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ПЫЛЕВАЯ ПЛАЗМА В СОЛНЕЧНОЙ СИСТЕМЕ

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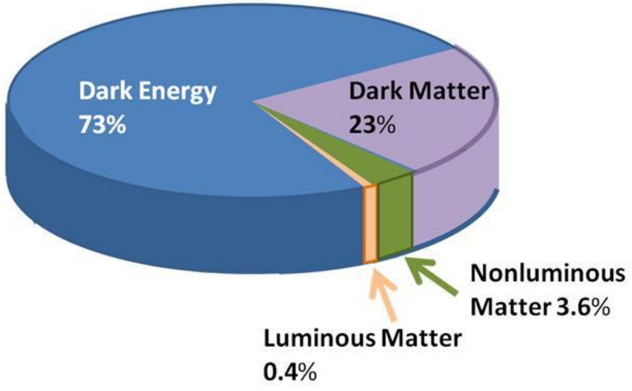
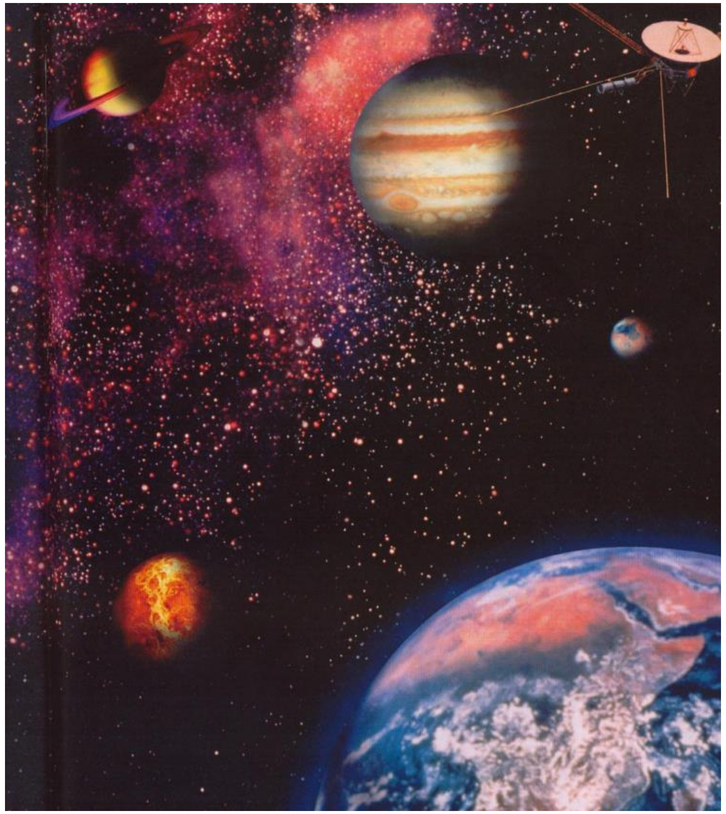
Dusty Plasmas in our Solar System

- Dusty plasma systems are the solar wind, a zodiac dust cloud, ionospheres and magnetospheres of planets, planetary rings, comets, etc. Only the inner heliosphere is an exception to this rule. In most situations, the interaction of solar radiation with fine particles plays a significant role. In Earth and planetary sciences, nano- and micro-sized components act as the main elements of their structure, and therefore, studies of nano- and micro-sized objects can lead to an expansion of our knowledge about the fundamental processes of geology and planetary formation. For example, protoplanetary dust has sizes from 10 nm to 150 nm. It refers to chondrites of class C1. If one differentiates carbonaceous chondrites, then the minerals that are part of the Earth's mantle can be obtained. It can be concluded that at least the planets of the terrestrial group of our Solar system originated from nanoscale particles, the composition of which corresponds to carbonaceous chondrites.





Physics of Plasmas ARTICLE scitation.org/journal/php

Dust dynamics in the lunar dusty plasmas: Effects of magnetic fields and dust charge variations

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DUSTY PLASMA

Dusty Plasma in the Solar System: Celestial Bodies without Atmosphere

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PLASMA, HYDRO- AND GAS DYNAMICS

Nonstationary Processes in the Formation of a Dusty Plasma near the Surface of Phobos

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PLASMA, HYDRO- AND GAS DYNAMICS

On Anomalous Dissipation in the Plasma of the Dusty Lunar Exosphere

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Dusty plasmas above the sunlit surface of Mercury

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www.nonlin-processes-geophys.net/13/223/2006/

Nonlinear Processes in Geophysics

Charged dust and shock phenomena in the Solar System

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Specific features of dusty plasmas

- The main features that distinguish the dusty plasma from ordinary (not containing charged dust particles) plasma is the possibility of self-organization, leading to the formation of macroscopic structures such as a dusty plasma crystal, dusty plasma clouds, droplets, etc.
- The occurrence of anomalous dissipation associated with dust particle charging leads to new physical phenomena, effects and mechanisms. The anomalous dissipation is responsible for the formation of a new kind of shock waves, which are important
- in the physics of comets, the Earth's atmosphere during active experiments, in the description of the primary Earth, etc.,
- in describing the modulational instability, in the consideration of weakly damped solitons, transformation of a soliton into a shock wave, etc.

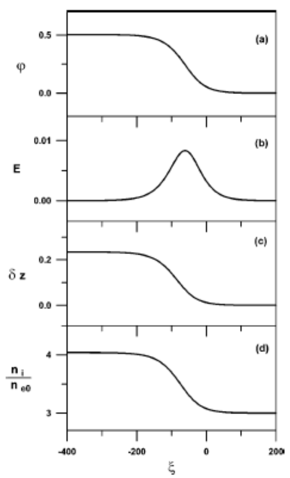


FIG. 1. The profiles of $\varphi(\xi)$ (a), $E(\xi)=-d_\xi\varphi(\xi)$ (b), $\delta z(\xi)$ (c), and $n_i(\xi)/n_{e0}$ (d) for the steady-state shock wave structure. The parameters are $Z_{d0}d=2$, $T_e/T_i=10$, $a/\lambda_D=0.01$, and $M=1.5$.

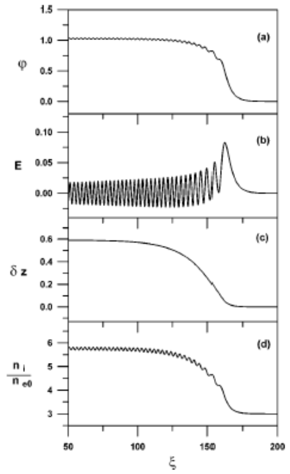
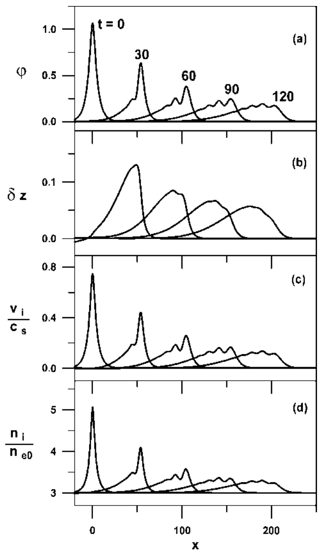
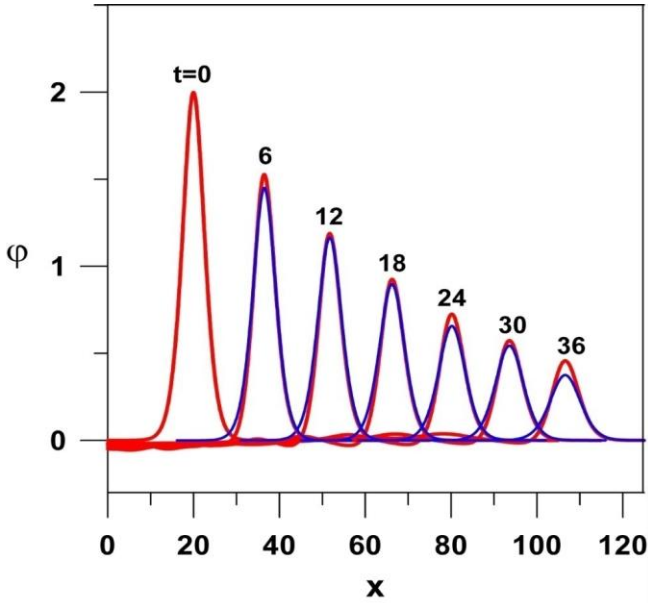


FIG. 2. The profiles of $\varphi(\xi)$ (a), $E(\xi)=-d_\xi\varphi(\xi)$ (b), $\delta z(\xi)$ (c), and $n_i(\xi)/n_{e0}$ (d) for the steady-state shock wave structure. The parameters are $Z_{d0}d=2$, $T_e/T_i=10$, $a/\lambda_D=0.01$, and $M=1.68$.





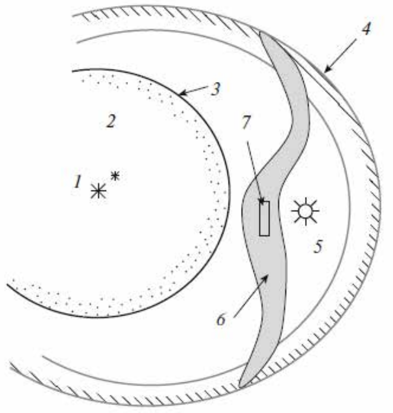
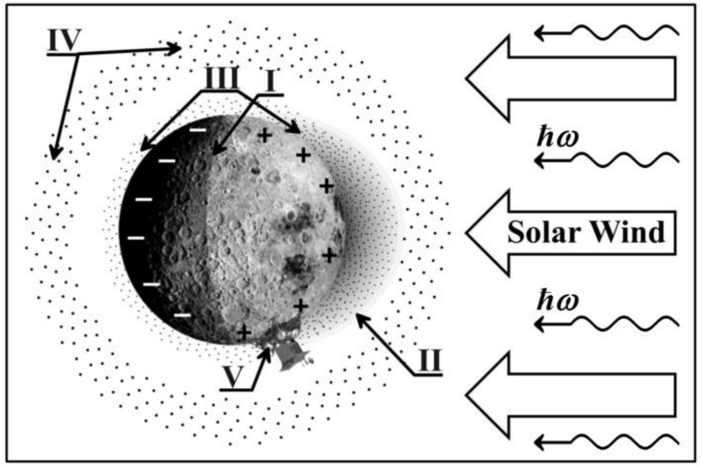
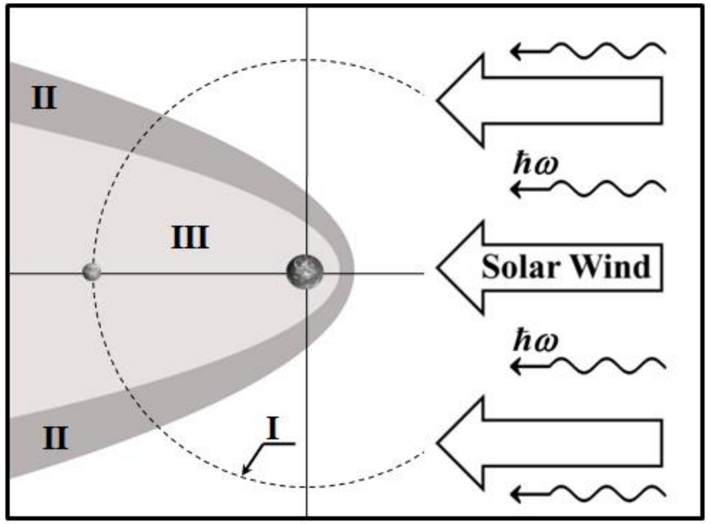


Fig. 11. The scheme of the interstellar medium. Here, 1 is the center of the Scorpius–Centaurus association, 2 is Loop I, 3 is Loop I envelope, 4 is the Local Cavern envelope, 5 are the Sun and the Solar system, 6 is Local Cloud, and 7 is the Sancini–van Woerden Fibre.

Dusty Plasma System in the Vicinity of the Moon

Dust over the lunar surface is a component of a dusty plasma system. The lunar surface is charged under the influence of the solar electromagnetic radiation, the solar wind plasma, and the plasma of the terrestrial magnetosphere tail. Upon interacting with the solar radiation, the lunar surface emits photoelectrons due to the photoelectric effect. This leads to the emergence of a layer of photoelectrons above the surface. The dust particles located on the lunar surface or over the Moon absorb photoelectrons, photons of the solar radiation, electrons and ions of the solar wind, and (if the Moon is located in the terrestrial magnetosphere tail) electrons and ions of the magnetosphere plasma. All these processes promote charging of the dust particles, their interaction with the charged lunar surface, and the dust levitation and motion.





Charged Dust (I)

The behaviour of dust particles in the near-surface layer is described by the following equations that cover their dynamics and charging:

$$m_d \frac{d^2\mathbf{r}_d}{dt^2} = q_d\mathbf{E} + \frac{q_d}{c}\mathbf{v}_d \times \mathbf{B} + m_d\mathbf{g}_0$$

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

where *h* is the height above the lunar surface, m_d and q_d are the dust particle mass and charge, g_M is the free fall acceleration at the surface of the Moon, $I_e(q_d)$ and $I_i(q_d)$ are the microscopic currents of the solar wind electrons and ions to the dust particle, $I_{ph}(q_d)$ is the photoelectron current (induced by the interaction of dust particles with the solar radiation) of electrons from the dust particle, and $I_{e,ph}(q_d)$ is the current of photoelectrons to the dust particle:

$$I_e \approx -\pi a^2 e n_{eS} \sqrt{\frac{8T_{eS}}{\pi m_e}} \left(1 + \frac{Z_d e^2}{a T_{eS}}\right),$$

(microscopic current of the solar wind electrons to the dust particle)

Charged Dust (II)

$$I_i \approx \pi a^2 e n_{iS} \sqrt{\frac{T_{iS}}{2\pi m_i}} \frac{u_{Ti}}{u_i} \left\{ \frac{u_i + u_0}{u_{Ti}} \exp\left(-\frac{(u_i - u_0)^2}{2u_{Ti}^2} \right) + \frac{u_i - u_0}{u_{Ti}} \exp\left(-\frac{(u_i + u_0)^2}{2u_{Ti}^2} \right) \right\} + \pi a^2 e n_{iS} \sqrt{\frac{T_{iS}}{4m_i}} \frac{u_{Ti}}{u_i} \times \left\{ \operatorname{erf}\left(\frac{u_i + u_0}{\sqrt{2} u_{Ti}} \right) + \operatorname{erf}\left(\frac{u_i - u_0}{\sqrt{2} u_{Ti}} \right) \right\} \left(1 + \frac{2Z_d e^2}{a T_{iS}} + \frac{u_i^2}{u_{Ti}^2} \right),$$

(microscopic current of the solar wind ions to the dust particle)

$$I_{ph} \approx -\pi a^2 e N_0 \sqrt{\frac{T_{e,ph}}{2\pi m_e}} \left(1 + \frac{Z_d e^2}{a T_{e,ph}} \right) \exp\left(-\frac{Z_d e^2}{a T_{e,ph}} \right),$$

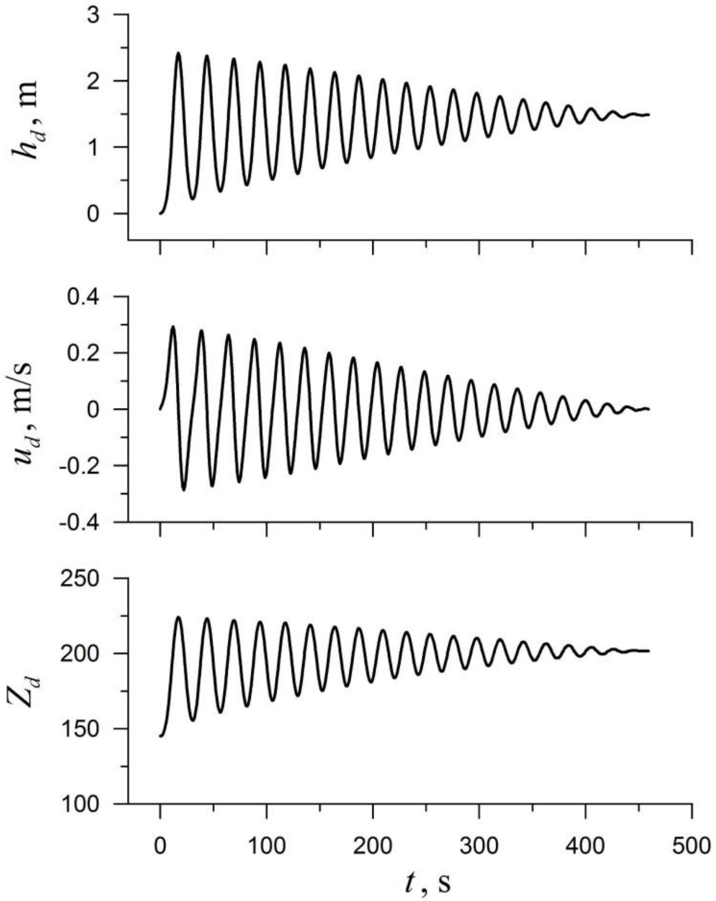
(the photoelectron current (induced by the interaction of dust particles with the solar radiation) of electrons FROM the dust particle)

$$I_{e,ph} \approx -\pi a^2 e n_{e,ph} \sqrt{\frac{8T_{e,ph}}{\pi m_e}} \left(1 + \frac{Z_d e^2}{a T_{e,ph}} \right).$$

