Dusty plasmas at Martian satellites

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Abstract. Dusty plasmas are shown to be formed in a surface layer over the illuminated part of Martian satellites Phobos and Deimos owing to photoelectric and electrostatic processes. The distribution functions of photoelectrons near surfaces of the satellites, altitude dependences of the density of dust particles, and their charges and sizes, as well as electric fields, have been determined within a physical-mathematical model for the self-consistent description of densities of photoelectrons and dust particles over the surface of the illuminated parts of Phobos and Deimos. In view of a weak gravitational field, dust particles rising over the surfaces of Phobos and Deimos are larger than those over the surface of the Moon. In this case, the role of adhesion, which is a significant process preventing the separation of dust particles from the lunar surface, is much smaller on Phobos and Deimos.

1. Introduction

The system of Mars is actively being studied with spacecrafts. The spacecrafts ExoMars Trace Gas Orbiter, Mars Express, etc, are operating successfully. The surface of Mars is being studied with Mars Exploration Rover Opportunity and Mars Science Laboratory Curiosity. The Phobos-Grunt 2 mission to the Martian satellite Phobos is under preparation. The study of Phobos and Deimos is of interest, in particular, because Phobos and Deimos are more accessible for manned missions than Mars in view of a weaker gravitational field. The gravitational acceleration on Phobos (Deimos) is approximately 0.0057 m/s\(^2\) (0.0039 m/s\(^2\)), and the landing of a spacecraft on it is more similar to a docking with another spacecraft than landing on a planet.

According to the data from the Viking spacecraft [1, 2] and, then, from Phobos-2 and Mars Express spacecrafts [3], the surfaces of Phobos and Deimos are covered by a dust consisting of uncoupled small regolith particles formed because of micrometeorite bombardment.

A weak gravitational field enhances the role of dust at Phobos and Deimos because even a weak perturbation can result in the formation of a massive dust cloud over the surfaces of these Martian satellites. Among the aims of the Phobos-Grunt 2 mission are to detect dust particles in an orbit around Mars and near the surface of Phobos and to determine the main parameters of dust particles (momentum, mass, velocity, and charge).

Furthermore, the measurement of the plasma parameters and the determination of the local electric field near the surface of Phobos are expected. To these ends, piezoelectric impact sensors, whose operation is based on the impact action of a dust particle (figure 1), and probes...
Figure 1. Schematic diagram of the orbital motion of the Phobos-Grunt 2 spacecraft (SC). Piezoelectric impact sensors IS-1 and IS-2 are expected to be able to determine the main parameters of dust particles (momentum, mass, velocity, and charge). The possibility of placing impact sensors on solar panels (Solar panel) is examined.

for measurements of the parameters of the plasma and the local electric field near the surface of Phobos will be used.

Phobos and Deimos, as well as the Moon, are atmosphere-free space bodies. It is commonly accepted that dust over the lunar surface is a component of the dusty plasma system [4–21]. It is expected that the situation over the surfaces of Phobos and Deimos is similar. The surfaces of Phobos and Deimos are charged under the action of the electromagnetic radiation of the Sun and of the plasma of the solar wind. Interacting with solar radiation, the surfaces of Phobos and Deimos emit electrons because of the photoelectric effect, which results in the formation of a layer of photoelectrons over the surface. Photoelectrons are also emitted by dust particles present over the surfaces of Phobos and Deimos because of the interaction of dust particles with electromagnetic radiation of the Sun. Dust particles located at the surfaces of Phobos and Deimos or in the surface layer absorb photoelectrons, photons of solar radiation, and electrons and ions of the solar wind. All these processes result in the charging of dust particles, their interaction with the charged surfaces of Phobos and Deimos, and rise and motion of dust.

