On dusty plasma formation in Martian ionosphere

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Abstract. A self-consistent model for the formation and evolution of dusty plasmas in the Martian ionosphere is developed. The effects of the initial distributions of dust particles, as well as condensation and absorption of carbon dioxide and water molecules by dust particles, are studied. Theory values of characteristic sizes of dust grains and their charges are obtained. The theoretical values of the sizes are in agreement with the data of observations. The possibility of the formation of dusty plasma structures in the Martian ionosphere which are analogous to noctilucent clouds in the atmosphere of the Earth is discussed.

Dusty plasmas are frequently encountered in nature. For example, charged dust grains are present in planetary magnetospheres and ionospheres, atmospheres of comets, lunar exosphere, and interstellar medium [1, 2]. The presence of dusty plasmas in the ionosphere of the Earth manifests itself in the form of noctilucent clouds (NLC), polar mesosphere summer echoes (PMSE), and meteor traces [3–5]. NLC consist of submicron particles. They can be observed by the unaided eye at sunset, whereas PMSE (which likely consist of charged nanometer-scale particles) are not observed optically but are manifested as strong radio reflections on radars operating at frequencies of 50 to 1000 MHz.

In the Martian atmosphere, the presence of dust grains was never questioned, because they can be lifted from the surface due to various processes [6]. The dust component can play a substantial (in some cases, decisive) role in the radiation balance. Dust grains get charged under the action of solar radiation, interaction with charged particles of the atmosphere and solar wind, triboelectric effect, and other factors. Interest in Mars has substantially increased in recent years. Spacecrafts Mars Express, ExoMars Trace Gas Orbiter, etc, are operating successfully. The surface of Mars is being studied with Mars Exploration Rover Opportunity and Mars Science Laboratory Curiosity. Therefore, investigation of the Martian atmosphere is quite challenging. The Martian atmosphere is somewhat similar to the atmosphere of the Earth. The density and pressure on the Martian surface amount to about 1/100 of those on the surface of the Earth, the main gaseous component (95%) of the Martian atmosphere being carbon dioxide.

There is an ionosphere on Mars with the maximum electron density of up to $10^5$ cm$^{-3}$ at altitudes of 135 to 140 km. The lower boundary of the ionosphere lies at 80 km; however, it can come down to 65 km in some cases [7]. The data on the presence of dust in the Martian ionosphere were obtained from instruments installed on orbital stations. However, estimates...
made by different methods yield somewhat different values of the main physical parameters of
dust grains [8]. These discrepancies can be explained, e.g., by the presence of clouds of condensed
grains. At altitudes about 100 km in the ionosphere, where the temperature is sufficiently low for
carbon dioxide freezing, clouds formed of dust grains with a size of about 100 nm (similar to NLC
in the atmosphere of the Earth) were observed by means of the SPICAM infrared spectrometer
installed on Mars Express orbiter [9]. In addition, clouds of micron-size grains were observed at
altitudes of about 80 km by means of the OMEGA spectrometer onboard Mars Express [10]. The
mechanisms of formation of such clouds are still unclear. We note also a possibility of formation
of grains of frozen water at lower altitudes in the Martian atmosphere [11,12]. Thus, dust grains
or grains of frozen carbon dioxide or water can be present in the Martian atmosphere. Taking
into account the presence of electrons and ions at different altitudes, as well as the photoelectric
effect in the day time, we can speak of the presence of dusty plasma systems in the Martian
atmosphere.

Here, we perform a development to the conditions of the Martian ionosphere of a theoretical
model by [4,13] that provides a self-consistent description of NLC and PMSE in the atmosphere
of the Earth. The model describes, in particular, sedimentation of dust grains in the atmosphere,
their growth in a supersaturated vapor, and dust grain charging processes, allowing for variations
of the ion-subsystem composition in the atmosphere and photoelectric emission. In this paper,
we pay attention to condensation and absorption of carbon dioxide and water molecules by dust
particles. The effect of the charges of particles on condensation processes is also taken into
account. Using the modified (to the conditions of the Martian ionosphere) model we illustrate
the effect of the initial distributions of dust particles, as well as the condensation and absorption
of carbon dioxide and water molecules by dust particles, on the formation and evolution of dusty
plasmas in the Martian ionosphere.

The conditions in the Martian ionosphere important for the physics of dust particle formation
and evolution are illustrated in figures 1 and 2. Figure 1 represents the altitude profiles of the
temperature of the neutral gas, pressure of saturated carbon dioxide vapor, as well as pressure of
carbon dioxide vapor. Figure 2 shows the analogous characteristics for the case of water vapor.
Figures 1 and 2 are constructed on the basis of the data given in [14,15]. The conditions for
the growth (nucleation) of carbon dioxide particles exist in the altitude range of 87–112 km,
where carbon dioxide vapor is supersaturated. Water particles can grow in the altitude range
of 88–116 km, where water vapor is supersaturated.