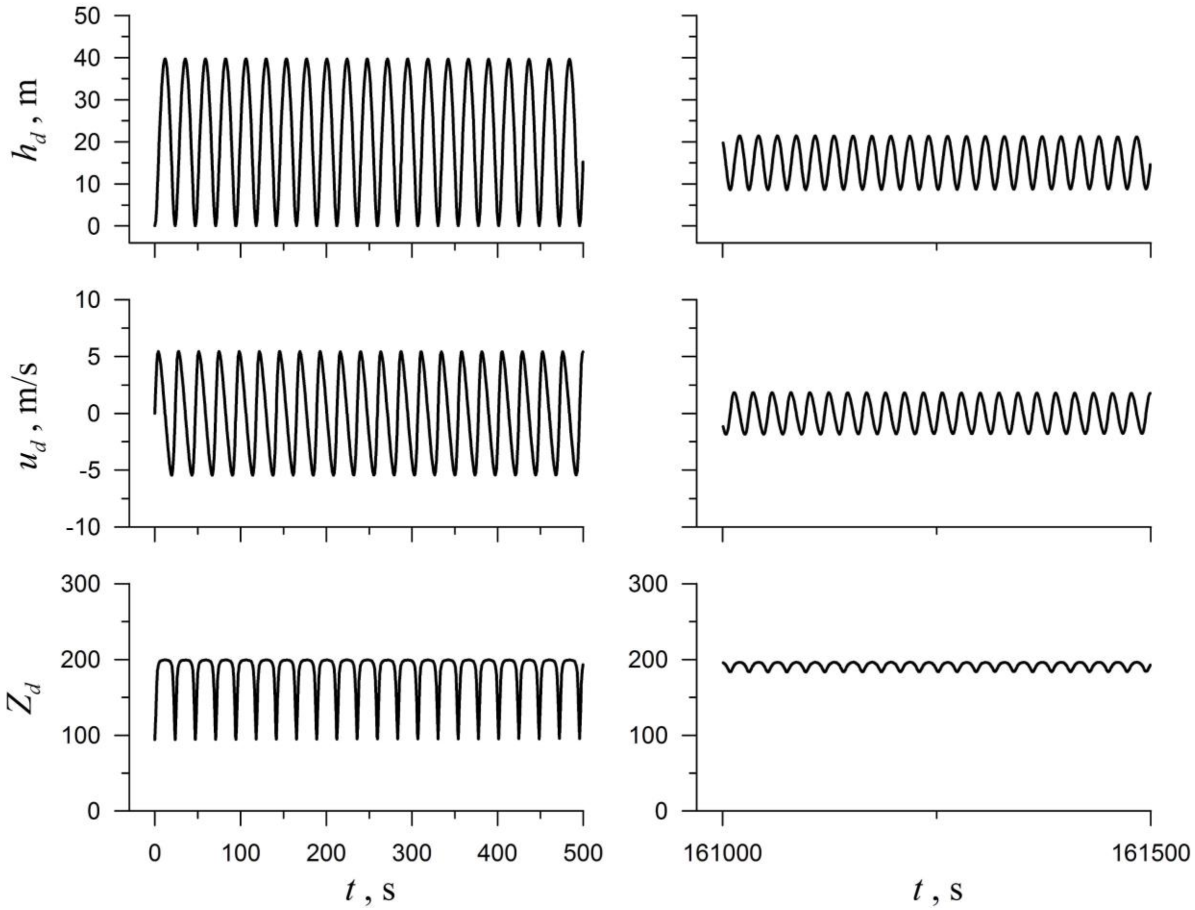
(the current of photoelectrons TO the dust particle)

Relations for $I_e(q_d)$ and $I_i(q_d)$ hold true in the case of positive dust particle charges. Relation for $I_{ph}(q_d)$ that describes the photoelectron current of electrons FROM the dust particle does not include a factor that characterized the radiation spectra. This becomes possible when the dust particle surfaces and the lunar surface have equal work function values. In this case the mentioned factor is expressed in terms of N_0. Relation for $I_{e,ph}(q_d)$ was derived specially for positive dust particle charges and arbitrary velocities of ion fluxes. The currents $I_e(q_d)$, $I_i(q_d)$, $I_{ph}(q_d)$, and $I_{e,ph}(q_d)$ correspond to the **orbit-limited probe model** which is used here for the description of dusty plasmas at the Moon. It assumes the spherically symmetric electric field originating from the dust surface charge, the perturbation by the electric field in the sheath being small. We do not take into account mutual grain-grain interactions.

Anomalous dissipation in a plasma of the dusty exosphere of the Moon (I)



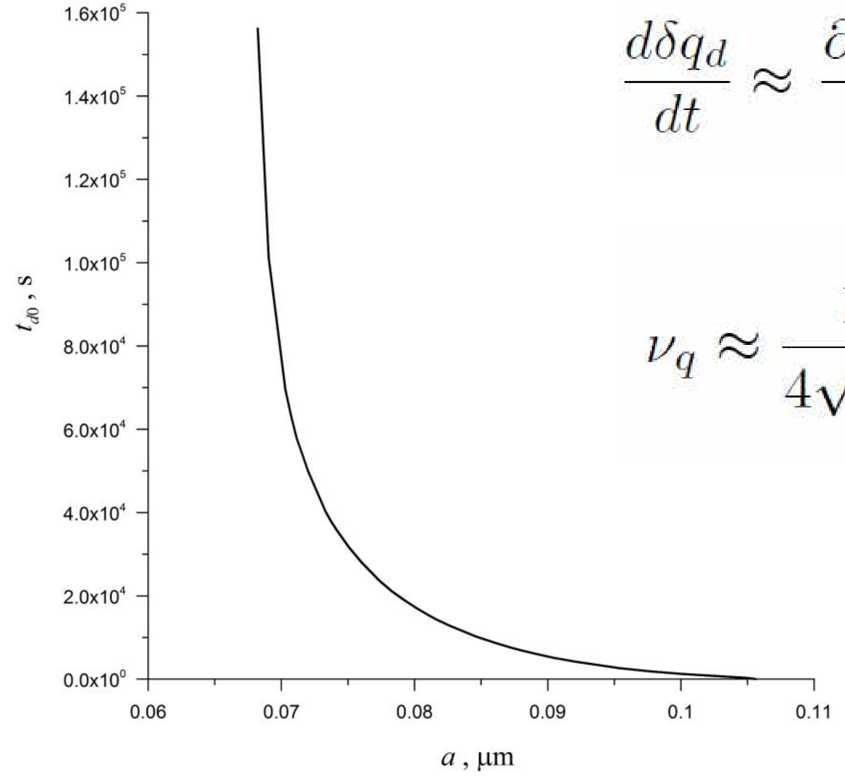
a = 105 nm, θ = 87°



a = 68 nm, θ = 87°

S. I. Popel, A. P. Golub', A. I. Kassem, L. M. Zelenyi // Phys. Plasmas 29, 013701 (2022)

Anomalous dissipation in a plasma of the dusty exosphere of the Moon (II)



$$\frac{d\delta q_d}{dt} \approx \left.\frac{\partial(I_e(q_d) + I_i(q_d) - I_{ph}(q_d) + I_{e,ph}(q_d))}{\partial q_d}\right|_{q_d=q_{d0}} \delta q_d \equiv -\nu_q \delta q_d$$

$$\nu_q \approx \frac{1}{4\sqrt{2\pi}} \frac{a v_{Te,ph}}{\lambda_D^2} \left(1 + \frac{Z_{d0}e^2}{aT_{e,ph}}\right) \exp\left(-\frac{Z_{d0}e^2}{aT_{e,ph}}\right) + \frac{1}{\sqrt{2\pi}} \frac{a v_{TeS}}{\lambda_{DeS}^2}$$

$$\frac{d^2\delta h}{dt^2} + \nu_q(a)\frac{d\delta h}{dt} + \omega_0^2 \delta h = 0$$

$$\omega_0^2 = \frac{Z_{d0} T_{e,ph} \cos\theta}{m_d(\lambda_D + h_0\sqrt{\cos\theta/2})^2}$$

$$\ln\left(\frac{h_{d,\max} - h_{d0}}{h^* - h_{d0}}\right) = 1$$

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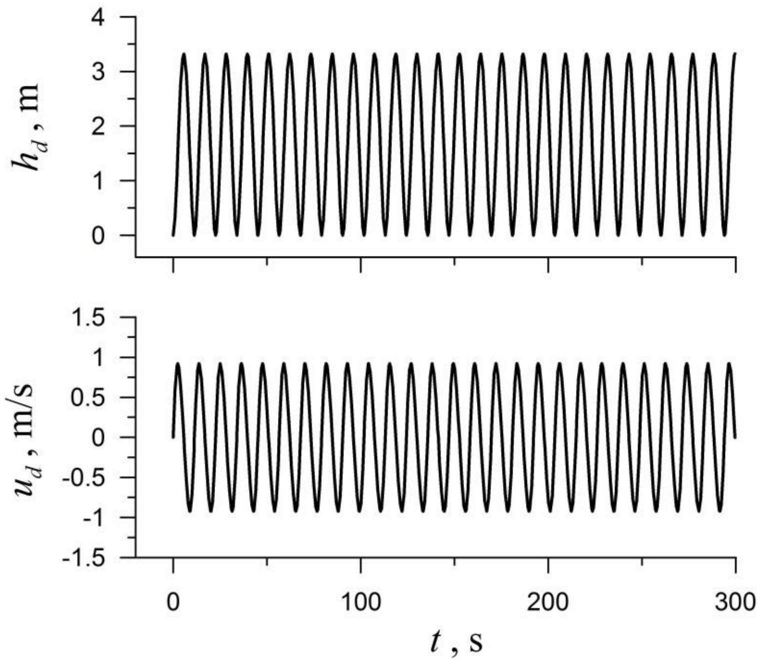
Anomalous dissipation in a plasma of the dusty exosphere of the Moon (III)



a = 105 nm, θ = 87°, but the charge of a dust particle is constant.

- Discussions are being held about the possibility of using the approximation of levitating dust particles to describe the circumlunar dusty plasma, i.e. particles for which it can be assumed that there is a balance between the electrostatic and gravitational forces acting on the particle, or the manifestations of dynamic effects (for example, oscillations) are significant. The condition, under which dust particles over the Moon can be considered levitating, is

$$2/\nu_q(a) \ll T_M$$

$T_M \sim 10^6$ с is a half of the synodic month, i.e. about 14 Earth days and 18 hours.

S. I. Popel, A. P. Golub' // JETP Letters 115, № 10, 596-601 (2022).

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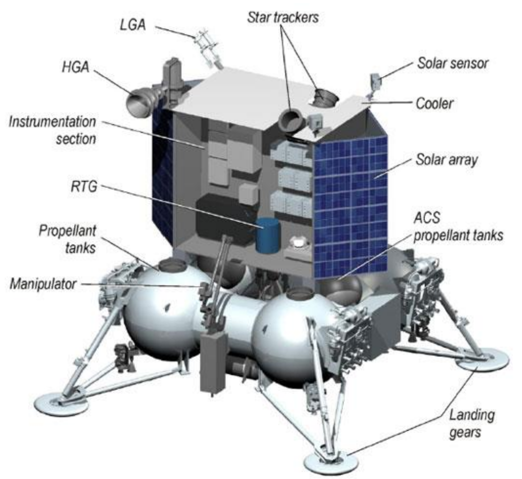
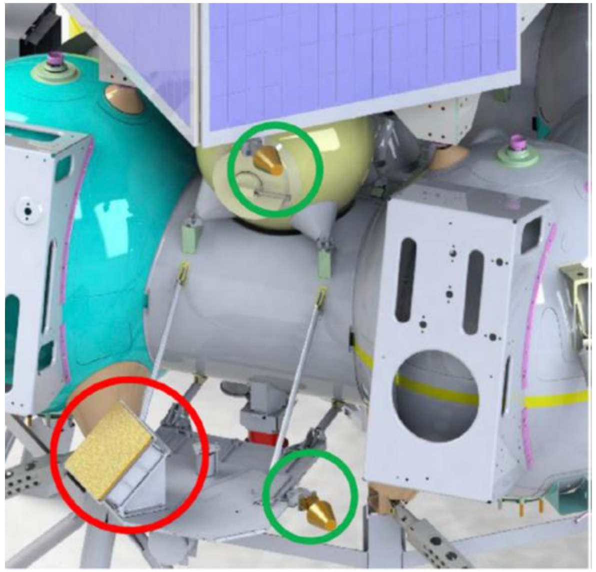


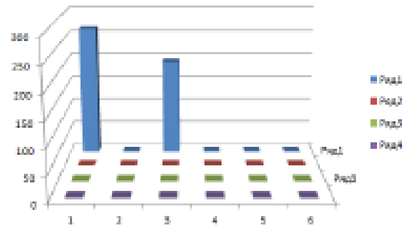
За период с 11.08.2023 2:11 (пт) по 19.08.2023 14:57 (сб) время мск. ПмЛ отработал 89 мин. 31 с.
(Данные второго 40-минутного включения ПмЛ с аппарата переданы в критично урезанном объеме):

Дата	Время работы ПмЛ	Длительность	Этап ЛИ
13.08 (вс)	09:32:14 – 09:33:13	59 с	Тестирование ПмЛ на траектории перелета к Луне
13.08 (вс)	12:23:15 – 12:24:14	59 с	Тестирование ПмЛ на траектории перелета к Луне
17.08 (чт)	12:46:20 – 13:27:52	41 мин. 32 с	Измерения на круговой окололунной орбите КА с высотой 100 км



<u>Перелёт</u> (проверка работоспособности): 3 минуты 22 секунды

<u>Окололунная орбита 100 х 100 км</u> получено 328 кадров телеметрии, утеряно 37 кадров телеметрии, 35 из них – при последнем приёме данных 19 авг.
После обработки измерений датчиков пыли идентифицировано 4 события 17 авг. 2023



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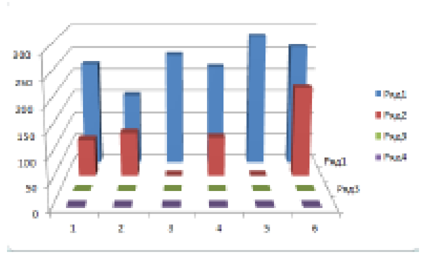
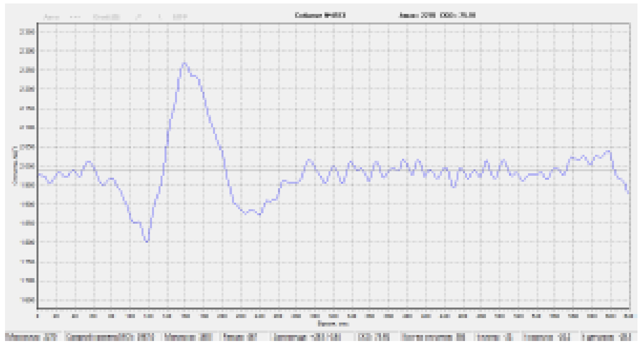