Impacts of meteoroids on the surfaces of Phobos and Deimos play an important role in the formation of the dusty plasma systems near Martian moons. Secondary particles knocked out from the surfaces of Phobos and Deimos because of bombardment by meteoroids acquire a velocity exceeding the escape velocity (approximately equal to 10 m/s for Phobos and 6 m/s for Deimos) and leave them. If the velocity of secondary particles is lower than the orbital velocity of the corresponding Martian satellite (2.1 km/s for Phobos and 1.35 km/s for Deimos), particles can appear in orbits around Mars. Finally, formation of a dust halo near the orbits of Phobos and Deimos is possible [3,22].
Papers [3, 22] were devoted primarily to the consideration of dust over Phobos and Deimos at high altitudes $h$ larger than the characteristic linear sizes of Phobos ($\approx 20$ km) and Deimos ($\approx 15$ km), respectively. Data on the parameters of dust in the near-surface layers ($h \ll 10$ km) are almost absent. By analogy with the situation near the Moon, it can be expected that most dust particles are located in the near-surface layers over Phobos and Deimos, where the formation of the dusty plasmas is due to the processes of charging of dust particles, their interaction with the charged surfaces of Martian moons, and rise and motion of charged dust in electric and gravitational fields, and the velocities of dust particles in this layer are much lower than 6 m/s. The properties of the dusty plasmas near the surfaces of Phobos and Deimos will be studied with taking into account possibilities and technique of the future Phobos-Grunt 2 mission. In this work, the properties of the dusty plasmas in the near-surface layers over the illuminated parts of Phobos and Deimos are described. Electric fields, as well as the parameters of photoelectrons and dust over the surfaces of Phobos and Deimos, are calculated.

2. Model
To describe the dusty plasma systems in the near-surface layers of the illuminated parts of Phobos and Deimos, we use the model [9], where the charging of dust particles over the surfaces of Phobos and Deimos is calculated with allowance for the effect of photoelectrons, electrons, and ions of the solar wind, as well as solar radiation. The effect of light pressure on the dynamics of dust particles is disregarded because estimates show that this effect is noticeable only for particles smaller than 1 nm. Photoelectrons both from the surface of a Martian moon and from the surfaces of dust particles over it are taken into account. Photoelectrons from the surfaces of dust particles should be described self-consistently because photoelectrons affect the distributions of dust particles, whereas the distributions of dust particles determine the number of photoelectrons. Since the problem is self-consistent, it can be solved only numerically.

To find the densities of photoelectrons over the surfaces of Phobos and Deimos, one solves the system of equations including a steady-state kinetic equation for the distribution function of photoelectrons and the Poisson equation for the electrostatic potential with the corresponding boundary conditions characterizing the behavior of the potential near the surface of a Martian moon and at infinite distance from it. The energy distribution functions $\Phi_e$ of photoelectrons near the surfaces of Phobos and Deimos are determined in a standard way [23] from the calculated flux density of photoelectrons emitted by an irradiated solid:

$$
\Phi_e(E_e)dE_e = 2\cos\theta \sqrt{\frac{2m_e}{E_e}} \int_{E_e+W}^{\infty} Y(E_{ph})F_{ph}d\rho dE_{ph},
$$

where $E_e$ is the energy of a photoelectron, $E_{ph}$ is the energy of a photon, $W$ is the photoemission work function, $\theta$ is the subsolar angle, $m_e$ is the mass of the electron, $Y(E_{ph})$ is the quantum yield depending on the energy of photons, $F_{ph}dE_{ph}$ is the number of photons of solar radiation with the energy $E_{ph}$ in the range $dE_{ph}$ intersecting a unit area perpendicular to the direction of motion of photons in unit time, and

$$
d\rho = \frac{6(E_{m} - E_e)}{E_m^3} E_e dE_e,
$$

is the probability [23] that the absorption of a photon with the energy $E_{ph}$ is accompanied by the emission of an electron with the energy $E_e$ in the energy range $dE_e$. A factor of 2 on the right-hand side of equation (1) appears because the number of electrons leaving the surface of a solid in the stationary state is equal to that absorbed by the surface. When deriving equation (1), the possible anisotropy of the velocity distribution function of photoelectrons, which is due to the irregularity of the surfaces of Phobos and Deimos, was neglected.
The distribution function given by equation (1) can be used to find the density \( N_0 \) and the temperature \( T_e \) of photoelectrons near the surfaces of Phobos and Deimos:

