Waves and instabilities in dusty plasmas at Phobos and Deimos

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One of important topics in space research is devoted to analyzing the properties and manifestations of dusty plasma near the surfaces of the Martian satellites, Phobos and Deimos [1–4]. At present several Mars mission are functioning on the Martian orbits such as MarsExpress, ExoMars Trace Gas Orbiter, Mars Reconnaissance Orbiter, Mars Odissey, and others. During the prepared mission Bumerang (Fobos-Grunt-2), it is planned to find dust grains on the Martian orbits and determine the main parameters of dust grains (momentum, mass, velocity, and charge). Interest in studying Martian satellites is caused, in particular, by the fact that they are more accessible for manned flights than Mars itself due to their weak gravitation. The gravitational accelerations on Phobos and Deimos in 10^4 times lower that on the Earth; hence, the landing of a spacecraft on them resembles docking with another spacecraft than landing on a planet. According to observations of Viking [5, 6] and MarsExpress [1] spacecrafts, the surfaces of Phobos and Deimos are covered with a dust consisting of small regolith grains formed as a result of micrometeoroid bombardment. The weak gravitation enhances the role of dust on Phobos and Deimos, because even a small perturbation can lead to the formation of massive dust clouds over their surfaces.

Like to the situation on the Moon, Phobos and Deimos have no atmosphere. Therefore, the methods by which dusty plasma near the Martian satellites is described [2–4] are similar to those applied for the Moon [7–14]). Illuminated patrts of surfaces of Phobos and Deimos are charged under the action of solar radiation and solar wind plasma. During the interaction with the solar radiation, the surfaces of the Martian satellites emit electrons due to the photoelectric effect. Dust grains levitating near surfaces of Phobos and Deimos are also produced photoelectrons during the interaction of solar radiation. Dust grains in the near-surface layers of the Martian satellites absorb electrons and ions of the solar wind and photoelectrons from the Phobos or Deimos surfaces. All these processes lead to the charging of dust grains and their interaction with the charged surfaces of the Martian satellites, as well as to the lifting and motion of dust.

Lifting of dust grains over the Phobos and Deimos surfaces are significantly larger (a ~ 1 μm) than those lifting over the lunar surface (a ~ 0.1 μm [8]) due to weak gravitation of Martian satellites. In this case, the role of adhesion, which is an important process preventing the detachment of dust grains from the lunar surface [15, 16], considerably diminishes on Phobos and Deimos. Photoelectric and electrostatic processes play important role in the formation of the dusty plasma over the Phobos and Deimos surfaces. The role of meteoroids in the formation of dusty plasma in the near-surface layers over Phobos and Deimos also turns out to be significantly lesser than on the Moon due to weak gravitation [15]. At the same time, at long distances from Phobos and Deimos (significantly exceeding their dimensions of ~10 km), it is the effects of meteoroids that lead to the formation of a dust halo consisting of grains with sizes of about 10 μm and a number density substantially lower than the dust grain density arising near the surfaces of Phobos and Deimos due to the photoelectric and electrostatic processes. In contrast to the Moon [13], the role of the planetary magnetosphere in the development of wave processes in the dusty plasma over the Phobos and Deimos surfaces is negligible.

Typical palasma parameters for Martian satellites: $n_{eS} = n_{iS} = 3.7$ cm^{-3}, $T_{eS} = 1.4 \times 10^5$ K, $T_{iS} = 7 \times 10^4$ K, and $u_i = 468 \times 10^5$ cm/s, work function of regolith of $W = 5.5$ eV. Here, $n_{e(i)}$ is the electron (ion) density, $T_{e(i)}$ is the electron (ion) temperature, the subscript S refers to the solar wind parameters, and u_i is the solar wind velocity, charge number of a dust grain Z_d ($q_d = Z_d e$, where e is the elementary charge).

By analogy with the situation near the Moon [9, 10], the photoelectron distributions functions near the surfaces of the Martian satellites can be represented as a superposition of two distribution functions characterized by different electron temperatures, T_{e1} ~ 0.1 eV (electrons knocked out by photons with energies close to the work function of regolith) and T_{e2} ~ 1 eV (photoelectrons associated with the H_α line in the solar radiation spectrum). We denote the densities of these photoelectrons as n_{01} and n_{02}, respectively. The photoelectrons distribution functions are isotropic in velocity space [2–4]. Therefore, one should not expect the development of any instability only due to the presence of these two photoelectron species. However, in the daytime, the Phobos and Deimos surfaces are subjected to the action of the solar wind. The solar wind motion relative to the photoelectrons and charged dust grains leads to the excitation of waves in the near-surface plasma over the Martian satellites.