17 авг. 12:59:23 мск



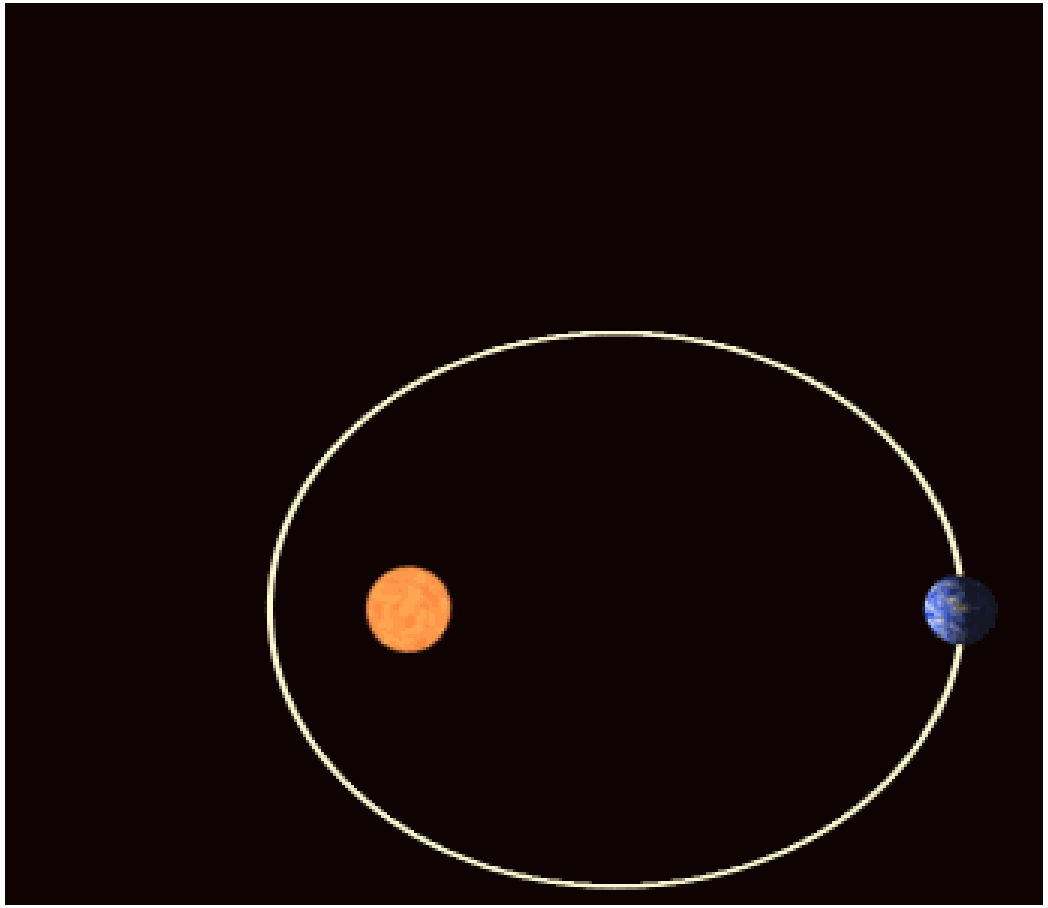
Вторая диаграмма и кадр полученного сигнала - возможный удар микрочастицы по корпусу прибора с минимально возможным импульсом – 1,3 × 10^{-9} Н·с, что может соответствовать соударению с частицей массой ~2,2×10^{-14} кг из метеорного потока Персеид

The Moon - Conclusions

- The distinguishing characteristic of the dust particle motion trajectory in dusty plasma above the lunar surface consists in the presence of oscillations that are damped due to variation of charges of dust particles, which is consistent with the concept of anomalous dissipation in dusty plasma. The processes causing changes in charge of the dust particles are too fast relative to the duration of the lunar day. Therefore, the oscillations have enough time to be damped for most (~83%) of the dust particles above the lunar surface illuminated by the Sun, and these dust particles can be considered as “levitating”. Only very small particles do not make a transition to the levitation regime during the lunar day, and the effects related to dusty plasma system being nonstationary should be taken into account when studying these particles.

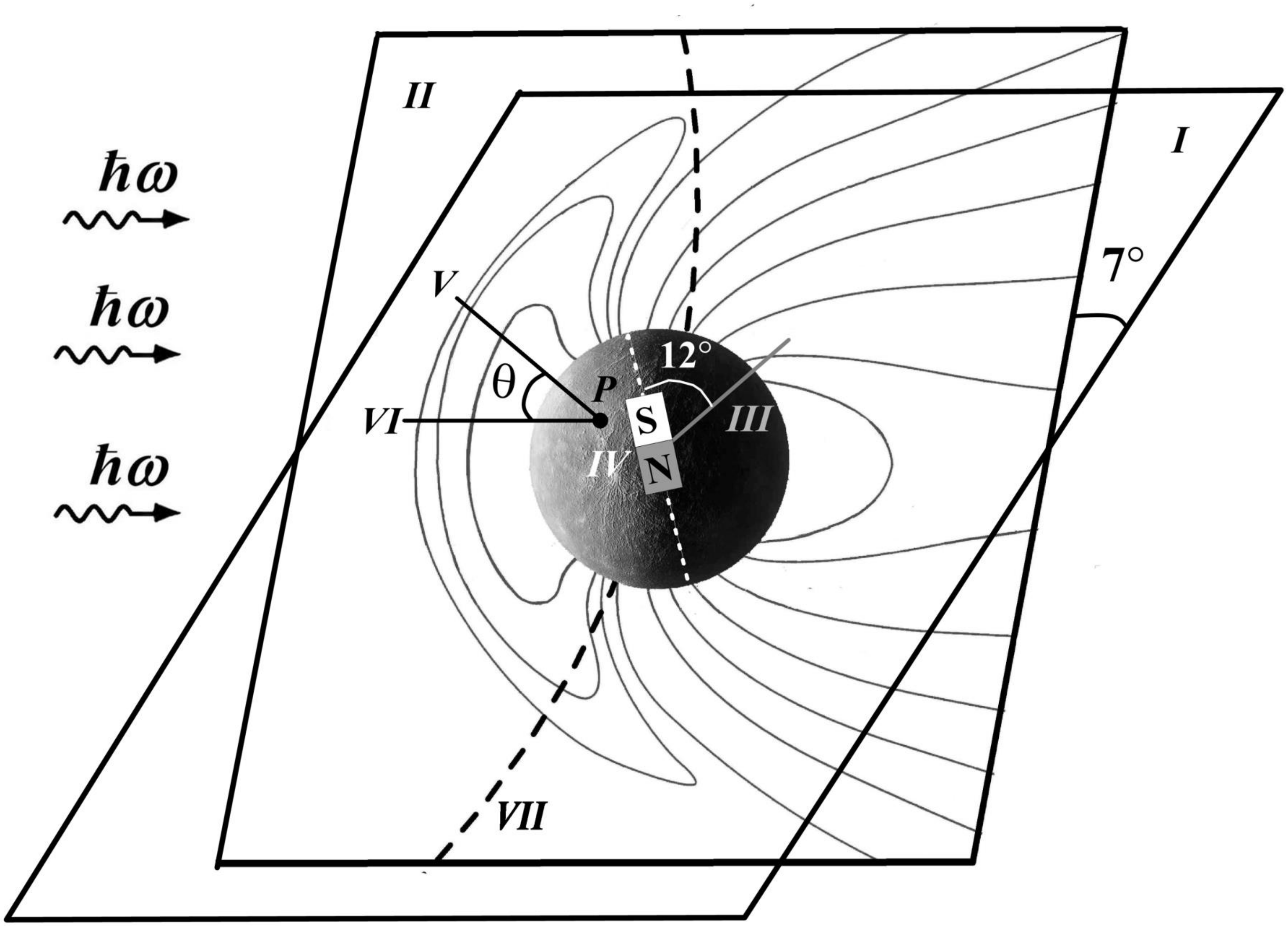
Specific Features of Mercury (I)

- Mercury is the innermost planet, the terrestrial planet closest to the Sun. It is very difficult to observe from the Earth because it can be viewed in visible light only just before sunrise or just before sunset, low above the horizon.
- Mercury’s orbital eccentricity is the largest of all known planets in the Solar System: at perihelion, Mercury's distance from the Sun is only about two-thirds (or 66%) of its distance at aphelion.
- Gravity at Mercury is 3.7 m/s^2 = $0.378g_E$ = $2.28g_{Moon}$.
- Mercury’s magnetic field is about 1.1% as strong as Earth’s (~300 nT=0.003 G).



The eccentricity of the orbit and the precession rate of the orbit are exaggerated for visualization. Mercury orbit has the largest eccentricity among the planets of the Solar System.

Specific Features of Mercury (II)

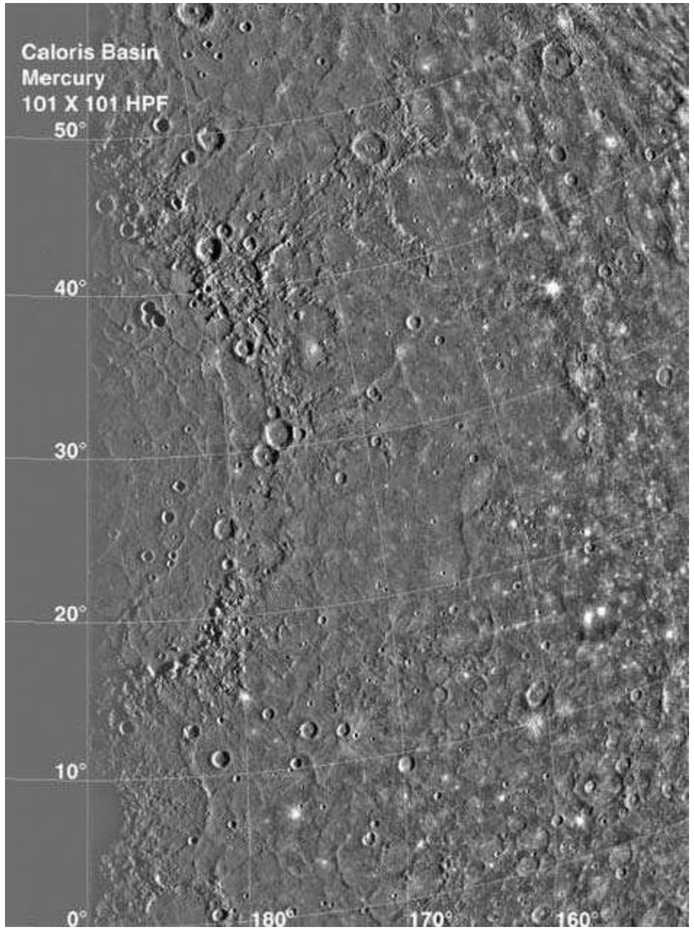


Schematic drawing showing the inclination of Mercury's orbit with respect to the plane of the ecliptic, an angle between the magnetic dipole of Mercury and the normal of its orbital plane, and the subsolar angle θ. Figure presents the plane of the ecliptic (I), the plane of Mercury's orbit (II), the normal of Mercury's orbital plane (III), the magnetic dipole of Mercury (IV) with its north (N) and south (S) magnetic poles, the local normal to the surface of Mercury (V) at the observation point P, the direction (VI) from the point of observation to the Sun, Mercury's orbit (VII). Photons of solar radiation ($\hbar\omega$) and the magnetosphere of Mercury are schematically marked.

Dusty Plasmas above the surface of Mercury

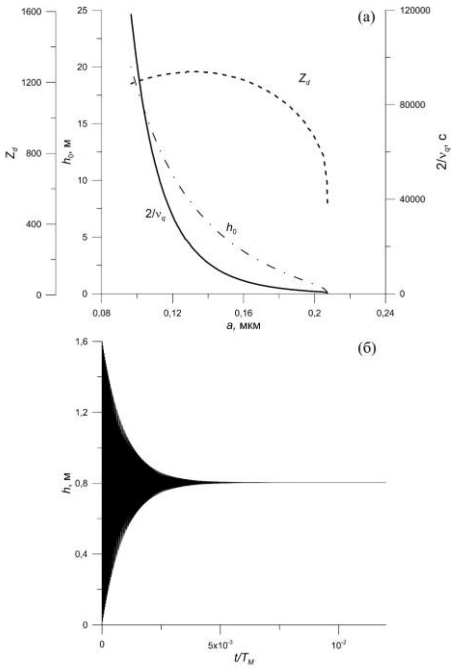
Dust over the surface of Mercury is a component of a dusty plasma system. The illuminated surface of Mercury becomes charged as a result of the action of the solar electromagnetic radiation and solar wind plasma. The surface of Mercury emits electrons upon interaction with the solar wind due to the photoelectric effect, which leads to the formation of a layer of photoelectrons above the surface. Photoelectrons are also emitted from the dust particles soaring above the surface of Mercury due to the interaction of the latter with the electromagnetic radiation of the Sun. Dust particles on the surface of Mercury or in the near-surface layer absorb photoelectrons, photons of solar radiation and (in the case of the regions of magnetic poles) electrons and ions of the solar wind. All these processes lead to the charging of the dust particles, their interaction with the charged surface of Mercury, their liftoff, and their motion.

S. I. Popel, A. P. Golub', and L. M. Zelenyi // Physics of Plasmas 30, No. 4 (2023) 043701.



The Caloris basin, one of the largest basins in the solar system. Its diameter exceeds 1,300 km, and in many ways it is similar to the great Imbrium basin on the Moon (diameter >1,100 km).

Dust over Mercury: Regions not Close to Magnetic Poles



For aphelion

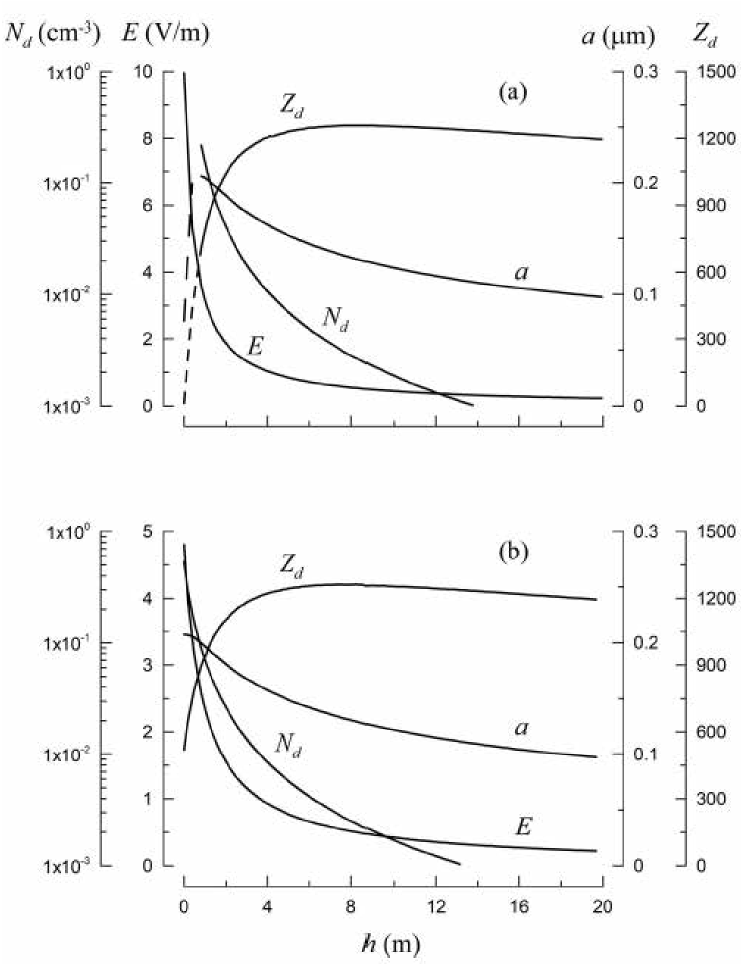
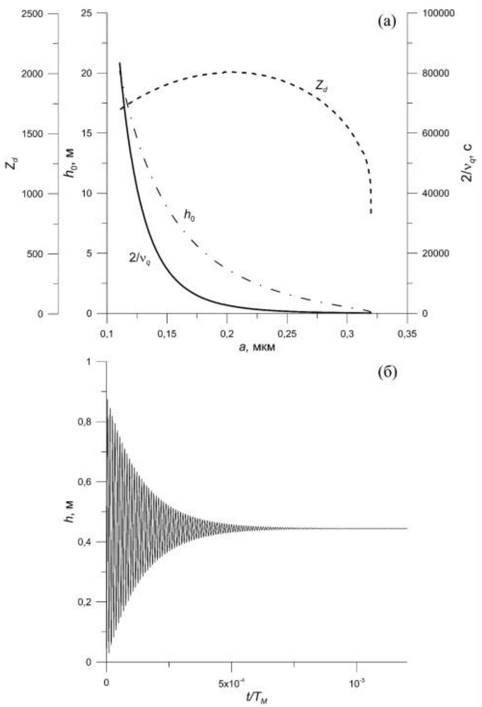


FIG. 4. The maximum sizes a, charge numbers Z_d, number densities N_d of levitating dust particles, and electric fields E depending on the altitude h above the surface of Mercury at aphelion for angles $\theta = 77^\circ$ (a) and 87° (b) calculated under the assumption that the regions under consideration are located not close to the magnetic poles. Dashed curves mark unstable equilibrium states of levitating dust particles.



