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On the Question of Calculating the Parameters of Vortices in the Near-Surface Atmosphere of Mars

Yu. N. Izvekova[a, b, *], S. I. Popel'[a, b], and O. Ya. Izvekov[b]

[a] *Space Research Institute, Russian Academy of Sciences, Moscow, Russia*

[b] *Moscow Institute of Physics and Technology, Dolgoprudny, Russia*

**e-mail: besedina_yn@mail.ru*

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Abstract—The paper is dedicated to the study of dust vortices on the Earth and Mars. The hydrodynamic similarity of convective vortices is considered, and the similarity criteria are determined. The motion of dust particles in a vortex is modeled. The conditions for the similarity of dust particle trajectories in a vortex in the terrestrial and Martian atmospheres are determined. It is shown that there is a similarity between terrestrial and Martian vortices. This fact can be useful for the study of the Martian atmosphere, given that there are proven methods for measuring the parameters of vortices on the Earth, while such measurements on Mars are difficult.

Keywords: convective vortices, similarity theory, dust particles, dust dynamics in vortices

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INTRODUCTION

At the present time, the Red Planet is being actively studied. The surface of Mars and the near-surface layer are being studied using the Mars Exploration Rover *Opportunity* and Mars Science Laboratory *Curiosity*; at the end of 2018, the *InSight* space probe made a successful landing on Mars. The atmosphere of Mars is sensed using the orbiters of several missions, including the Russian–European mission *ExoMars*. Continuous flow of data on the state of the Martian atmosphere makes it possible to build models of global atmospheric circulation (Forget et al., 1999; Bougher et al., 2015) and to study the seasonal variability and altitude distribution of atmospheric components (González-Galindo et al., 2005; Forget et al., 2009; Němec et al., 2011).

Despite the Martian atmosphere being sparse, at different times and at different altitudes, suspended particles of surface dust or condensed carbon dioxide and water are observed in it (Montmessin et al., 2006; 2007; Fedorova et al., 2014). In recent decades, considerable attention has been paid to the study of the parameters of dust and dusty plasma in space (Popel' and Gisko, 2006; Popel' et al., 2011), as well as in the atmospheres and exospheres of planets (Michael et al., 2008; Fedorova et al., 2014; Izvekova and Popel', 2017) and satellites (Stubbs et al., 2006, 2007; Sternovsky et al., 2008; Popel' et al., 2013; Popel' et al., 2017, 2018), which is due to the significant role of dust in the conditions of a rarefied atmosphere or its absence. While the redistribution of dust particles in the Earth's atmosphere is of major ecological importance, in rarefied atmospheres, the dust component may play a decisive role in climate formation. In the case of the charging of dust particles and formation of a plasma–dust system, the behavior of dust particles changes significantly, which must be taken into account when planning space missions.

The objective of this study is to describe convective vortices on Mars using the data obtained from the observations in the Earth's atmosphere. Convective processes resulting from the presence of vertical temperature gradients play an important role in planetary atmospheres. The role of convection is significant, in particular, in the formation of clouds, not only in the Earth's atmosphere, but also on other planets. For example, clouds of carbon dioxide, presumably of convective origin, were observed in the Martian atmosphere (Montmessin et al., 2007). In addition, convection is considered to be the main cause of dust vortices on the Earth and on Mars. On the Earth, dust vortices, as a rule, have sizes of the order of several meters, large vortices up to 100 meters in diameter being rare, while in the Martian atmosphere, there are vortices of hundreds of meters and even kilometers in diameter. Dust vortices on Mars attracted the attention of scientists in the middle of the last century, even before the first visual confirmation of their existence was obtained after processing the data from the *Viking* mission in the 1980s. This phenomenon has been actively investigated (Balme and Greeley, 2006; Delory et al., 2006; Onishchenko et al., 2014, 2016;

Barth et al., 2016); however, no final generally accepted model has been constructed so far. Laboratory modeling of meteorite impacts on Mars was carried out using the similarity theory (Rybakov et al., 1997); as a result, it was found that meteorite impacts could contribute to the formation of convective dust vortices. Dust vortices can lift and carry large amount of dust from the surface, which is especially important in the rarefied atmosphere of Mars.

It should be noted that the similarity theory is an important tool for the study of processes in atmospheres of planets. The similarity theory was developed for the circulation of planetary atmospheres (Golitsyn, 1970, 2004). In this paper, we consider the hydrodynamic similarity of convective near-surface vortices.