For high-frequency waves when the relations $kv_{TiS} << kv_{Te1} << \omega << kv_{Te2} << kv_{TeS}$ are satisfied. Here, $\mathbf{k}$ is the wave vector, $k = |\mathbf{k}|$, w is the wave frequency, $v_{Te(i)S}$ is the thermal velocity of solar wind electrons (ions), and $v_{Te1(2)}$ is the thermal velocity of photoelectrons knocked out by photons with energies close to the work function of regolith (photoelectrons associated with the H_α line in the solar radiation spectrum). In this case, the linear dispersion relation has the form $1 - \frac{\omega_{pe1}^2}{\omega^2} + \frac{1}{k^2\lambda_{De2}^2} - \frac{\omega_{piS}^2}{(\omega - ku_S)^2} = 0$, where $\omega_{pe(i)}$ is the electron (ion) plasma frequency, λ_{De} is the electron Debye length, and subscripts 1 and 2 characterize photoelectrons knocked out by photons with energies close to the work function of regolith and associated with the H_α line in the solar radiation spectrum, respectively. The condition for the development of instability is the existence of at least two complex roots of this dispersion relationwhich is possible at $ku_S < \omega_{pe1}$. The unstable solution of this equation is $\omega = ku_S\left(1 + i\omega_{piS}/\sqrt{\omega_{pe1}^2 - k^2u_S^2}\right)$. The wave vector and growth rate g corresponding to the fastest instability are approximately equal to $k_{\max} \approx \omega_{pe1}/u_S$ and $\gamma_{\max} \approx \omega_{pe1}v_{Te2}/u_S$. Therefore, the relative motion of the solar wind and photoelectrons leads to the excitation of high-frequency waves with frequencies in the range of Langmuir and electromagnetic waves in the near-surface plasma of the Martian satellites.

The waves in the dusty plasma near the Phobos and Deimos surfaces can also exist if $kv_{Td} << \omega << kv_{TiS}$. In this case (with allowance for the characteristic dusty plasma parameters presented in the previous section), the linear dispersion relation takes the form $1 + \left(1/k^2\lambda_{De1}^2\right) - \left(\omega_{pd}^2/\omega^2\right) = 0$ and has solutions corresponding to dust acoustic waves [17]. Here, v_{Td} is the thermal velocity of dust grains and ω_{pd} is the dust plasma frequency. Dispersion relation has no unstable solutions. By analogy with the situation near the Moon [10–12], dust acoustic waves can be excited, e.g., in the terminator regions of Phobos and Deimos. The propagation velocities of the terminators exceed the speed of dust sound. Therefore, instability resulting in the excitation of dust acoustic waves can develop.

Solitons are an important kind of nonlinear waves in plasma mediaFor dusty plasmas, a typical kind of oscillations is dusty plasma waves. We consider the properties of dust acoustic solitons, which can exist in the near-surface plasmas of Phobos and Deimos using standart Sagdeev approach, as functions of heights above the satellite surface. In our case, dust acoustic solitons induce a positive electrostatic potential, which plays the role of a potential well for electrons. Soliton amplitudes can reach rather large values ($\varphi > T_e/e = 1.9$ V). One should bear in mind that, in general, taking into account the trapped electrons (and, accordingly, the use of the Gurevich formula instead of the Boltzmann distribution for electrons) expands the domain of possible Mach numbers toward their larger values and somewhat increases the possible soliton amplitude compared to the case where the electrons obey a Boltzmann distribution.

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References

1. A. Zakharov, M. Horányi, P. Lee, O. Witasse, and F. Cipriani, Planet. Space Sci. **102**, 171 (2014).
2. S. I. Popel, A. P. Golub', A. V. Zakharov, and L. M. Zelenyi, JETP Lett. **106**, 485 (2017).
3. S. I. Popel, A. P. Golub', and L. M. Zelenyi, Plasma Phys. Rep. **44**, 723 (2018).
4. S. I. Popel, A. P. Golub', A. V. Zakharov, and L. M. Zelenyi, J. Phys. Conf. Ser. **1147**, 012110 (2019).
5. P. Thomas, Icarus **40**, 223 (1979).
6. P. Thomas and J. Veverka, Icarus **42**, 234 (1980).
7. T. J. Stubbs, R. R. Vondrak, and W. M. Farrell, Adv. Space Res. **37**, 59 (2006).
8. S. I. Popel, S. I. Kopnin, A. P. Golub', G. G. Dol'nikov, A. V. Zakharov, L. M. Zelenyi, and Yu. N. Izvekova, Solar System Research **47**, 419 (2013).
9. S. I. Popel, A. P. Golub', Yu. N. Izvekova, V. V. Afonin, G. G. Dol'nikov, A. V. Zakharov, L. M. Zelenyi, E. A. Lisin, and O. F. Petrov, JETP Lett. **99**, 115 (2014).
10. T. I. Morozova, S. I. Kopnin, and S. I. Popel, Plasma Phys. Rep. **41**, 799 (2015).
11. S. I. Popel, L. M. Zelenyi, and B. Atamaniuk, Phys. Plasmas **22**, 123701 (2015).
12. S. I. Popel, L. M. Zelenyi, and B. Atamanyuk, Plasma Phys. Rep. **42**, 543 (2016).
13. S. I. Popel and T. I. Morozova, Plasma Phys. Rep. **43**, 566 (2017).
14. Yu. N. Izvekova, T. I. Morozova, and S. I. Popel, IEEE Trans. Plasma Sci. **46**, 731 (2018).
15. S. I. Popel, A. P. Golub', E. A. Lisin, Yu. N. Izvekova, B. Atamanyuk, G. G. Dol'nikov, A. V. Zakharov, and L. M. Zelenyi, JETP Lett. **103**, 563 (2016).
16. C. M. Hartzell and D. J. Scheeres, Planet. Space Sci. **59**, 1758 (2011).
17. N. N. Rao, P. K. Shukla, and M. Y. Yu, Planet. Space Sci. **38**, 543 (1990).