For perihelion

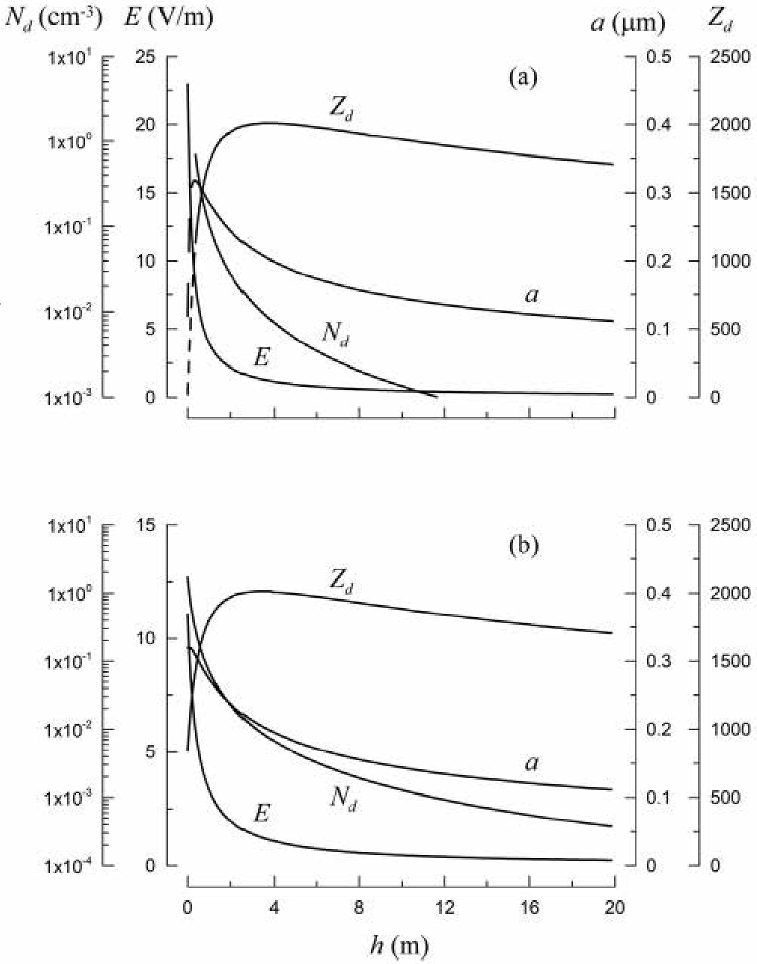
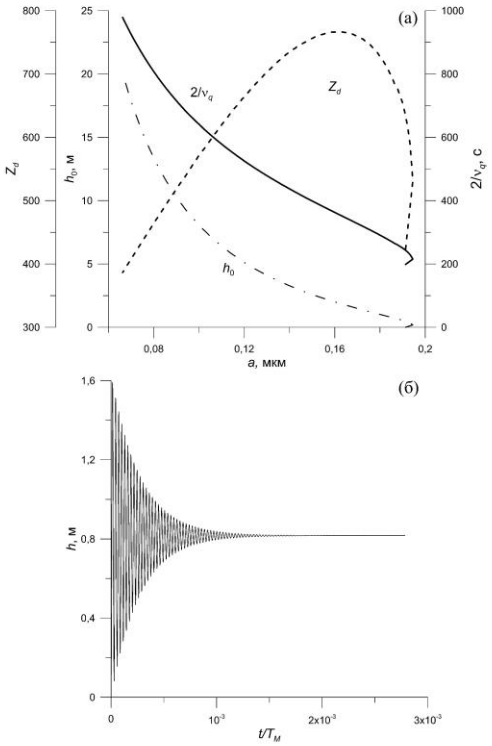


FIG. 5. The maximum sizes a, charge numbers Z_d, number densities N_d of levitating dust particles, and electric fields E depending on the altitude h above the surface of Mercury at perihelion for angles $\theta = 77^\circ$ (a) and 87° (b) calculated under the assumption that the regions under consideration are located not close to the magnetic poles. Dashed curves mark unstable equilibrium states of levitating dust particles.

Dust over Mercury: Regions Close to Magnetic Poles



For aphelion

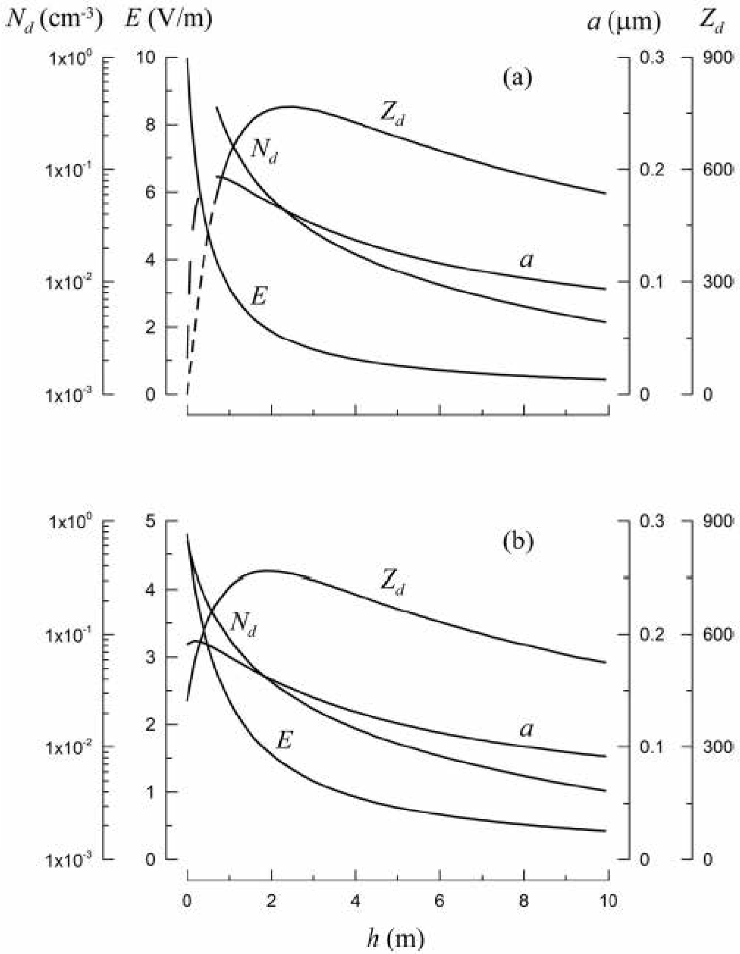
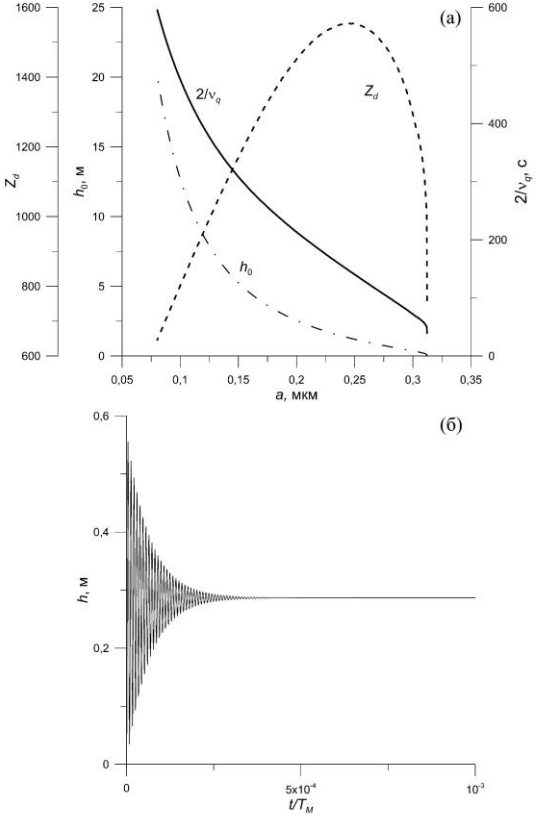


FIG. 6. The maximum sizes a, charge numbers Z_d, number densities N_d of levitating dust particles, and electric fields E depending on the altitude h above the surface of Mercury at aphelion for angles $\theta = 77^\circ$ (a) and 87° (b) calculated under the assumption that the regions under consideration are located in the vicinity of the magnetic poles. Dashed curves mark unstable equilibrium states of levitating dust particles.



For perihelion

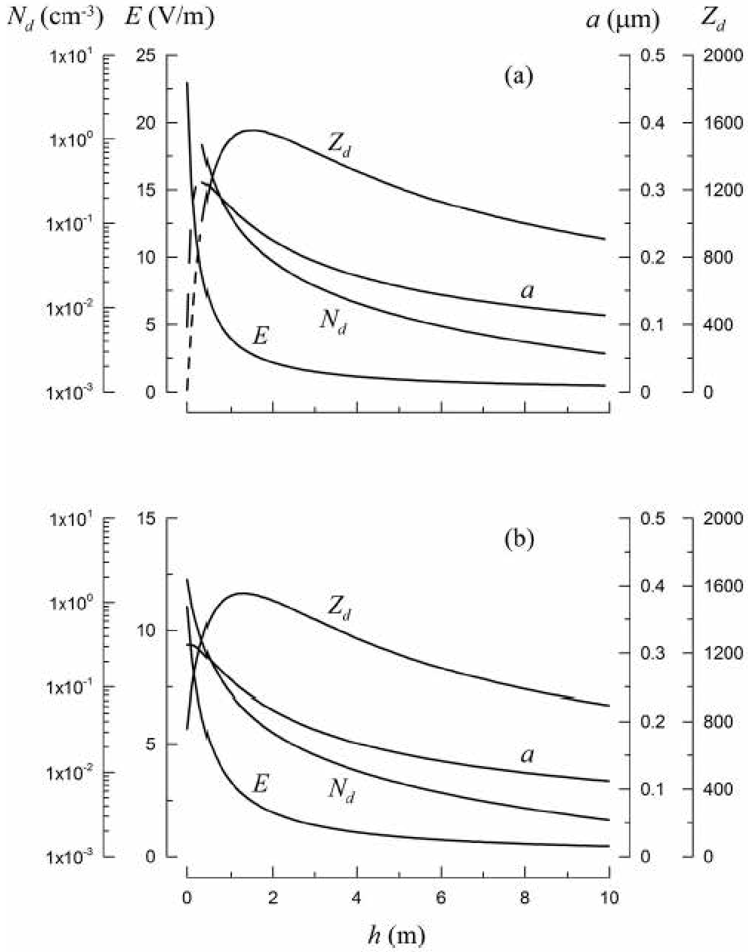


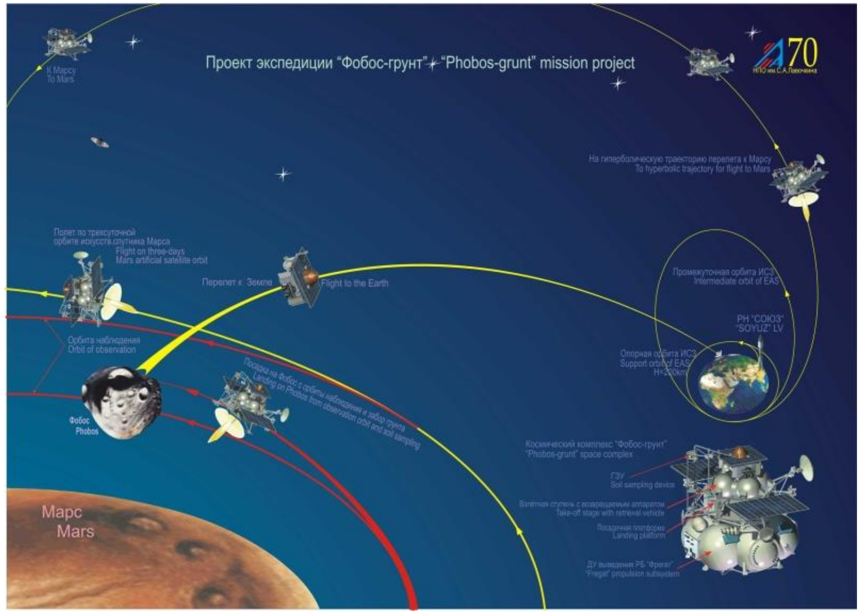
FIG. 7. The maximum sizes a, charge numbers Z_d, number densities N_d of levitating dust particles, and electric fields E depending on the altitude h above the surface of Mercury at perihelion for angles $\theta = 77^\circ$ (a) and 87° (b) calculated under the assumption that the regions under consideration are located in the vicinity of the magnetic poles. Dashed curves mark unstable equilibrium states of levitating dust particles.

Mercury - Conclusions

- Anomalous dissipation plays a significant role in justifying the use of the model of levitating dust particles in describing dusty plasmas above Mercury. Based on numerical calculations, it is demonstrated that, as a rule, it is possible to use the approximation of levitating dust particles to describe the dusty exosphere of Mercury above areas of its surface illuminated by solar radiation.

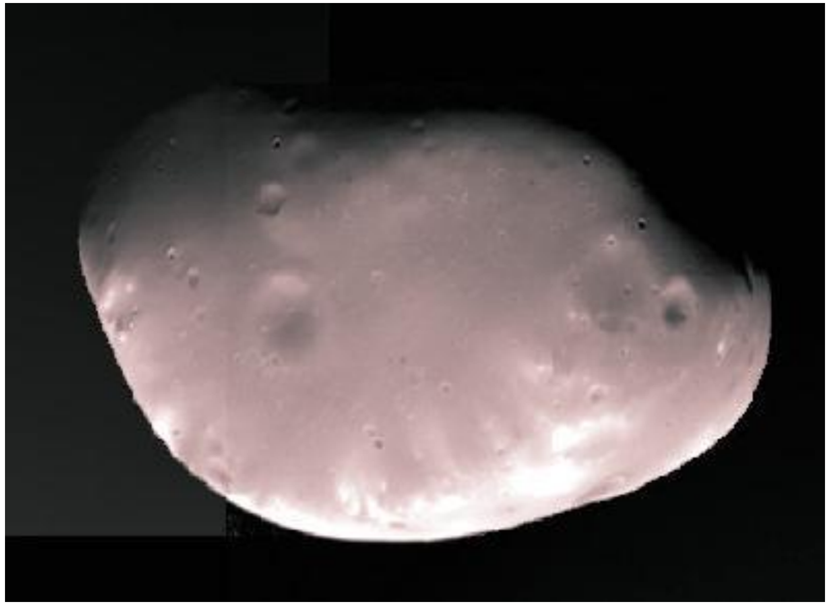
Phobos

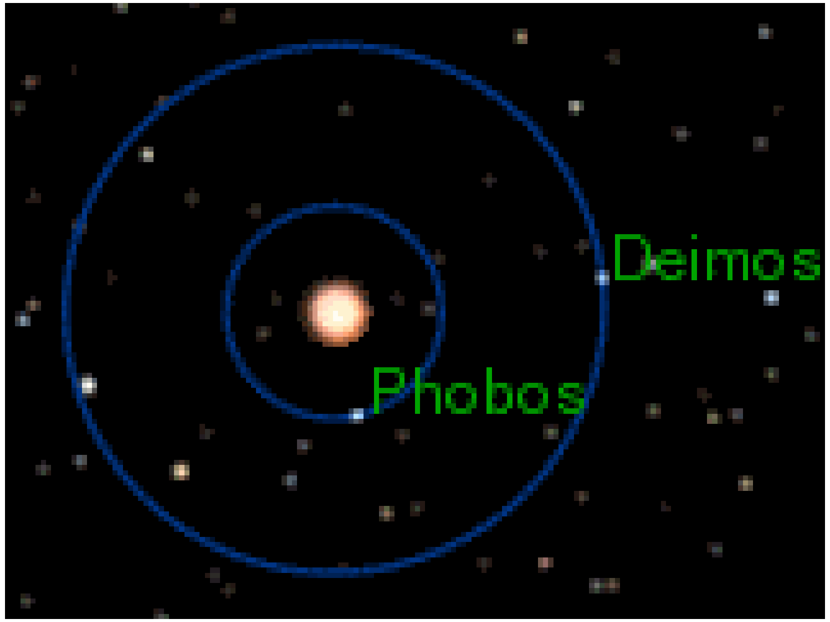
- Phobos is the dimensions of 27 × 22 × 18 km. So its gravitational pull is only one-thousandth that of Earth, making landing on Phobos more like docking with a spaceship. Russia is gearing up to launch the Phobos-Grunt II mission that will attempt to land a craft on Phobos, collect the first samples from the moon's surface and return them to Earth. The project could help to determine if there is any hydrogen or water present.
- Dust could be a huge problem in Phobos's weak gravity field. There could be a layer of dust four or five metres thick that would be easily mobilised. On Phobos, even the slightest disturbance could raise a massive dust cloud.
- Since Phobos is in the solar wind plasma flow for part of its orbit, Phobos dust constitutes a part of a dusty plasma system.



Deimos

- **Deimos** is the smaller and outer of the two natural satellites of the planet Mars, Deimos has a mean radius of 6.2 km and takes 30.3 hours to orbit Mars. Deimos is highly non-spherical with triaxial dimensions of 15 × 12.2 × 11 km, making it 0.56 times the size of Phobos. Deimos is 23,460 km from Mars, much farther than Mars's other moon, Phobos. The surface gravity is 0.003 m/s^2 at Deimos and 0.0057 m/s^2 at Phobos. The escape velocity is approximately equal to 10 m/s for Phobos and 6 m/s for Deimos.



