface layer. This effect can be one of the explanations of the relatively high number density of dust grains in the Martian atmosphere, the sources of which still remain unclear.

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