The paper is structured as follows. The next section of the paper provides an overview of the parameters of the Martian atmosphere; the section "Similarity of Convective Structures" is dedicated to the application of the similarity theory to describe Martian vortices; the section "Modeling of Vortices on Mars and on the Earth" describes the results of numerical modeling of vortex structures; and in the last section conclusions are given.

PARAMETERS OF THE MARTIAN ATMOSPHERE

The atmosphere of Mars has certain similarities with the Earth's atmosphere. The density and pressure on the surface are approximately one hundredth of those on the Earth; the primary gas component of the atmosphere (95%) is carbon dioxide. The temperature distribution makes it possible to distinguish the region of the troposphere from the surface to an altitude of 50–60 km, the middle atmosphere from the troposphere to 110 km, and the thermosphere above 110 km (González-Galindo et al., 2005). The average surface temperature is 210 K; the temperature profile undergoes significant diurnal and seasonal variations, especially in the troposphere. Mars has an ionosphere with electron concentrations reaching maximum values of 10^5 cm^{-3} at altitudes of 135–140 km; the lower boundary of the ionosphere usually starts from 80 km, but in some cases it can drop to 65 km (Pätzold et al., 2005). In addition, the conductivity of the gas shell of the Martian near-surface is very high (it exceeds the air conductivity near the Earth's surface by almost two orders of magnitude), and according to various estimates it ranges from 2.8×10^{-12} S/m (Zhai et al., 2006) to 10^{-11} S/m (Michael et al., 2008). The concentrations of electrons and ions at the surface of the planet during the day reach values up to approximately 1 cm^{-3} for electrons and 10^3 cm^{-3} for ions (Michael et al., 2008).

At altitudes up to 50–70 km, an important atmospheric parameter is the distribution of suspended dust particles, which varies greatly in time and space. The dust component plays a significant role in the dynamics of the Martian atmosphere and in the radiation balance, especially during dust storms, when the concentration of suspended dust particles sharply increases. But even in quiet periods, atmospheric dust on Mars poses a number of questions, such as the causes of dust clouds at different altitudes from 4 to 80–100 km (Montmessin et al., 2006) and sources of fine-mode dust particles with an average diameter of approximately 44 nm, which were observed for a long time at altitudes of 30–40 km in the northern hemisphere and up to 70 km in the southern hemisphere (Fedorova et al., 2014). Possible sources of dust particles are dust vortices (dust devils), which are regularly observed on the surface of Mars along with dust storms. Strong electrification in these vortices suggests that in some cases electrical breakdowns may occur (Zhai et al., 2006; Renno et al., 2003). The main parameters of dust vortices on the Earth, such as size, vertical and horizontal velocities, and electric fields (Farrell et al., 1999; Jackson and Farrell, 2006), are measured experimentally in deserts, where these vortices often occur. On the Earth, such vortices typically range in size from meters to a kilometer in height and less than 100 m in diameter (Mattsson et al., 1993). Table 1 shows some of such data measured at different times in vortices at a height of 2 m (3.5 m for (Tratt et al., 2003)) above the Earth's surface.

SIMILARITY OF CONVECTIVE STRUCTURES

Let us find out whether dust vortices on the Earth and on Mars are similar. First we discuss the main aspects of the similarity theory. Let some physical value a be a function of n other physical values and dimensional parameters $a_1, a_2, \ldots a_n$:

$$a = f\left(a_1, a_2, \ldots a_n\right). \tag{1}$$

In the theory of dimensions (see, e.g., Sedov, 1977; Barenblatt, 1982), the following statement is proved (pi-theorem).

Let k values from $a_1, a_2, \ldots a_n$ have an independent dimensionality; dependence (1) can then be represented as follows:

$$\Pi_a = f\left(\Pi_1, \Pi_2, \ldots \Pi_{n-k}\right), \tag{2}$$

where Π_a is the dimensionless unknown quantity, and $\Pi_1, \Pi_2, \ldots \Pi_{n-k}$ are dimensionless complexes.

Phenomena are called similar if their physical parameters differ in magnitude, but dimensionless complexes $\Pi_1, \Pi_2, \ldots \Pi_{n-k}$ coincide. It is also obvious that the physics of the phenomena should be the same. Similar phenomena are widely used in the planning of laboratory experiments.