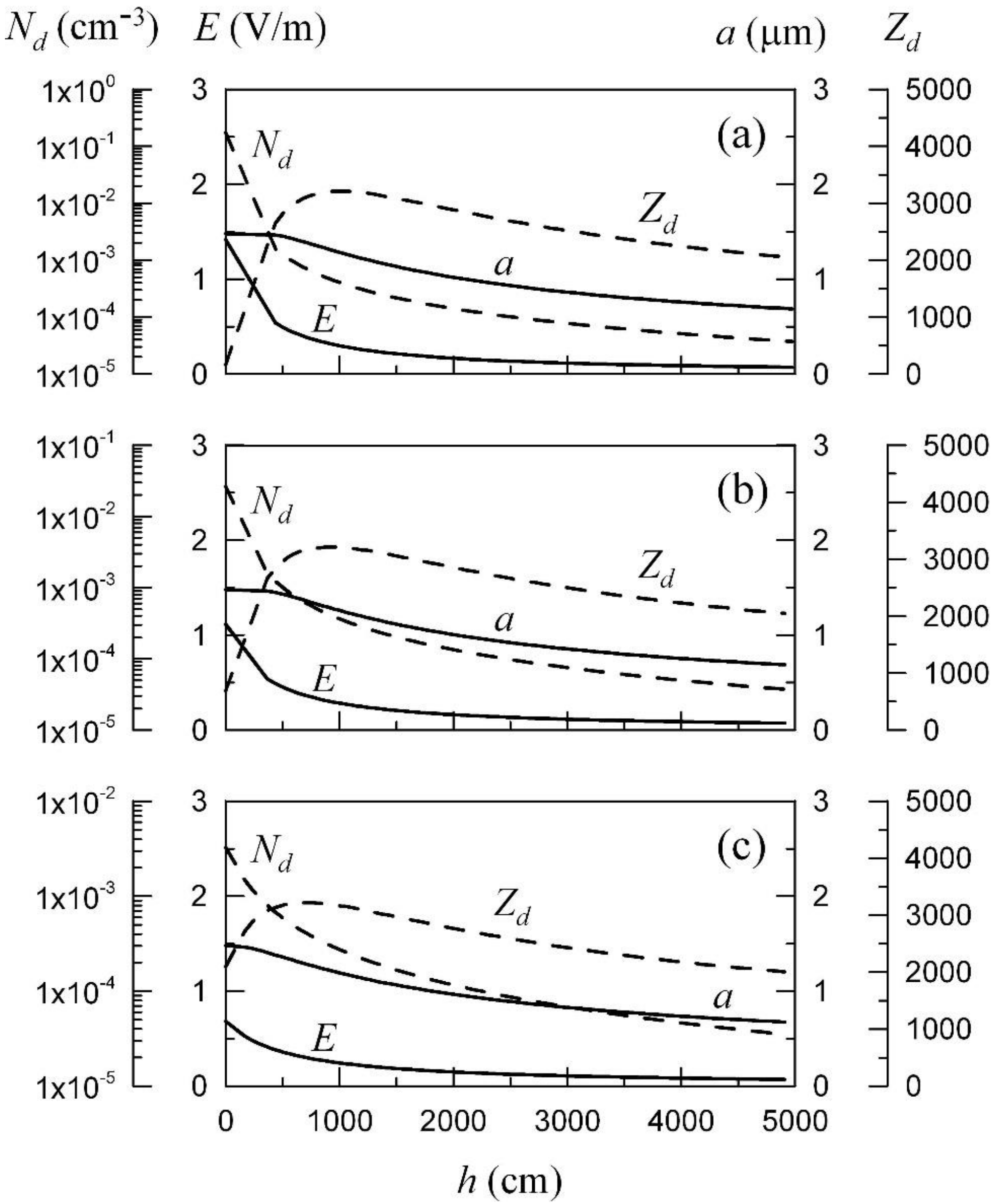


Dusty plasmas at Phobos and Deimos

- Paper [Soter S, 1971] was devoted primarily to the consideration of dust over Phobos and Deimos at high altitudes *h* larger than the characteristic linear sizes of Phobos (~ 20 km) and Deimos (~ 15 km), respectively. Data on the parameters of dust in the near-surface layers (*h* << 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.

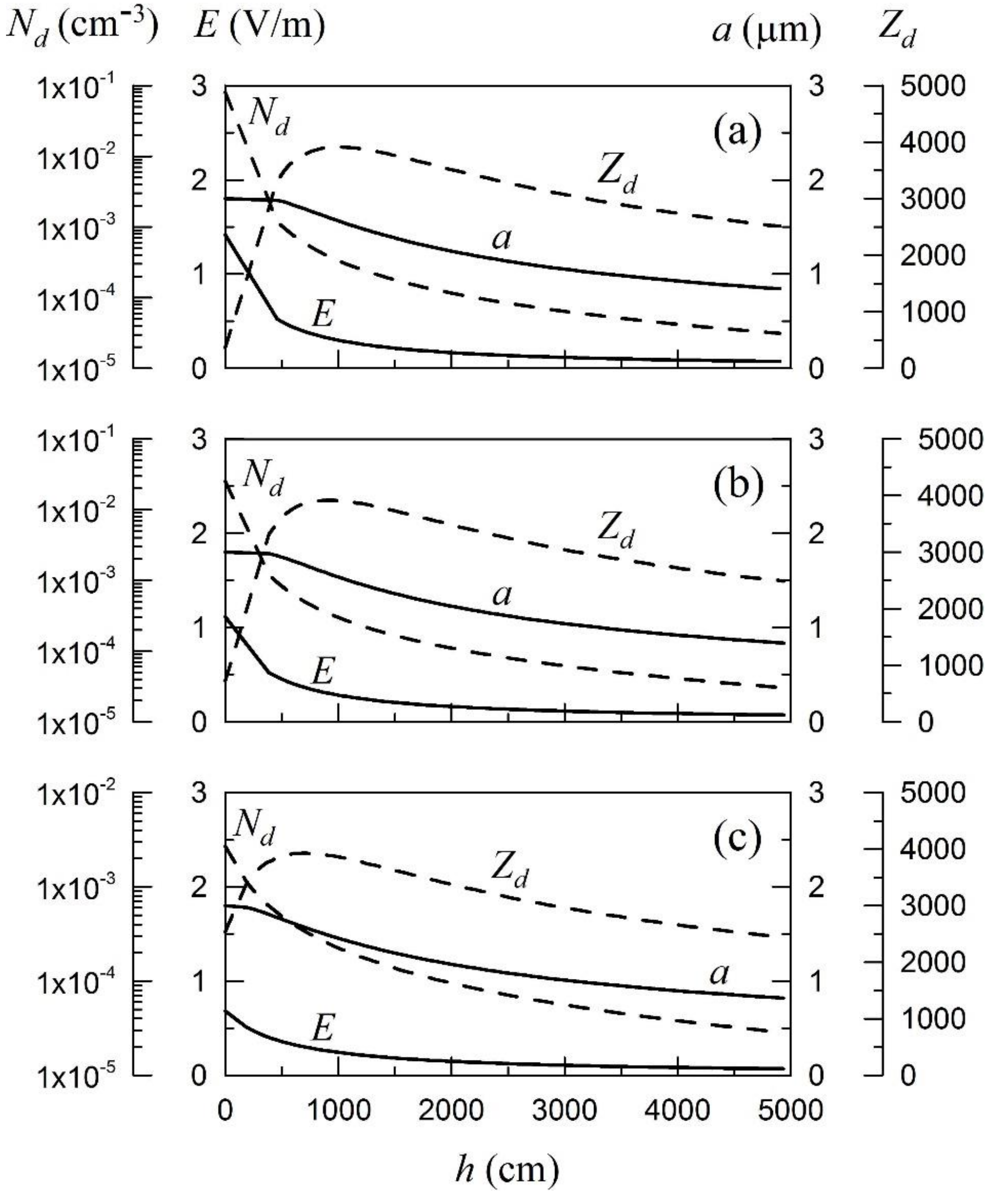
Results of Calculations (I)

- 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 ~ 1 μm versus a ~ 0.1 m). 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. In fact, the formation of the dusty plasmas over the surfaces of Phobos and Deimos can be attributed to photoelectric and electrostatic processes.

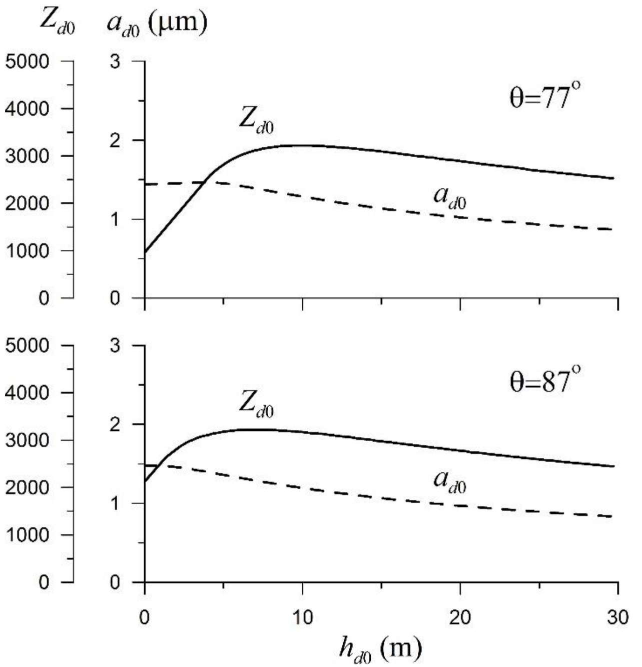


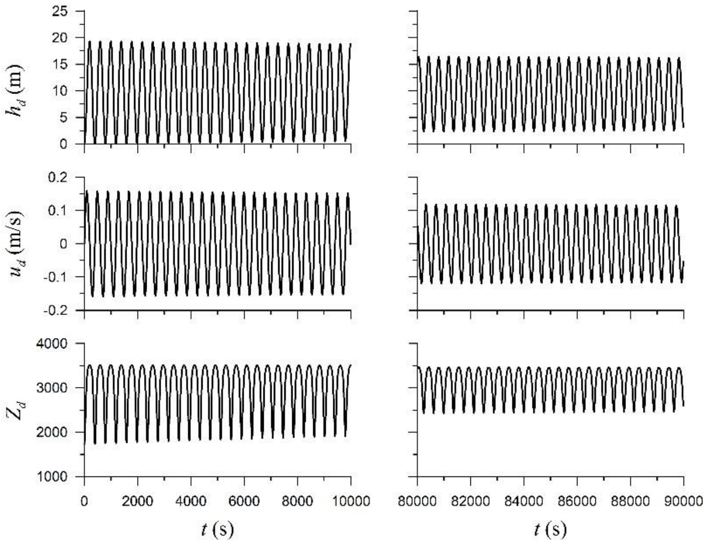
Results of Calculations (II)

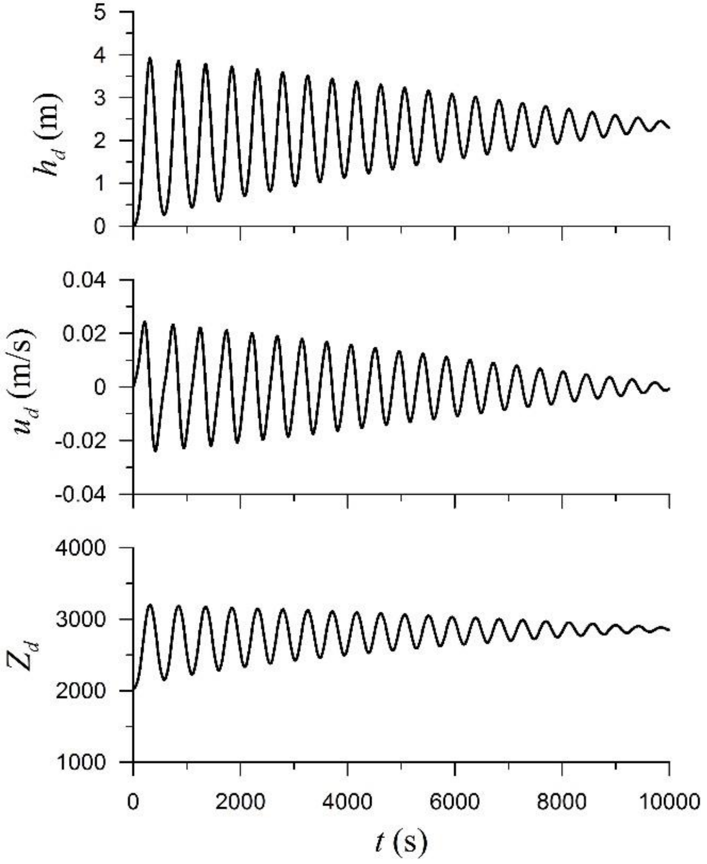
- The role of meteoroids in the formation of the dusty plasmas in the near-surface layers over Phobos and Deimos is also signicantly smaller than that in the case of the Moon. At the same time, at large distances from a Martian satellite (signicantly larger than its linear size of the order of 10 km), the effects of meteoroids are responsible for the formation of a dust halo consisting of particles with sizes of about 10 μm and density of $N_d \sim 10^3$ km^{-3} (which is much lower than the density of dust particles $N_d \sim 10^{-3}$ - 10^{-1} cm^{-3} near the surfaces of the Martian satellites associated with photoelectric and electrostatic processes).