\[
N_0 = \int_0^\infty \Phi_e(E_e) dE_e,
\]

\[
T_e = \frac{2}{3} \langle E_e \rangle = \frac{2}{3 N_0} \int_0^\infty E_e \Phi_e(E_e) dE_e.
\]

The spectrum of solar radiation, quantum yield, and work function of regolith are important parameters for the calculation of the distribution function, density, and temperature of photoelectrons. Typical values of the work function and quantum yield for regolith on Phobos and Deimos are unknown. We assume that they are close to the analogous values on the Moon [12]. In particular, the work function was taken within the range of 5 to 6 eV and a dependence presented in [24] was used for the quantum yield in the calculations. The maximum quantum yield [24] approximately equal to 0.09±0.003 is reached at an electromagnetic wavelength of about 900 Å, which in turn corresponds to \( E_{ph} \approx 13.7 \) eV. The quantum yield at \( E_{ph} \) higher and lower than 13.7 eV is much lower (by several orders of magnitude). In particular, the \( Y(E_{ph}) \) value at \( E_{ph} \approx 7 \) eV decreases to \( \sim 10^{-6} \), and the quantum yield decreases additionally by one or two orders of magnitude when \( E_{ph} \) approaches the work function.

The shape of spectra of solar radiation corresponds to the shape of spectra near the Moon [12], but the intensity is lower because the solar constant in the orbit of Mars is 592 W/m², which is 43% of the solar constant in the orbit of the Earth. Correspondingly, spectra of solar radiation in the orbit of Mars vary significantly during an 11-year cycle of solar activity—see spectra characterizing different solar activity levels in figure 2. However, despite the variation of the energy emitted by the Sun in the ultraviolet range (primarily, from the point of view of emission of photoelectrons) in the indicated cycle, significant (by orders of magnitude) variations of \( N_0 \) and \( T_e \) values do not occur. Table 1 summarizes the parameters of photoelectrons \( (N_0, T_e) \) calculated with equations (1) to (3) at \( \cos \theta = 1 \) in the near-surface layer of the illuminated part of Phobos or Deimos for various solar activity levels corresponding to an X28 solar flare (column I), solar maximum (column II), and solar minimum (column III) and various values of the work function \( W \) (the first and second pairs of rows for \( N_0 \) and \( T_e \) values with subscripts 1 and 2 correspond to \( W = 6 \) and 5.5 eV, respectively). According to table 1, the variation of \( W \) does not hardly affects \( N_0 \) and \( T_e \) values because the quantum yield [24] is nearly zero when \( E_{ph} \) approaches the work function. The dependence of the parameters \( N_0 \) and \( T_e \) on the solar activity level is also insignificant. The values \( N_0 \) at \( \cos \theta \neq 1 \) are the values of the data presented in table 1 multiplied by \( \cos \theta \). The electron temperature \( T_e \) is independent of \( \cos \theta \).

Figure 3 shows the distribution functions \( f_e(E_e) \equiv \Phi_e(E_e)/N_0 \) that are normalized to unity \( (\int_0^\infty f_e(E_e) dE_e = 1) \) and are calculated for data corresponding to \( W = 6 \) and 5.5 eV and to different solar activity levels. These distribution functions are strongly different from Maxwellian distributions.

|   | I          | II         | III        |
|---|------------|------------|------------|
| \( N_{01}, \text{cm}^{-3} \) | 3.7 × 10¹   | 1.3 × 10¹  | 0.57 × 10¹ |
| \( T_{e1}, \text{eV} \)     | 2.1         | 1.9        | 1.2        |
| \( N_{02}, \text{cm}^{-3} \) | 3.7 × 10¹   | 1.3 × 10¹  | 0.65 × 10¹ |
| \( T_{e2}, \text{eV} \)     | 2.1         | 1.9        | 1.2        |
Figure 2. Flux of solar radiation in the orbit of Mars versus the energy of photons corresponding to the (a) X28 solar flare, (b) solar maximum, and (c) solar minimum.