The main role in the formation of dust vortices on Mars and Earth is played by thermal convection. Let us estimate the parameters (characteristic scale and

Table 1. The results of air velocity measurements in dust vortices on the Earth. The tangential velocity component is the air rotation rate relative to the center of the vortex. Average velocities are given

Source	Number of vortices	Tangential velocity component, m/s	Horizontal velocity component, m/s	Vertical velocity component, m/s
Sinclair (1964)	4		9.3	
Ryan and Carroll (1970)	80	4.2		0.7
Fitzjarrald (1973)	11	7.3		1.3
Sinclair (1973)	3	10.8		13.3
Metzger (1999)	5	13.6		5.2
Balme et al. (2003)	10		17.0	
Tratt et al. (2003)	3		8.8	3.3

gas flow velocity) of a vortex on Mars, which is similar to a typical vortex on the Earth.

Let us write the system of equations for the convective motion of viscous gas in the gravity field. With sufficiently slow flows, the gas can be considered incompressible, while the effect of gas expansion during heating is significant. Let us represent the temperature field T, density ρ, and pressure p as a sum of equilibrium values (with a subscript "0") and their perturbations (with a prime):

$$T = T_0 + T', \quad \rho = \rho_0 + \rho', p = p_0 + p'.$$

T_0 and ρ_0 have constant values, and the value of p_0 corresponds to the mechanical equilibrium at constant T_0 and ρ_0:

$$p_0 = -\rho_0 g z.$$

The density perturbation is proportional to the temperature perturbation.

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

where β is the coefficient of thermal expansion of the gas.

The continuity equation for an incompressible gas is

$$\operatorname{div}\mathbf{v} = 0. \tag{3}$$

The equation of motion is a consequence of the Navier–Stokes equation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\nabla)\mathbf{v} = -\frac{\nabla p'}{\rho_0} - \mathbf{g}\beta T' + \nu \Delta \mathbf{v}, \tag{4}$$

where ν is the kinematic viscosity.

The consequence of the energy conservation law is the equation of the thermal conductivity of an incompressible viscous gas.

$$\frac{\partial T'}{\partial t} + (\mathbf{v}\nabla)T' = \chi \Delta T' + \frac{2\nu}{c_p} J, \tag{5}$$

where Δ is the Laplace operator, χ is the coefficient of thermal diffusivity, c_p is the specific heat of the gas at constant pressure, $J = D_{ij}D_{ij}$, and $D_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$.

According to the formulated equations (3)–(5), the gas flow rate is a function of the following parameters: $\mathbf{x}$, t, l, τ, ΔT, χ, β, ν, ρ_0, T_0, and $\mathbf{g}$, where l and τ are the characteristic length and time scales, and ΔT is the maximum temperature difference. In the conditions of thermal convection, the Peclet number $\nu l/\chi$ or the Reynolds number $\nu l/\nu$ may be the dimensionless form of the unknown variable (in this case, velocity) and the similarity criterion is the combination of the Grashof criterion Gr and Prandtl criterion Pr (Gukhman, 1973). The Grashof criterion (number) is the ratio between the Archimedean buoyant force caused by the uneven distribution of the gas density in a nonuniform temperature field, and the viscous force:

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

The Prandtl criterion (number) $\mathrm{Pr} = \nu/\chi$ characterizes the ratio between the intensities of molecular transfer of momentum and heat transfer by thermal conductivity; the Prandtl number is a physical characteristic of the environment and depends only on its thermodynamic state. For gases, it is almost independent of temperature; for diatomic gases, the Prandtl number is approximately 0.72, for polyatomic gases, it ranges from 0.75 to 1. For gases, it can be assumed that $\chi \propto T^{3/2}/\left(p\sqrt{m}\right)$, where T is the temperature, p is the pressure, and m is the molar mass of the gas. In fact, in this case, the Prandtl number becomes equal to one, $\mathrm{Pr} = 1$.