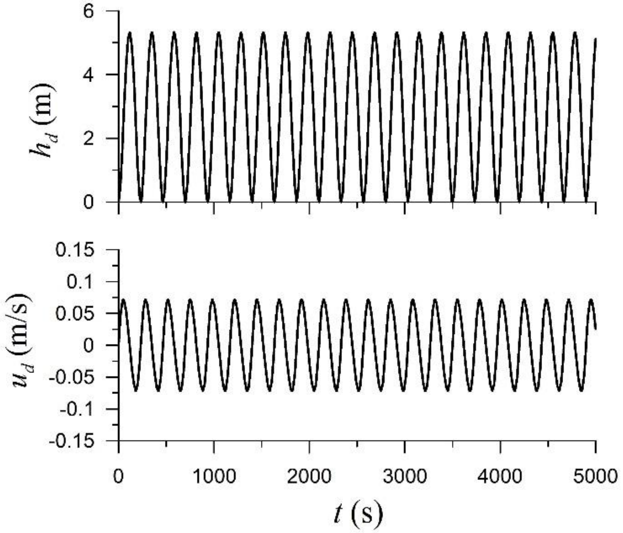


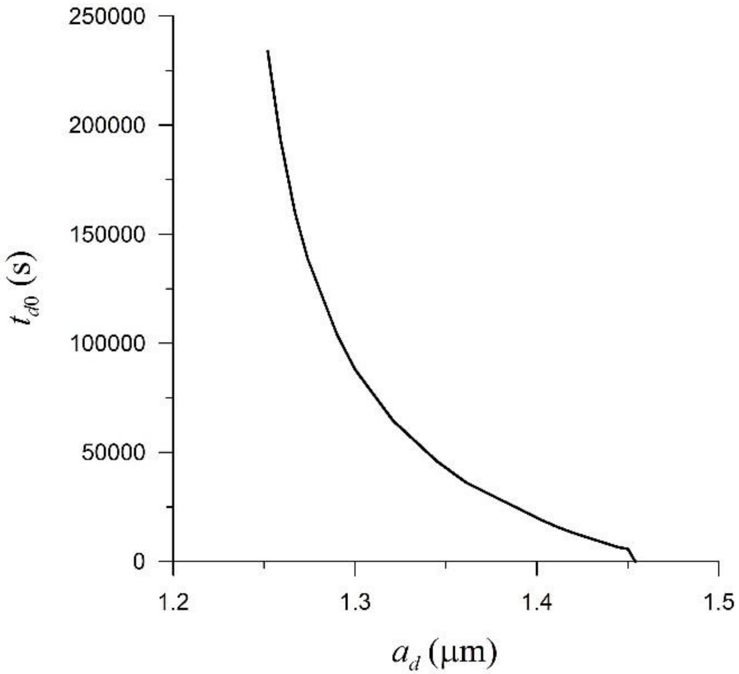
Behavior of dust at Phobos



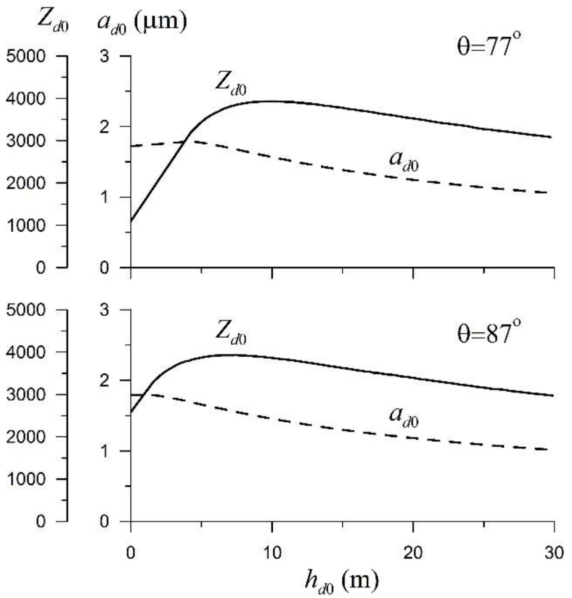


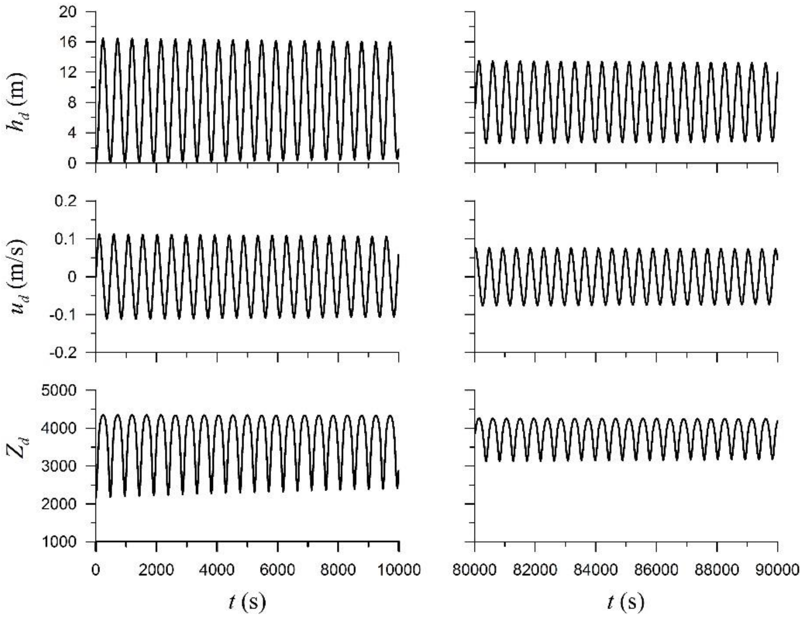


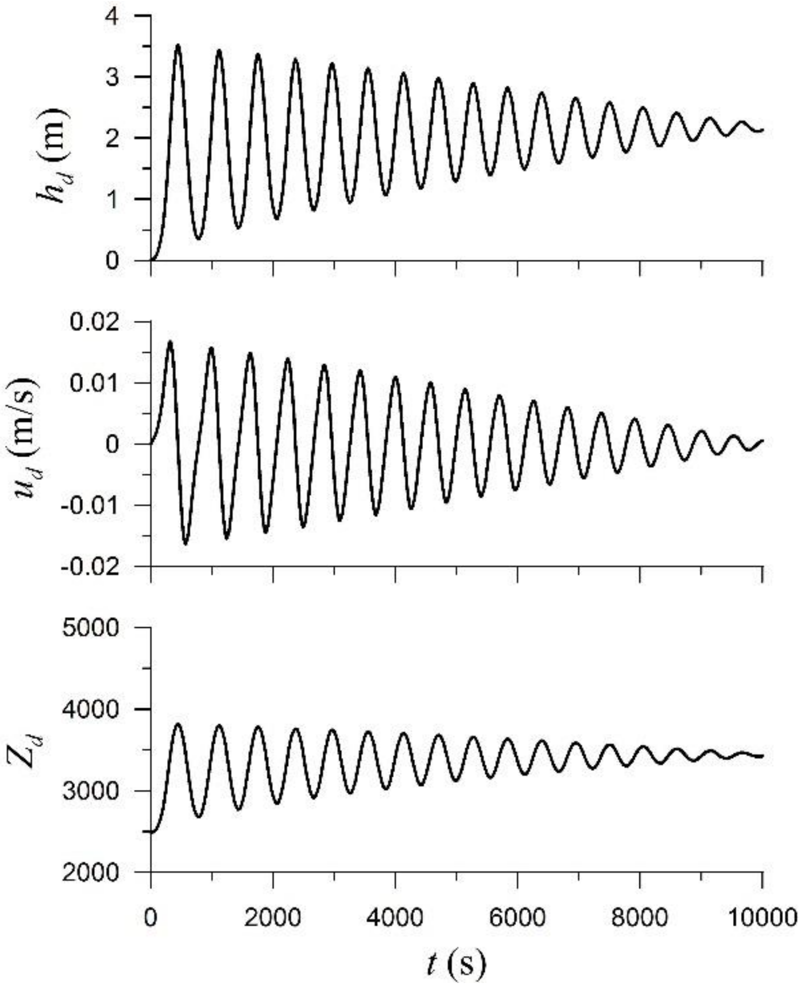


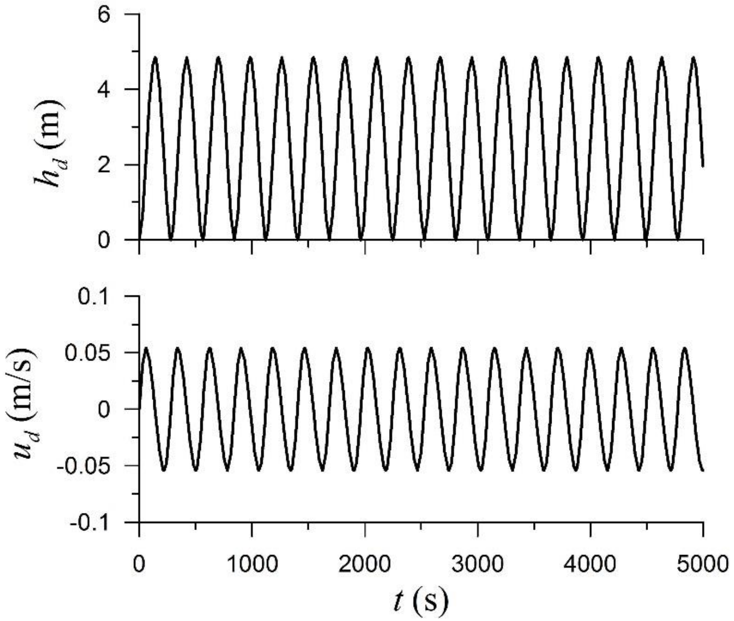


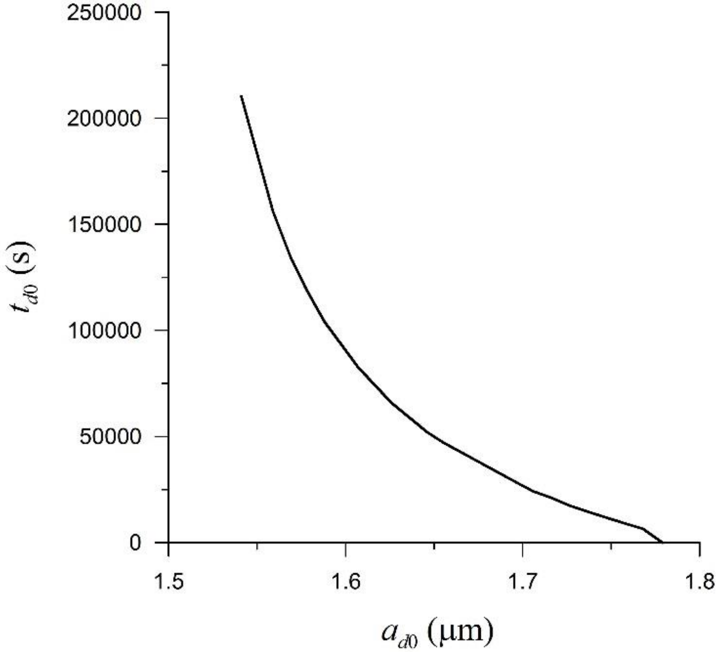
Behavior of dust at Deimos











Martian moons - Conclusions

- The formation of the dusty plasma system in the near-surface layer over the illuminated part of Phobos or Deimos has a nonstationary character during almost entire daytime. Variations of the charges of dust particles resulting in the damping of their oscillations over the surface of Phobos or Deimos are too slow compared to the day on this Martian satellite. In this case, it is possible to estimate the main parameters (densities of dust particles and photoelectrons, charges and rising altitudes of dust particles, etc.) characterizing the dusty plasma system over this moon of Mars. To obtain more definite data on the parameters of the dusty plasma system near Phobos or Deimos, it is necessary to have considerable information on the properties of soil on the moon of Mars , e.g., such as the work function and quantum yield of soil. We hope that these data will be obtained in future space missions.

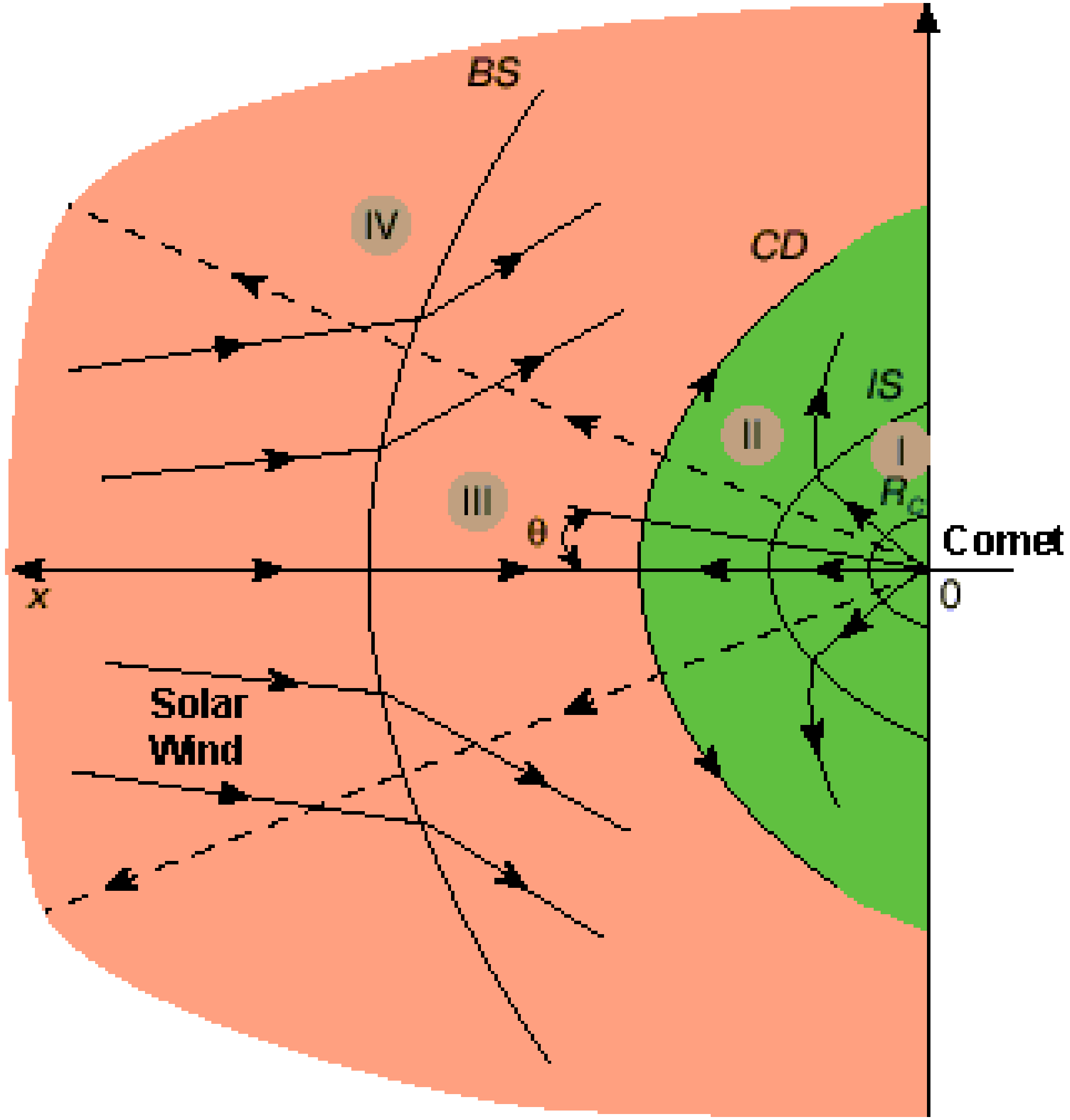
Comets and Dust

- Disintegration of cometary nuclei and collisions of bodies in the asteroid belt are the sources of small particles filling our Solar system. Release of dust upon cometary-nucleus disintegration occurs in the following way. When approaching the Sun, a comet usually has characteristic structure consisting of a visible giant tail, a nucleus (usually, dark) that has a very small size relative to the tail, and an atmosphere surrounding the nucleus and referred to as the comet coma. The coma and the tail form as a result of ejection of the comet material from the nucleus. Ice layers in the nucleus that consist of frozen gases are interspersed with dust layers. Upon heating by the solar radiation, gases sublimate and burst out of the nucleus entraining dust clouds. The cometary nucleus thus becomes the source of a gas-dust flow that propagates toward the solar wind, i.e., follows the nucleus.

Images of the Hale–Bopp comet [11]. The upper tail of the comet consists mainly of CO^{+}_{+} ions, while the lower tail consists mainly of dust particles with a size of ~1 µm.

Anomalous dissipation and shock waves. Applications (I)

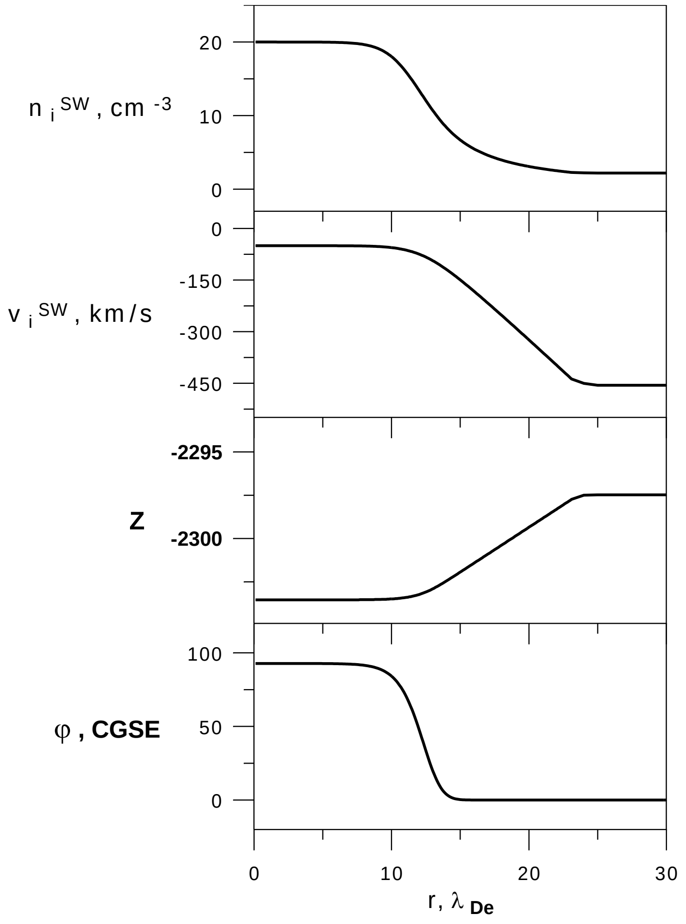
- The presence of dust in a cometary coma modifies the shock wave formed as a result of the interaction of the solar wind with the comet.
- The external shock wave can be considered as an ion-acoustic shock wave, since it is formed as a result of the interaction of cometary ions with solar wind protons => its modification due to the charging of dust particles.
- Possible formation of dust structures in the region of interaction of the solar wind with a cometary coma.