The dust-particle behavior in the near-surface layer is described by equations characterizing the dynamics and charging of the particles:

\[ m_d \frac{d^2 h}{dt^2} = q_d E(h, \theta) - m_d g_0, \]
(4)

\[ \frac{dq_d}{dt} = I_e(q_d) + I_i(q_d) - I_{ph}(q_d) + I_{e,ph}(q_d), \]
(5)

where \( m_d \) is the mass of a dust particle; \( h \) is the altitude above the surface of Phobos or Deimos; \( q_d \) is the charge of a dust particle; \( g_0 \) is the gravitational acceleration near the surface of the Martian satellite; \( I_e(q_d) \) and \( I_i(q_d) \) are the microscopic currents to a dust particle from electrons and ions of the solar wind, respectively; \( I_{ph}(q_d) \) is the current of photoelectrons from
Figure 3. (Solid lines) Energy distribution functions $f_e$ of photoelectrons near the illuminated parts of the surfaces of Phobos and Deimos corresponding to the (a) X28 solar flare, (b) solar maximum, and (c) solar minimum. The work function of lunar regolith is $W = 6$ eV (■) and $W = 5.5$ eV (▲), and the quantum yield is determined by the dependence from [24]. The dashed lines are the Maxwellian distributions that are calculated for average energies of photoelectrons characterizing the corresponding distributions shown by solid lines and almost coincide at $W = 6$ and 5.5 eV.

$$I_e \approx -\pi a^2 e n_e S \sqrt{\frac{8T_e S}{\pi m_e}} \left(1 + \frac{Z_de^2}{aT_e S}\right),$$

where $I_{e,ph}(q_d)$ is the current of photoelectrons to a dust particle; and $I_{e,ph}(q_d)$ is the current of photoelectrons to a dust particle:
charged surface of Phobos (or Deimos) is the dominance of the electrostatic force over the gravitational force, see equation (4). The condition of the separation of a positively charged dust particle from the positively charged surface of Phobos or Deimos is impossible. For particles smaller than 10 μm in the dusty plasma over Phobos or Deimos, the critical value of the angle \( \theta \) is no more than 76.3°. This limit exists because a dust particle is subjected to oppositely directed electrostatic and gravitational forces, see equation (4). The condition of the separation of a positively charged dust particle from the positively charged surface of Phobos or Deimos is the dominance of the electrostatic force over other factors.

Here, \( a \) is the size of a dust particle, \( Z_d \) is its charge number \( (q_d = Z_de) \), \( e \) is the elementary charge, \( n_{e(i)S} \) is the density of electrons (ions) of the solar wind, \( T_{e(i)S} \) is the temperature of electrons (ions) of the solar wind, \( m_i \) is the mass of an ion, \( u_i \) is the velocity of the solar wind, \( u_{T_i} \) is the thermal velocity of ions of the solar wind, and \( T_{e,ph} \) and \( n_{e,ph} \) are the temperature and density of photoelectrons emitted from the surface of Phobos or Deimos and the surfaces of dust particles.

Expressions (6) to (9) are valid for positively charged dust particles. Expression (8) for the current \( I_{ph} \) does not include a factor containing the characteristics of spectra of radiation, which is possible because the work functions near the surfaces of dust particles and a Mars moon are identical. In this case, this factor can be expressed in terms of \( N_0 \). Expression (7) was derived specially for the case of positively charged dust particles and arbitrary velocities of ion fluxes [25].