As a result, the relationship for the dimensionless velocity $\tilde{\mathbf{v}}$ in the stationary case takes the following form:

$$\tilde{\mathbf{v}} = f\left(\frac{\mathbf{x}}{l}, \mathrm{Gr}, \mathrm{Pr}\right). \quad (6)$$

Since a developed dust vortex can be considered as a situation when the inertial force has a large relative value in comparison with the viscosity effects, we take the dimensionless velocity as $\tilde{\mathbf{v}} = \mathbf{v}\, l/\chi$, and we will use the value of $\mathrm{Gr}\mathrm{Pr}^2$ as the similarity criterion, rather than Gr and Pr separately. It should be noted that in the case of the dominant role of viscosity, the GrPr criterion is used (Gukhman, 1973). In our case, (6) will look as follows:

$$\mathbf{v} = \frac{\chi}{l} f\left(\frac{\mathbf{x}}{l}, \mathrm{Gr}\,\mathrm{Pr}^2\right). \quad (7)$$

Let us denote the parameters of the Earth's atmosphere by the subscript "E" and parameters of the Martian atmosphere by the subscript "M". Using (7), we find the ratio of the similarity criteria for the terrestrial and Martian vortices:

$$\frac{\left(\mathrm{Gr}\,\mathrm{Pr}^2\right)_E}{\left(\mathrm{Gr}\,\mathrm{Pr}^2\right)_M} = \frac{g_E}{g_M}\frac{l_E^3}{l_M^3}\frac{\beta_E}{\beta_M}\frac{\Delta T_E}{\Delta T_M}\frac{T_M^3}{T_E^3}\frac{P_E^2}{P_M^2}\frac{m_E}{m_M}. \quad (8)$$

We will use the following ratios of the parameters:

$$\frac{g_E}{g_M} = 2.65, \ \frac{\beta_E}{\beta_M} \approx 1, \ \frac{T_M^3}{T_E^3} \approx \left(\frac{200}{300}\right)^3 \approx 0.3,$$
$$\frac{P_E^2}{P_M^2} \approx 10000, \ \frac{m_E}{m_M} = \frac{29}{44} \approx 0.66.$$

According to the measurements of the *Viking* spacecraft (Balme and Greeley, 2006), the maximum temperature variation in Martian vortices is 5–6°C, which matches terrestrial vortices. Then, $\Delta T_E/\Delta T_M \approx 1$.

Assuming for such vortices

$$\frac{\left(\mathrm{Gr}\,\mathrm{Pr}^2\right)_E}{\left(\mathrm{Gr}\,\mathrm{Pr}^2\right)_M} = 1,$$

and taking into account (8), we obtain the relation between the characteristic scales:

$$l_M \approx 17 l_E. \quad (9)$$

Further, from the equality of dimensionless velocities for the Earth and Mars

$$\frac{\mathbf{v}_E l_E}{\chi_E} = \frac{\mathbf{v}_M l_M}{\chi_M},$$

we obtain the relation of the characteristic speeds

$$v_M \approx 2.6 v_E. \quad (10)$$

The resulting values do not contradict the available data. The vertical velocities in the Earth's vortices have values of the order of 10 m/s, while the velocities in the Martian vortices, according to the estimates based on the measurements of the *Viking-1* and *Viking-2* landers (Ryan and Lucich, 1983), are several times greater.

SIMULATION OF VORTICES ON MARS AND ON THE EARTH

Hydrodynamic equations (3)–(5) that describe convective motions can be transformed in such a way that they can describe three-dimensional vortex structures (Onishchenko et al., 2014, 2016; Izvekova and Popel', 2017, 2018). The basic equations describing gas dynamics in dust vortices will be rewritten in the following form:

$$\frac{\partial}{\partial t}\left(\tilde{\Delta}\psi + \frac{d\ln\rho_0}{dz}\frac{d\psi}{dz}\right) + \frac{1}{r}J\{\psi, \tilde{\Delta}\psi\} = -r\frac{d\xi}{dr} + \frac{r}{\rho_0^2}J\{\rho', p'\}, \quad (11)$$

$$r\frac{\partial\xi}{\partial t} - N^2\frac{\partial\psi}{\partial r} + J\{\psi, \xi\} = 0, \quad (12)$$

$$\frac{\partial\omega_z}{\partial t} + v_r\frac{\partial\omega_z}{\partial r} = \omega_z\frac{\partial v_z}{\partial z}, \quad (13)$$

where $\tilde{\Delta} = r\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}$ is the Grad–Shafranov operator; ψ is the function of the poloidal current flow; $\xi = g\rho'/\rho_0$ is the normalized density perturbation; $N = g^{1/2}\left(\frac{1}{\gamma p}\frac{\partial p}{\partial z} - \frac{1}{\rho}\frac{\partial\rho}{\partial z}\right)^{1/2}$ is the Väisälä–Brent frequency; γ is the adiabatic index; $J\{a,b\} = \frac{\partial a}{\partial x}\frac{\partial b}{\partial y} - \frac{\partial a}{\partial y}\frac{\partial b}{\partial x}$ is the Jacobian; the density and pressure perturbations are small, $|\rho'| \ll \rho_0$, $|p'| \ll p_0$; ω_z is the toroidal vorticity; and the poloidal velocity components v_r and v_z are determined by the function of current: $v_r = -\frac{1}{r}\frac{\partial\psi}{\partial z}$, $v_z = \frac{1}{r}\frac{\partial\psi}{\partial r}$.