To describe the sedimentation of dust grains in the Martian atmosphere and their growth
we use the following equations. A kinetic equation for the dust particle velocity distribution
function $f_d(h, a, v, t)$ at an altitude $h$ over the surface of Mars is (compare with [4])

$$\frac{\partial f_d}{\partial t} + \frac{\alpha_{cd(w)} m_{cd(w)} v^{th}_{cd(w)} (n_{cd(w)} - n^s_{cd(w)})}{4 \rho_d} \frac{\partial f_d}{\partial a} + v \frac{\partial f_d}{\partial h} + \left( g - \frac{\pi \rho c_s a^2 F_d (v + v_{wind})}{m_d} \right) \frac{\partial f_d}{\partial v} = 0. \quad (1)$$

In equation (1), the second and fourth terms describe, respectively, dust particle growth in the
ambient supersaturated vapor of carbon dioxide (water) and either sedimentation or rise of dust
grains subject to neutral drag. Here, $a$ is the characteristic dust particle size, $m_d$ is the dust
particle mass, $m_{cd(w)}$ is the carbon dioxide (water) molecule mass, $\alpha_{cd(w)}$ is the accommodation
coefficient for carbon dioxide (water) molecules colliding with a dust grain (normally, $\alpha_{cd(w)} \sim
1$), $v^{th}_{cd(w)}$ is the thermal speed of carbon dioxide (water) molecules, $c_s$ is the local acoustic speed,
$\rho$ and $\rho_d$ denote the densities of the ambient air and grain material, $n^s_{cd(w)}$ and $n_{cd(w)}$ are the
number densities of saturated carbon dioxide (water) vapor over the dust particle surface and
of carbon dioxide (water) vapor in the ionosphere, $v_{wind}$ and $v$ are the upward components of
the wind and dust particle velocity, respectively, the factor $F_d$ (of the order of unity) reflects
the effect of grain geometry, $g$ is the gravity of Mars.
Figure 1. Schematic altitude profiles of (solid line) the temperature of air, (dashed line) the pressure of carbon dioxide vapor and (dash-dotted line) the pressure of saturated carbon dioxide vapor. Carbon dioxide vapor is supersaturated in the altitude range of 87–112 km.

Figure 2. Schematic altitude profiles of (solid line) the temperature of air, (dashed line) the pressure of water vapor and (dash-dotted line) the pressure of saturated water vapor. Water vapor is supersaturated in the altitude range of 88–116 km.
An equation relating the pressure $P_S$ of saturated carbon dioxide (water) vapor over the dust particle with the size $a$ and surface charge $q_d$ to the pressure $P_0$ of saturated carbon dioxide (water) vapor over the planar surface is (compare with [13])

$$v_d \left( P_S - \frac{N_A \mu_D q_d}{\mu g a^2 v_d} L \left( \frac{\mu D q_d}{k_B T a^2} \right) - P_0 \right) - \frac{N_A k_B T}{\mu g} \ln \left( \frac{P_S}{P_0} \right) + \frac{2\sigma v_d}{a} + \frac{q_d^2 v_d}{8\pi a^4} \left( \frac{1}{\varepsilon} - 1 + \nu(\lambda, a) \right) = 0,$$

(2)

where

$$\nu(\lambda, a) = \int_a^{\infty} \frac{a^2(\lambda + r)^2}{r^2} \frac{2a \exp \{2(a - r)/\lambda\}}{\lambda(\lambda + a)^3} \text{d}r,$$

(3)

$\nu(\lambda, a)$ being caused by Yukawa potential characterizing the electric field of a dust particle, $\varepsilon$ is the dielectric function of the grain material, $v_d$ is the specific volume of the dust particle, $N_A$ is the Avogadro number, $\mu_D$ is the dipole moment of carbon dioxide (water) molecule, $\mu g$ is the molar mass of carbon dioxide (water) vapor, $T$ is the temperature, $k_B$ is the Boltzmann constant, $L(x)$ is the Langevin function, $\sigma$ is the surface tension coefficient.

Solution of equation (2) allows us to determine the number density $n_{cd(w)}^e$, included in equation (1) by means of the relationship $n_{cd(w)}^e = P_S/(k_B T)$. Equation (2) has been derived using the thermodynamic potential $\Omega$ [16] of the system consisting of the charged dust particle, on the surface of which molecules (carbon dioxide or water) are condensed; a gaseous layer of indicated molecules; surface tension on the dust particle; electric fields inside and outside the dust particle. The assumption has been used that the electric field outside the dust particle is characterized by Yukawa potential. Correspondingly, the term containing the Langevin function appears in equation (2); the last term on the left-hand-side of equation (2) is related to the dust particle electric field, an appearance of the term $\nu(\lambda, a)$ [see equation (3)] being caused by Yukawa potential characterizing the dust particle electric field.