Calculations within the set of equations (4) and (5) make it possible, in particular, to determine the charges of dust particles and the electric field over the surfaces of Phobos and Deimos. In these calculations, it is necessary to take into account the following expression for the electric field \( E \) produced by the charged surface of a Martian moon as a function of the altitude \( h \) above this surface:

\[
E(h, \theta) = \frac{2T_{e,ph}}{e} \sqrt{\frac{\cos \theta / 2}{\lambda_D + h \sqrt{\cos \theta / 2}}},
\]

where \( \lambda_D \) is the Debye length of photoelectrons near the surface of the Martian moon.

Expression (12) was obtained by jointly solving the kinetic equation for photoelectrons and the Poisson equation. The dependence of the electric field on the angle \( \theta \) in equation (12) is due to the dependence of the number of photons absorbed by the unit-area surface of the Martian moon on the angle \( \theta \). The distribution of the electric field similar to equation (12) was obtained in [26–28].

For each size of dust particles, there is a critical value of the subsolar angle

\[
\theta \approx \arccos \left[ \frac{1}{4} \left( 1 - \sqrt{2} m_d g_0 \lambda_D e^2 / (aT_e^2) \right) \right]
\]

(exceeding 75.52°) such that the rise of particles over the surface of Phobos or Deimos for smaller values \( \theta \) is impossible. For particles smaller than 10 μm in the dusty plasma over Phobos or Deimos, the critical value of the angle \( \theta \) is no more than 76.3°. This limit exists because a dust particle is subjected to oppositely directed electrostatic and gravitational forces, see equation (4). The condition of the separation of a positively charged dust particle from the positively charged surface of Phobos (or Deimos) is the dominance of the electrostatic force over the gravitational force.
Figure 4. Maximum sizes $a$, charge numbers $Z_d$, and densities $N_d$ of dust particles, as well as electric fields $E$, versus the altitude $h$ over the surface of Phobos for angles $\theta = 77^\circ$ (a), $82^\circ$ (b) and $87^\circ$ (c).

attractive gravitational force. The magnitude of the electrostatic force depends on the charge of the particle $q_d$. In turn, the charge $q_d$ depends significantly on the density of photoelectrons. At angles $\theta$ smaller than the critical value, photoelectrons, which reach a dust particle and, thus, reduce its (positive) charge, prevent the dominance of the electrostatic force over the attractive gravitational force. However, at angles $\theta$ smaller than the critical value, irregularities of the profile of the surface of the Martian satellite can ensure the rise of particles to altitudes of about the characteristic sizes of irregularities owing to electrostatic effects. As a result, the particle can acquire a positive charge sufficient for the dominance of the electrostatic force over the gravitational force and, consequently, a further rise of the particle occurs.
Figure 5. Maximum sizes $a$, charge numbers $Z_d$, and densities $N_d$ of dust particles, as well as electric fields $E$, versus the altitude $h$ over the surface of Deimos for angles $\theta = 77^\circ$ (a), $82^\circ$ (b) and $87^\circ$ (c).

When considering the dusty plasma system near the Moon [7, 9], data on lunar regolith [29] were used to construct the distributions of dust particles with sizes from 20 to 500 $\mu$m on the surface of the Moon. Such experimental data for Phobos and Deimos are absent. For this reason, to determine the density $N_d$ of dust particles, we used the condition that dust particles in the considered situation acquire charges owing primarily to the emission of photoelectrons, i.e.,

$$N_d \approx \frac{(n_{e,ph} - n_{e,ph0})}{Z_d}.$$  \hspace{1cm} (14)

Here, it is taken into account that photoelectrons are emitted not only from the surfaces of dust particles but also from the surface of a Martian moon. The altitude dependence of the density
\[ n_{e,\text{ph}} = N_0 \cos \theta / \left[ 1 + \sqrt{\cos \theta / 2(h/\lambda_D)} \right]^2 \]

characterizes photoelectrons knocked out from the surface of the Martian moon by photons [26–28]).