Numerical solution of system (11)–(13) allows us to determine the velocity field of the vortex. Dust particles raised from the surface are an important component of a dust vortex. In the context of the approach used in this study, dust particles are considered as an admixture that does not significantly affect the hydrodynamic parameters of the vortex. It should be noted that the influence of the dust component on the gas flow was previously considered in the context of the study of the Martian atmosphere when investigating the motion of turbulent flows with suspended particles during dust storms (Barenblatt and Golitsyn, 1974; Golitsyn, 1973; Leovy et al., 1973; Gierasch and Goody, 1972). Dust storms are more prolonged and larger-scale phenomena than dust vortices, and cover most of the planet. Moving in a vortex, particles acquire an electric charge as a result of collisions; as noted in (Melnik and Parrot, 1998; Lacks and Levandovsky, 2007), when particles of the same material collide, large particles accumulate a positive charge, while smaller particles accumulate a negative charge.

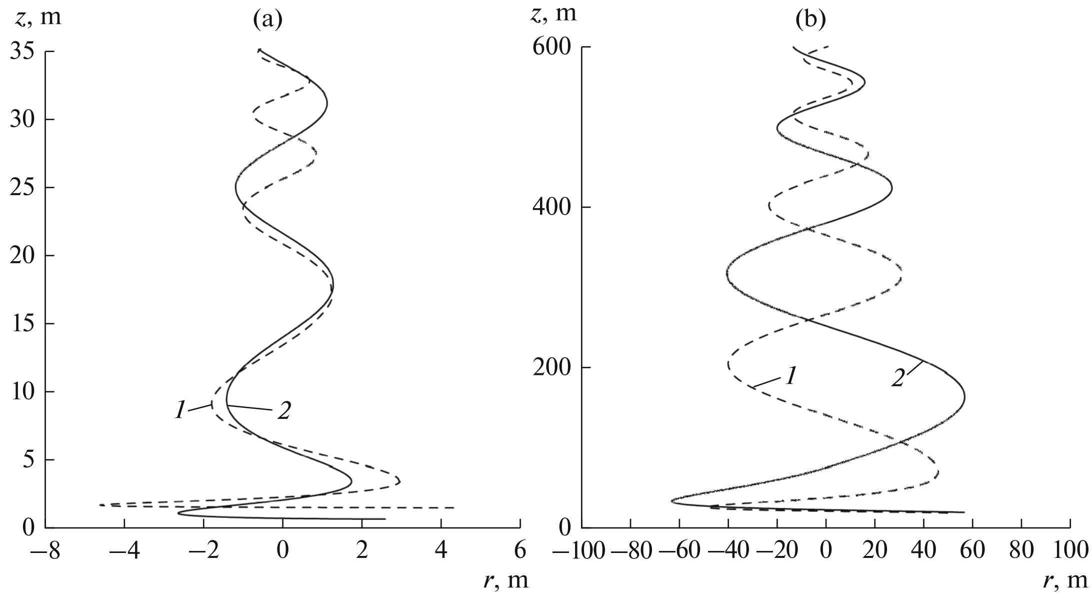

Fig. 1. Trajectories of dust particles with a size of 1 μm (curve *1*) and 10 μm (curve *2*): (a) on the Earth in a vortex of 10 m in size and (b) on Mars in a vortex 170 m in size.