Anomalous dissipation and shock waves. Applications (II)

Model (**S.I. Popel, A.A. Gisko // Nonlin. Processes Geophys. 13, 223 (2006)**), which takes into account solar radiation, charging of dust particles, evaporation and formation of neutral particles, photoionization, electric fields, evolution of solar wind ions and cometary ions, as well as dust particles, makes it possible to determine the structure of the shock front. For sufficiently high dust number densities ($n > 10^6$ cm^{-3} near the comet nucleus) in the shock wave region, dust particles acquire a positive variable charge, which significantly affects the structure of the shock front. Its width corresponds to the theoretical estimate

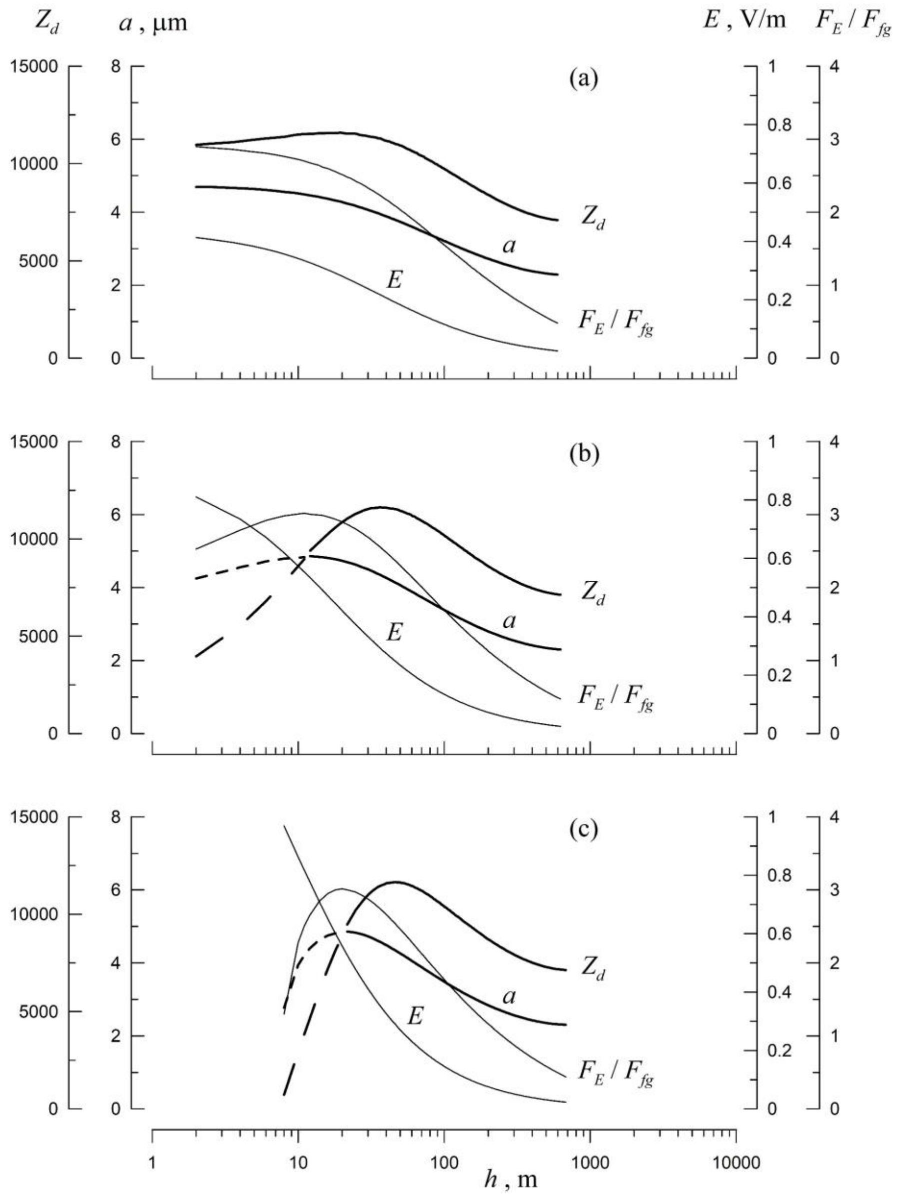
$$\Delta\xi \sim M c_s / \nu_q,$$



$$m_p n_p \frac{dV_{p\alpha}}{dt} = -\frac{\partial p_p}{\partial x_\alpha} + \eta^{SW} \frac{\partial W_{p\alpha\beta}}{\partial x_\beta} - e n_p \frac{\partial \varphi}{\partial x_\alpha} + R_{id}^{SW} + R_{ii}^{SW}, \qquad W_{p\alpha\beta} = \frac{\partial V_{p\alpha}}{\partial x_\beta} + \frac{\partial V_{p\beta}}{\partial x_\alpha} - \frac{2}{3}\delta_{\alpha\beta}\,\mathrm{div}\,\mathbf{V}$$

Dusty Plasmas at Comet Nucleus

- Dusty plasma processes can also reveal themselves in the situations when the comet is far from the Sun. For a comet exhibiting parameters of the nucleus close to those of the nucleus of the Halley's comet, the dusty plasma in the vicinity of the nucleus forms due to electrostatic interactions, i.e., analogous to dusty plasma formation near other bodies without atmosphere (e.g., Mars satellites), provided that the distance from the comet to the Sun is at least ~3 AU. On the contrary, if the comet is closer to the Sun, the dynamics of dust particles is determined by the gas flow from the comet nucleus. It is possible to use the steady-state description of the dusty plasma above the comet nucleus because $2/\nu_q \sim 100$ s.



Comets - Conclusions

- The shock wave can sometimes be interpreted as a kind of the ion-acoustic shock wave. The presence of charged dust leads to the interaction of protons of the solar wind with dust particles in the comet coma. For a typical comet nucleus with a radius of ~1 km and relatively dense coma (dust number density exceeding 10^6 cm^{-3}), anomalous dissipation caused by charging of dust particles plays an important role in shock wave formation. Apparently, the nature of such a shock wave is similar to that of the dust ion-acoustic shock waves observed in laboratory.
- For a comet exhibiting parameters of the nucleus close to those of the nucleus of the Halley's comet, the dusty plasma in the vicinity of the nucleus forms due to electrostatic interactions, i.e., analogous to dusty plasma formation near other bodies without atmosphere (e.g., Martian satellites), provided that the distance from the comet to the Sun is at least ~3 AU. On the contrary, if the comet is closer to the Sun, the dynamics of dust particles is determined by the gas flow from the comet nucleus.

Ionosphere of Mars

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DUSTY PLASMA

Plasma–Dust System in the Martian Ionosphere[1]

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Dust and dusty plasma effects in Schumann resonances on Mars: Comparison with Earth

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К вопросу о формировании облаков в запыленной ионосфере Марса

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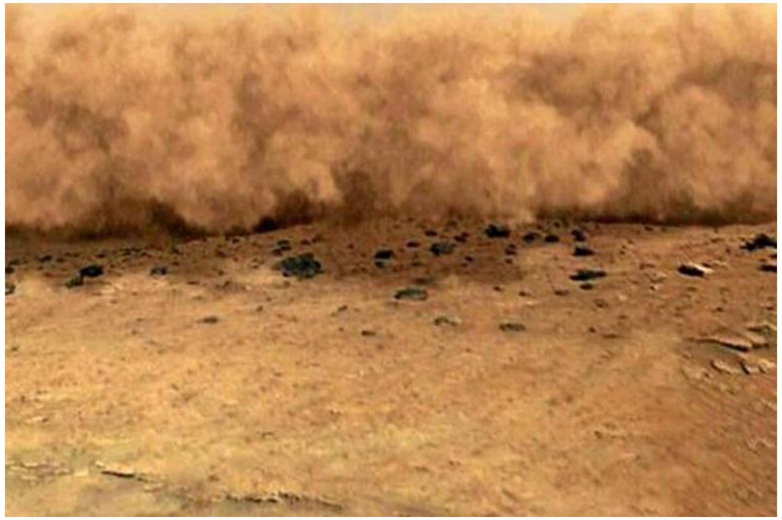
Recent and Future Martian Missions (Russia)

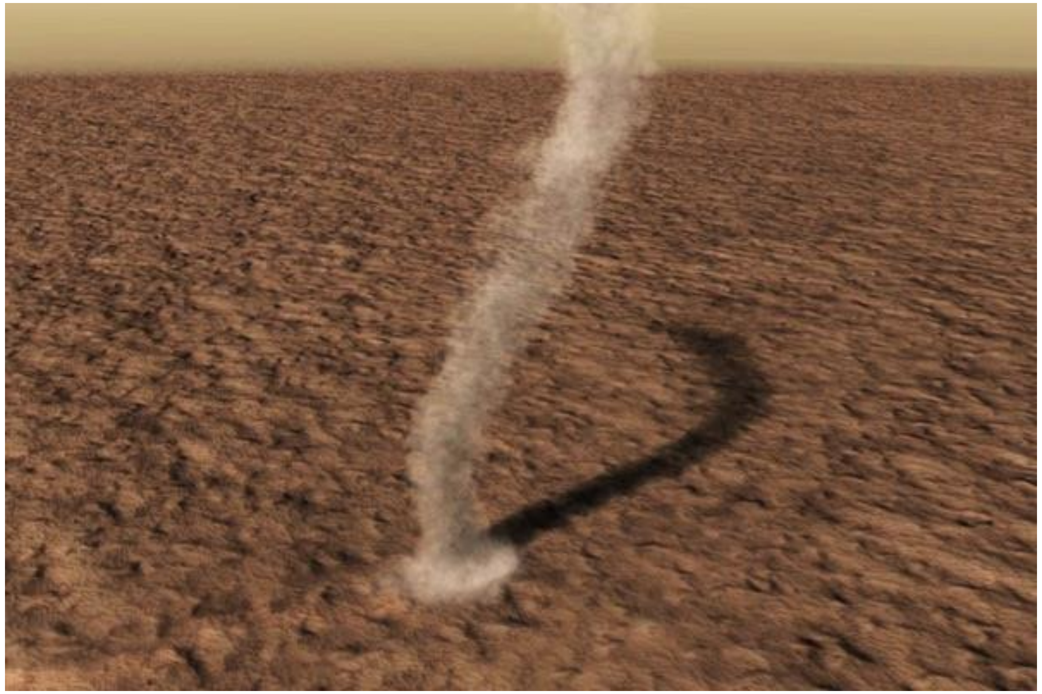
- Interest in Mars has substantially increased in recent years. Spacecrafts Mars Express, ExoMars Trace Gas Orbiter, etc, are operating successfully. The surface of Mars is being studied with Mars Exploration Rover Opportunity and Mars Science Laboratory Curiosity. The main objectives of the ExoMars programme are to search for evidence of trace atmospheric gases that could be signatures of active biological or geological processes and to test key technologies for subsequent missions to Mars.

- The Phobos-Grunt II mission might be restarted for a launch. 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, and probes for measurements of the parameters of the plasma and the local electric field near the surface of Phobos will be used.

Dust in Martian atmosphere (I)

- The atmosphere of Mars is much thinner than the Earth's atmosphere, and its ability to hold dust grains for a long time is very low. High dust density is observed only during dust storms or other events that lift dust from the Martian surface. The data on the presence of dust in the Martian atmosphere were obtained from Mars rovers and instruments installed on orbital stations.

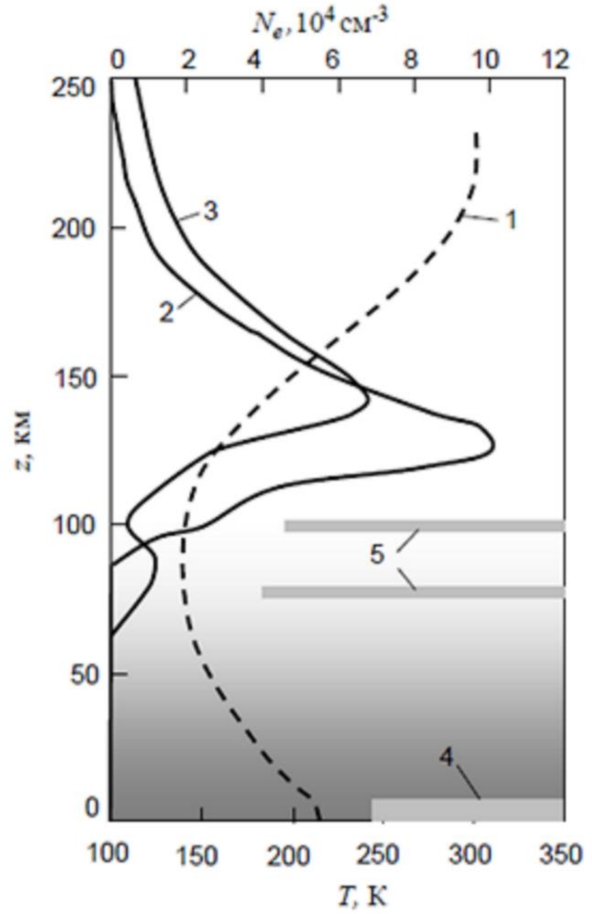




Mars atmospheric and surface dust must be assessed for its impact on human health, the operation of Mars surface systems (e.g., spacesuits, habitats, ascent rockets, etc.) and surface operations and exploration (e.g., reduced atmospheric visibility, hampering of regular habitat maintenance, etc.).

Dust in Martian atmosphere (II)

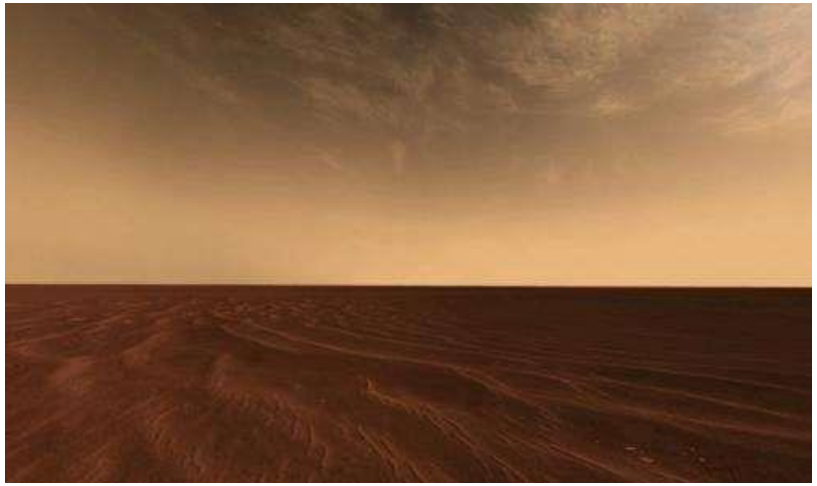
- At altitudes of 100 km in the mesosphere, where the temperature is sufficiently low for carbon dioxide freezing, clouds formed of dust grains with a size of about 100 nm (similar to noctilucent clouds in the Earth's atmosphere) were observed by means of the SPICAM infrared spectrometer installed on Mars Express orbiter. Clouds of micron-size grains were observed at altitudes of about 80 km by means of the OMEGA spectrometer onboard Mars Express. There are also regions near the surface and at an altitude of about 4 km, where clouds consisting of frozen water were observed in the nighttime. Polar clouds are usually located relatively low above the surface (at altitudes below 10 km) and, according to the data obtained by the Mars Climate Sounder installed on Mars Reconnaissance orbiter, represent thin formations consisting of H_2O ice in summer and CO_2 ice in winter.



Altitude profiles of the (*1*) temperature, (*2*) electron density in the daytime ionosphere, and (*3*) density of ionospheric electrons at the time of sporadic layer formation at altitudes of 65–100 km.

Dust in Martian atmosphere (III)

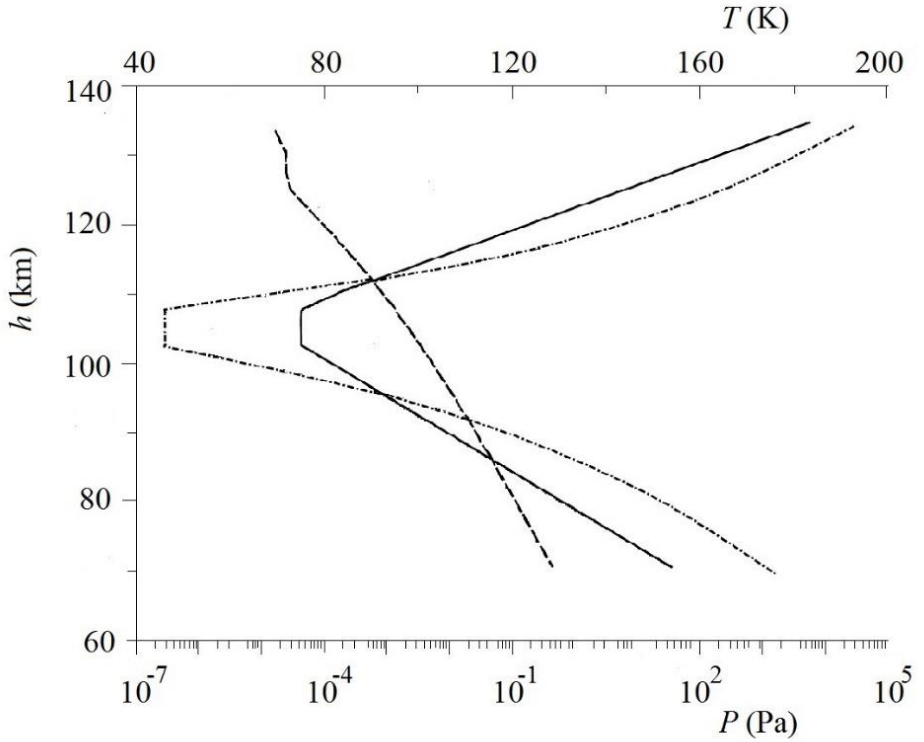
- In recent years, using the data obtained by the SPICAM IR and UV spectrometer installed on Mars Express orbiter, several modes of aerosols were discovered in the Martian atmosphere. The capabilities of the SPICAM spectrometer do not allow one to unambiguously determine the grain material, and measured values can be interpreted as the presence of either dust grains with an effective radius of 0.76 μm and a number density of 0.4–2 cm^{-3} or ice grains with an effective radius of 0.9–1.2 μm and a number density varying from 0.005–0.05 cm^{-3} in the southern hemisphere to 0.01–0.3 cm^{-3} in the northern hemisphere. In addition, a fine mode with an average diameter of about 44 nm was stably detected during entire observation period of about 76 Martian days. In the northern hemisphere, fine-mode grains were present mainly at altitudes of 30–40 km, whereas in the southern hemisphere, they were observed at altitudes of up to 70 km. The number density was found to decrease from 10^3–10^4 cm^{-3} at an altitude of 2 km to 1–5 cm^{-3} at 60–70 km.