3. Results of calculations

Within the considered physical-mathematical model, the parameters characterizing the altitude distributions of dust particles over the surfaces of Phobos and Deimos can be obtained numerically taking into account the emission of photoelectrons by dust particles present over these surfaces. The calculations were performed with the following parameters of the solar wind: \( n_{eS} = n_{iS} = 3.7 \times 10^{-3} \text{ cm}^{-3} \), \( T_{eS} = 1.4 \times 10^5 \text{ K} \), \( T_{iS} = 7 \times 10^4 \text{ K} \), and \( u_i = 468 \times 10^5 \text{ cm/s} \). Protons were considered as ions of the solar wind. Data characterizing dust particles and electric fields over the surfaces of Phobos and Deimos under the conditions corresponding to the solar maximum, see figure 2(b), work function of regolith \( W = 5.5 \text{ eV} \), and angles \( \theta = 77^\circ \), \( 82^\circ \), and \( 87^\circ \) are shown in figures 4 and 5, where \( a \) is the maximum size of particles at the altitude \( h \). The charge numbers \( Z_d \) were calculated for \( a \) values indicated in these figures. The characteristic velocities of dust particles at altitudes \( h \sim 1 \text{ m} \) are about 10 cm/s. Calculations with the work function \( W = 6 \text{ eV} \) give similar results because the quantum yield [24] is close to zero when \( E_{\text{ph}} \) approaches the work function.

So, in view of a weak gravitational field, dust particles rising over the surfaces of the Martian satellites are larger than those over the surface of the Moon (\( a \sim 1 \mu \text{m} \) versus \( a \sim 0.1 \mu \text{m} \) [9]). In this case, the role of adhesion, which is a significant process preventing the separation of dust particles from the lunar surface [19, 30], is much smaller on Phobos and Deimos. In fact, the formation of the dusty plasmas over the surfaces of Phobos and Deimos can be attributed to photoelectric and electrostatic processes described in this work. The role of meteoroids in the formation of the dusty plasmas in the near-surface layers over Phobos and Deimos is also significantly smaller than that in the case of the Moon [19]. At the same time, at large distances from a Martian satellite (significantly larger than its linear size of the order of 10 km), the effects of meteoroids are responsible for the formation of a dust halo consisting of particles with sizes of about 10 \( \mu \text{m} \) and density of \( N_d \sim 10^3 \text{ km}^{-3} \) [31] (which is much lower than the density of dust particles \( N_d \sim 10^{-3} \times 10^{-1} \text{ cm}^{-3} \) near the surfaces of the Martian satellites associated with photoelectric and electrostatic processes).

4. Conclusions

Thus, photoelectric and electrostatic processes in the near-surface layers over the illuminated parts of Phobos and Deimos result in the formation of the dusty plasmas for subsolar angles \( \theta \) exceeding about 76\(^\circ\). Within the physical-mathematical model for the self-consistent description of densities of photoelectrons and dust particles over the surfaces of the illuminated parts of Phobos and Deimos, we obtained the distribution functions of photoelectrons near the surfaces of the Martian moons, as well as the altitude dependences of the density of dust particles, their charges and sizes, and electric fields. It has been shown that dust particles with the characteristic sizes of about 1 \( \mu \text{m} \) rise over the surfaces of Phobos and Deimos and electric fields with a strength of about 1 V/m exist near their surfaces. The typical densities of dust particles and photoelectrons are \( \sim 10^{-3} \) to \( 10^{-1} \text{ cm}^{-3} \) and \( \sim 10 \text{ cm}^{-3} \), respectively.

To summarize, the dusty plasma systems in the near-surface layers over Phobos and Deimos have been described within a self-consistent model. This model cannot be used to describe nonstationary processes occurring, e.g., in the terminator region on Phobos or Deimos. Consequently, the model should be further developed in future. It is also necessary to have more definite data on the parameters of the dusty plasma systems near Phobos and Deimos, which we expect will be obtained in future space missions.
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