The opposite charging of particles of different sizes leads to a spatial separation of charge and the generation of an electric field. In terrestrial vortices, fields of 4.35 kV/m were measured for a 7-m diameter (Farrel et al., 2004) and 20 kV/m for a vortex with a diameter of 30 m (Delory et al., 2006). Due to the lower value of the electrical breakdown field on Mars, the study of the electrification of Martian vortices is important. According to contemporary models (Barth et al., 2016), the electric field values may lie near the breakdown values. However, at present, there is no definitive answer to the question of lightning activity in dust vortices on Mars. Ground-based measurements by means of a radio telescope (Ruf et al., 2009) suggest the excitation of the Schumann resonator on Mars during dust storms. This may indicate the presence of electrical discharges during measurements. However, measurements using orbiters (Yair, 2012) gave no confirmation of thunderstorm activity. An unambiguous answer to this question requires measurements of the electric fields on the Martian surface; these are planned as part of the second stage of the *ExoMars* mission. To build a complete dust vortex model, it is necessary to take into account the effects of electrification. The modeling of motion of dust particles takes into account their electrification due to collisions (triboelectric effect) and the generated electric field (Izvekova and Popel', 2017). Detailed consideration of electrical processes from the point of view of the similarity theory appears to be rather complicated. In this paper, we will focus on considering the motion of a particle without the addend determined by the force of electrical interaction, since previous calculations (Izvekova and Popel', 2017, 2018) showed that for the most part of the trajectory, the influence of the electric field can be neglected. Let us write down the motion equation of a dust particle with a density ρ_p and size a in the velocity field of the vortex:

$$\frac{d\mathbf{V}_p}{dt} = \mathbf{g} + \frac{18\eta}{C_c\rho_p a^2}\mathbf{V}_{pr}. \quad (14)$$

Here $\mathbf{V}_p$ is the velocity of the dust particle; $\mathbf{V}_{pr}$ is the velocity of the particle relative to the vortex; η is the dynamic viscosity; and $C_c = 1 + \mathrm{Kn}(A + B\exp(-b/\mathrm{Kn}))$ is the Cunningham correction (Aloyan, 2002), where $A = 1.257$, $B = 0.4$, $b = 1.10$, and $\mathrm{Kn} = 2\lambda/a$ is the Knudsen number, while λ is the mean free path of gas molecules. We note that for particle sizes comparable to the free path, the Cunningham correction is significant. On Earth, the correction will be negligible, but on Mars, where the mean free path is approximately 5 μm, it should be considered. Let us make Eq. (14) nondimensional with the characteristic values of length r_0 and velocity V_0. In the dimensionless form, we have

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

where $\tilde{\mathbf{V}}_p = \mathbf{V}_p/V_0$, $\tilde{\mathbf{V}}_{pr} = \mathbf{V}_{pr}/V_0$, and $\tilde{\mathbf{g}} = \frac{r_0}{V_0^2}\mathbf{g}$.

It can be seen that the dimensionless values of the acceleration of gravity on the Earth and on Mars are the same. For the similarity of trajectories, it is necessary that the coefficients before the relative velocities are equal:

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

Using the relationships between the characteristic dimensions and velocities (9), (10) and assuming that the particle densities coincide, and the viscosity of the Martian atmosphere is 0.6 of the Earth's (estimated by the viscosity of carbon dioxide at 210 K) (Babichev et al., 1991), we find

$$a_M \approx a_E.$$

Let us construct a vortex with a core size of 10 m on the Earth and 170 m on Mars. The trajectories of dust particles in these vortices are shown in Fig. 1. It can be seen that the particle trajectories qualitatively correspond to the parameters chosen according to the estimates of the similarity theory.

CONCLUSIONS

In this study, we have considered the similarity of convective structures in the atmospheres of the Earth and Mars. The similarity criteria have been obtained. The characteristic parameters of the vortices and dust particles that satisfy the similarity criteria have been estimated. The relations between the velocities in the vortex and the dimensions of the vortex structures in the terrestrial and Martian atmosphere have been obtained, under which the similarity conditions are satisfied. The motion of dust particles in the velocity field of dust vortices have been considered, and the sizes of particles whose trajectories can be considered similar have been estimated. A vortex structure has been simulated, and the trajectories of dust particles in a vortex have been constructed. The estimates and simulations show that there is a similarity between dust vortices on the Earth and on Mars. Given that measurements on Earth are available to experimenters but are difficult on Mars, these conclusions may be useful in the studies of Martian vortices.

It should be noted that the above consideration is based mainly on hydrodynamic processes. Such an approach is typical for atmospheric physics (see, e.g., Golitsyn, 2004). That being said, one should take into account the possibility of the development of plasma processes in the planetary atmospheres, such as the generation of electric fields and charging of dust particles (Izvekova and Popel', 2016, 2017). At the same time, due to the prevailing role of the neutral component in the near-surface atmosphere, the dynamics of vortices in it are determined by hydrodynamic processes. This fact makes it possible to construct a theory of hydrodynamic similarity of convective surface vortices.

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