An image of the Martian clouds obtained by the Mars Science Laboratory Curiosity in March 2021 The clouds were detected at altitudes exceeding 60 km and most probably consist of CO2-ice particles.

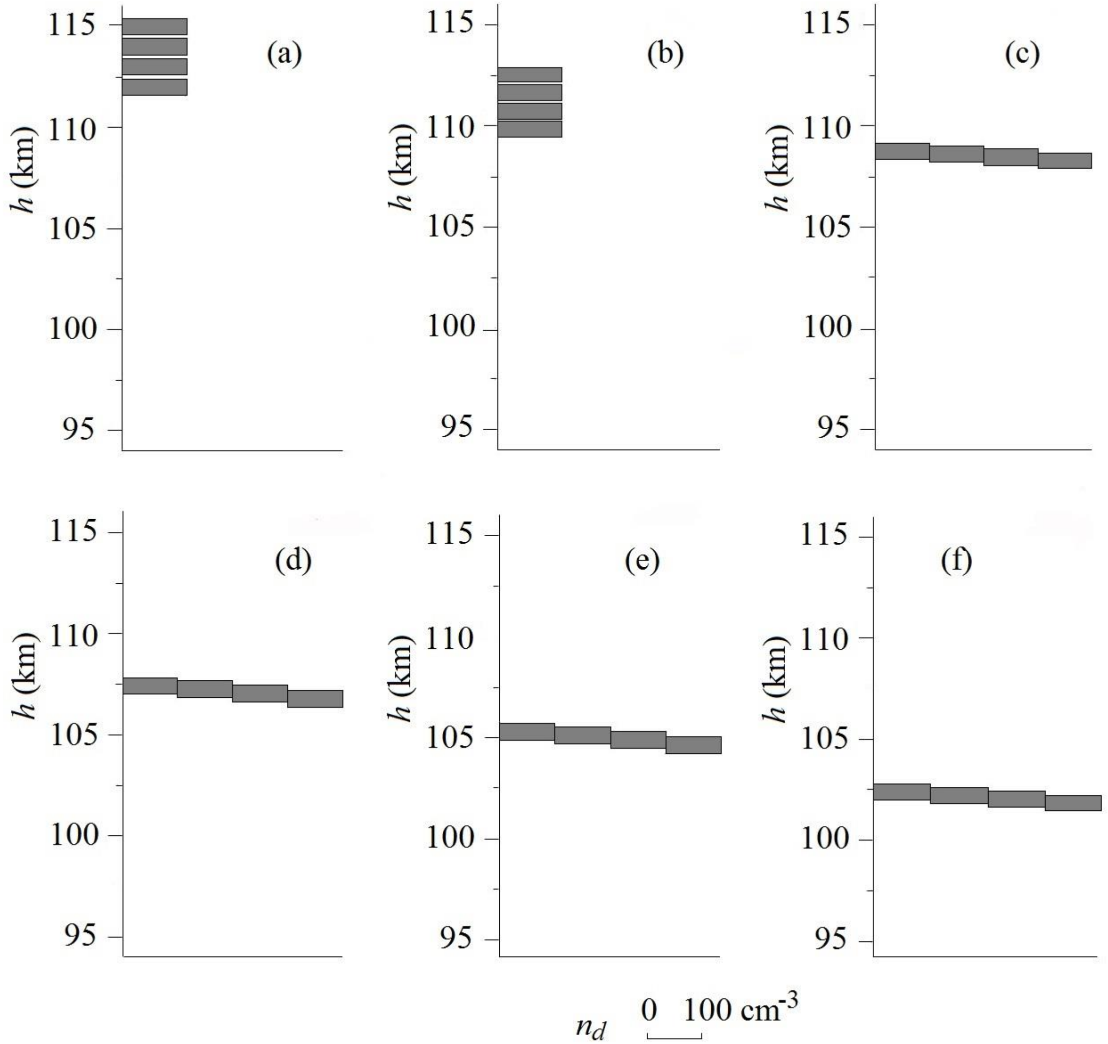
Effects of Condensation (I)

- The calculations within the framework of the model [B.A. Klumov, G.E. Morfill, and S.I. Popel, JETP 100, 152 (2005)] allow us to draw the following main conclusions concerning clouds of condensed particles.
- (1) Ice particles of CO_2, which are initially in the zone of supersaturation of CO_2 vapor, collect on their surfaces most of the CO_2 vapor and are precipitated downward together with absorbed CO_2 molecules. Particles of different dust layers absorb different amounts of carbon dioxide molecules. This leads to the possibility of the interfusion of layers and the formation of dust clouds. The characteristic time for the sedimentation of solid dust particles consisting of CO_2 molecules in the condensation zone is about several minutes. Below the condensation zone, the particles evaporate. In the condensation zone, particles of CO_2 ice can reach sizes of the order of 100 nm. This value is in accordance with the data of observations performed by the Mars Express orbiter. In the daytime, dust particles can acquire charges of the order of 100e.



Schematic altitude profiles of the (solid line) temperature of air, (dashed line) pressure of carbon dioxide vapor, and (dash-dotted line) pressure of saturated carbon dioxide vapor. Carbon dioxide vapor is supersaturated in the altitude range of 87–112 km.

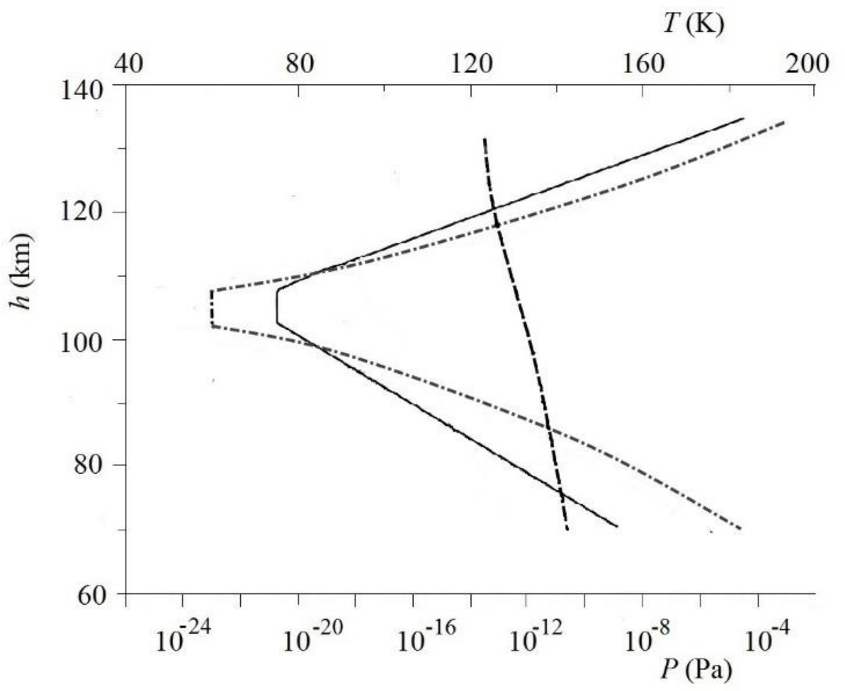
Effects of Condensation (II)



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), 280 s (f)). The initial dust particle radius is 4.5 nm. The dust particle number density in each layer is n_d = 100 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.

Effects of Condensation (III)

- (2) Similar to the situation at the Earth, particles with a characteristic size of several nanometers may exist in the Martian ionosphere over the condensation zone due to the bombardment of Mars by micrometeorites. Those particles that are initially located above the upper boundary of the condensation zone (even when reaching the condensation zone in definite time) cannot be significantly increased in size due to the insufficient (residual) amount of CO_2 molecules in this zone. These nanoscale particles exist at altitudes from 112 to 115 km during several hours, which can lead to phenomena in the atmosphere of Mars, which are similar to PMSE at the Earth.
- (3) Water ice particles grow very slowly and sediment in the condensation zone during dozens of hours. The maximum values of the H_2O ice size are of the same order of magnitude as the initial ones (before the absorption of water vapor in the condensation zone on the particles). Different layers consisting of H_2O ice are not mixed with each other. The reason for this behavior is the very low concentration of water vapor in the Martian ionosphere. All these facts explain the absence of observations of dust clouds consisting of particles of water ice at high altitudes (88-116 km) in the atmosphere of Mars.



Schematic altitude profiles of the (solid line) temperature of air, (dashed line) pressure of water vapor, and (dash-dotted line) pressure of saturated water vapor. Water vapor is supersaturated in the altitude range of 88–116 km.

Saturn’s Magnetosphere

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DUSTY PLASMA

Dust Acoustic Solitons in Saturn’s Dust-Filled Magnetosphere

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DUSTY PLASMA

Two-Dimensional Description of Nonlinear Wave Perturbations in the Dusty Saturn’s Magnetosphere

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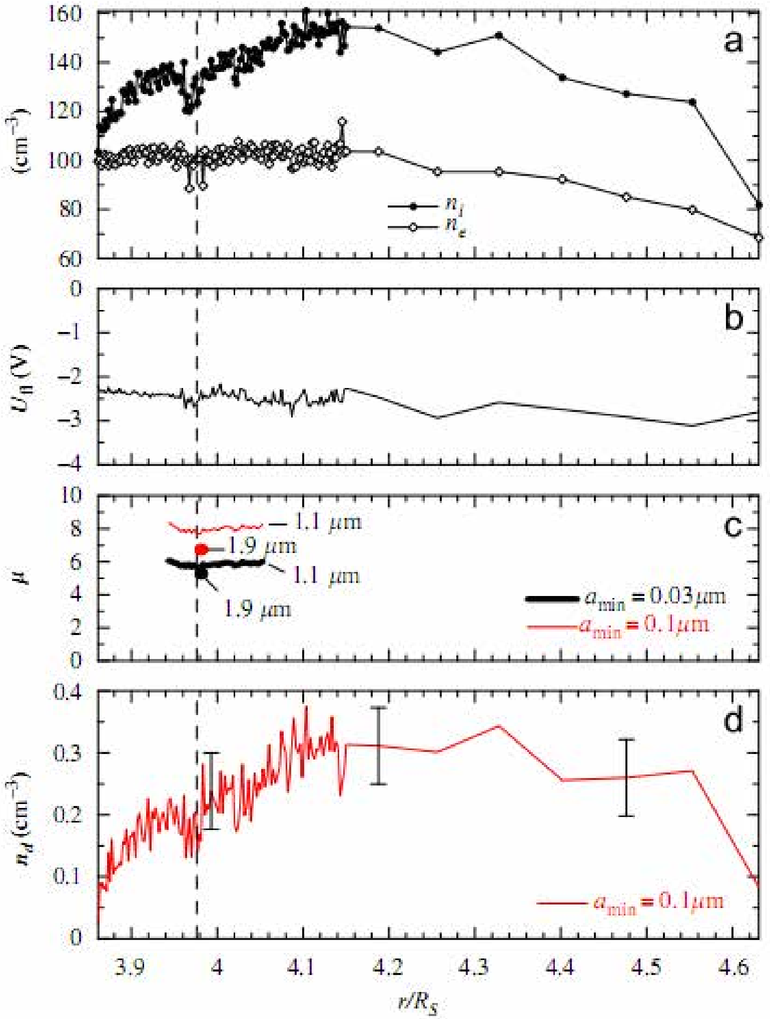
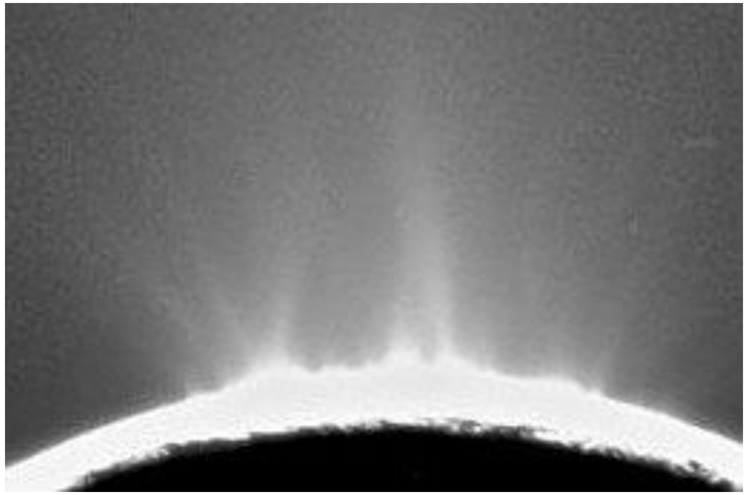
Saturn's Magnetosphere

- The dusty plasma in the vicinity of Saturn's satellite Enceladus was discovered during the Cassini mission.
- It has a number of specificities compared with other space systems that are now actively studied. For example, measurements of the parameters of electrons in Saturn's magnetosphere obtained by the Voyager and Cassini missions showed the existence of two types (hot and cold) of electrons. It turned out that the velocities of these electron populations are subject to the so-called kappa distribution with independent low values of *κ*.





To be continued…

Conclusions (I)

- A feature of the circumlunar space is the presence of a dusty plasma system. The dusty plasma system above the Moon includes charged dust, photoelectrons, electrons and ions of the solar wind and Earth's magnetosphere. Dusty plasma sheath-like structure is formed in the region of the lunar terminator. At the Moon, interactions of the Earth’s magnetosphere tail with dusty plasmas can result in the development of nonlinear wave plasma processes. Study of the influence of magnetic fields on the Earth’s magnetotail on the dust transport above the lunar surface shows a possibility of the existence of positively charged dust and correspondingly the presence of dusty plasmas at the sunlit part of the Moon for the whole range of the lunar latitudes. Dust grain transport from the region of lunar latitudes exceeding about 76º toward the equator of the Moon due to the uncompensated magnetic part of the Lorentz force is a new quality effect that does not exist in the absence of the magnetic field.
- There are qualitative differences between the dusty plasma systems of Mercury and the Moon related to the fact that Mercury has a magnetosphere and Mercury’s orbit is one of the most eccentric of all planetary orbits in the Solar System. The effects of magnetic fields can slightly influence the dust particle transport and, correspondingly, the expansion of the region of the existence of dusty plasmas above the surface of Mercury due to the effect of dust particle transport is not so significant as at the Moon. Furthermore, due to the presence of Mercury’s magnetosphere, the solar wind is important for the formation of dusty plasmas at Mercury only in the vicinity of the regions of themagnetic poles. In other regions of Mercury, in contrast to the situation at the Moon, the solar wind does not influence significantly the dusty plasma properties. The dusty plasma parameters are different in the cases of aphelion and perihelion of the orbit of Mercury.

Conclusions (II)

- There is a possibility of the existence in the Martian ionosphere of carbon dioxide dust clouds analogous to noctilucent clouds. Phenomena in Martian atmosphere analogous to polar mesosphere summer echoes are also possible.
- 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 exceeding about 76°. Dust particles with the characteristic sizes of about 1 μm 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 10^{-3} - 10^{-1} cm^{-3} and 10 cm^{-3}, respectively. The dust particle motion starts from the satellite's surface and represents damped oscillations around a stable position above the satellite's surface. The damped oscillations of a particle are caused by variations in its electric charge.
- Dusty plasmas were observed in the vicinity of Saturn's satellite Enceladus during the Cassini mission. It has a number of specificities compared with other dusty plasma systems in our Solar system. In particular, measurements of the parameters of electrons in Saturn's magnetosphere obtained by the Voyager and Cassini missions showed the existence of two types (hot and cold) of electrons obeying the so-called kappa distribution. Its research is a problem for the future.

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