An equation describing the dynamics of carbon dioxide (water) vapor is

$$\frac{\partial n_{cd(w)}}{\partial t} + \frac{\partial \Gamma_{cd(w)}}{\partial h} = - P_{cd(w)} - n_{cd(w)} \nu_{cd(w)} L_{cd(w)} - \pi a_{cd(w)} r_{cd(w)}^{th} n_{cd(w)} \langle a^2 n_d \rangle,$$

(4)

where $\Gamma_{cd(w)}$ is the vertical diffusion flux of carbon dioxide (water) vapor [17], $P_{cd(w)}$, $L_{cd(w)}$ are photochemistry sources and sinks of carbon dioxide (water) vapor in the ionosphere, the last term on the right-hand-side of equation (4) describes the absorption of carbon dioxide (water) molecules by dust particles. The rest equations of the model which describe the plasma properties of the ionosphere are given by analogy with [4].

We have considered evolution of different layers constituting the initial rectangular profile of dust particle number density for solid carbon dioxide and wat er ice dust. The two examples of such a consideration are given in figures 3 and 4. The behaviour of the layers allows us to make the following conclusions concerning dust particles in the Martian ionosphere:

- The solid carbon dioxide particles being initially at the upper part of the condensation zone, i.e., in the zone where carbon dioxide vapor is supersaturated, gather (on their surfaces) the main part of carbon dioxide vapor and sediment downward together with the absorbed carbon dioxide molecules. Particles of different layers absorb different amounts of carbon dioxide molecules. This results in a possibility of mixing of the layers and the formation of dust clouds. The characteristic time of sedimentation of solid carbon dioxide dusts within the condensation zone is about several minutes. Below the condensation zone the dusts are evaporated. Correspondingly, the characteristic time of sedimentation of the dusts within the condensation zone determines the characteristic time of the existence of the dust clouds analogous to NLC in the ionosphere of the Earth. In the condensation zone the solid carbon
Figure 3. Evolution of layers constituting the initial rectangular profile of carbon dioxide dust particle number density vs altitude for different moments of time: \( t = 0 \) (a), 40 (b), 120 (c), 200 (d), 240 (e) and 280 s (f). The initial dust particle radius is 4.5 nm. The dust particle number density in each layer is \( n_d = 100 \text{ cm}^{-3} \). During the evolution the layers overlap. Initially the two bottom layers overlap (b). Later all the layers overlap (c)–(f). Because the overlap in (c) to (f) is significant, the columns characterizing the layers are expanded along the abscissa axis.

Carbon dioxide particles can reach the sizes of the order of 100 nm. This value is in accordance with observations performed on Mars Express orbiter with the aid of the SPICAM infrared spectrometer [9]. The dust particles can acquire the charge values \( q_d \sim 10e \) at night time and \( q_d \sim 100|e| \) at day time, where \( e \) is the electron charge.

- Analogously to the situation at the Earth [18], particles with a characteristic size of several nanometers can exist in the Martian ionosphere above the condensation zone owing to the bombardment of the Mars by micrometeorites. Those particles which are initially higher than the upper border of the condensation zone (even when reaching the condensation zone in some time) cannot grow significantly because of only small amount of the residual carbon dioxide molecules in this zone. These small-size-particles exist at the altitudes of 112 to 115 km during hours, that can result in the phenomena in Martian atmosphere analogous to PMSE.

- Particles of water ice grow very slowly and settle in the condensation zone for tens of hours. The maximum sizes of dust particles are of the same order of magnitude as the original ones. Different layers of such particles do not mix with each other. The reason for their behavior is the very low concentration of water vapor in the Martian ionosphere. All these facts explain the absence of observations of water ice dust clouds at the altitudes of 88–116 km.
Figure 4. Evolution of layers constituting the initial rectangular profile of water ice dust particle number density vs altitude for different moments of time: $t = 0 \ (a)$, 4 \ ($b$), 8 \ ($c$), 12 \ ($d$), 16 \ ($e$) and 20 h \ ($f$). The initial dust particle radius is 4.5 nm. The dust particle number density in each layer is $n_d = 100 \ cm^{-3}$.

Thus, we briefly described a self-consistent model of dusty plasma in the Martian ionosphere. Our calculations illustrate the effect of the initial distributions of dust particles. We have shown a possibility of the existence in the Martian ionosphere of carbon dioxide dust clouds analogous to NLC. Furthermore, phenomena in Martian atmosphere analogous to PMSE are also possible. We have obtained theory values of characteristic sizes of carbon dioxide dust grains and their charges. The theoretical values of the sizes are in agreement with the data of observations.

Acknowledgments
This work was supported in part by the Russian Foundation for Basic Research (project No. 18-02-00341).

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