



Dust at the Martian moons and in the circummartian space

Alexander Zakharov^{a,*}, Mihály Horanyi^b, Pascal Lee^c, Olivier Witasse^d, Fabrice Cipriani^d

^a Space Research Institute, Moscow, Russia

^b Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, USA

^c Mars Institute and SETI Institute, NASA Ames Research Center, USA

^d ESA, ESTEC, The Netherlands

ARTICLE INFO

Article history:

Received 12 June 2013

Received in revised form

21 November 2013

Accepted 11 December 2013

Available online 31 December 2013

Keywords:

Dust

Martian moons

Plasma

Dust tori

Particle dynamic

ABSTRACT

The paper provides the current understanding of the dust particle dynamics near the surface and in the circummartian space of the Martian moons based on existing models developed for airless and non-magnetized bodies. In particular we discuss the response of the regolith of the Martian moons to exposure to radiation, the dynamics of charged dust on their surfaces, their plasma environments, the models and indirect observations of their putative dust tori. It is concluded that there is a good theoretical understanding of the behavior of the dynamics of dust particles near the moons Phobos and Deimos. Current models predict dust rings near orbits of the Martian moons based on detailed estimates for the sources and sinks of the dust particles as well as their lifetimes. However, there is no compelling observational evidence for the predicted dust torus around Phobos or Deimos orbits, and there are no observations yet of dust dynamics near their surfaces. Naturally, in order to detect the motion of dust near the surfaces of these moons, and their dust tori we need measurements using a complementary set of sensitive instruments, including impart dust detectors, electric field sensors, and optical cameras in future missions to Mars and its moons.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

The surfaces of the Martian moons Phobos and Deimos, as well as the surfaces of the Moon and other bodies without atmosphere, are exposed to solar ultraviolet radiation, solar wind plasma, solar energetic particles, galactic cosmic rays, and are bombarded by hypervelocity interplanetary micrometeoroid fluxes. Due to this exposure a complex plasma environment develops immediately above these dusty surfaces, creating a plasma sheath—a non-neutral layer at the physical boundary of the plasma, where velocity differences between electrons and ions give rise to a potential gradient, hence an electric field above the surface. According to the Viking Orbiter (Thomas, 1979; Thomas and Veverka, 1980) the surface of both Phobos and Deimos, are covered by layer of loose small grains of regolith, produced by micrometeoroids bombardment processing. Due to interplanetary dust bombardment, and possibly other processes, dust particles can be injected into the plasma sheath from the regolith, leading to unusual dust dynamics, including levitation and transport. This effect was observed on the Moon during the Apollo era (e.g. McCoy and Criswell, 1974). Secondary ejecta particles with sufficient

initial velocities, as well as some charged dust particles that gain sufficient energy from the near surface electrostatic fields, can escape the surface, and may form dust tori around the orbits of their parent bodies (Soter, 1971).

In this paper we discuss the response of the regolith of the Martian moons to exposure, the dynamics of charged dust particles of submicrons to several tens of microns sizes on their surfaces, their plasma environments, and the models and indirect observations of their putative dust tori.

2. Dust particles dynamics near the surface

The surfaces of Phobos and Deimos, as well as all airless, non-magnetized bodies in our Solar System (e.g. the Moon, asteroids) are directly exposed to the solar wind plasma flow and UV radiation. The illuminated sides of these objects lose electrons, and their surface potentials are raised positive due to the dominating photoelectron flux, while their shadowed sides accrete electrons and acquire negative potentials (Manka, 1973; Criswell, 1973; De and Criswell, 1977; Whipple, 1981; Horanyi, 1996; Lee, 1996). Fig. 1 presents an illustration of global electric field near Phobos.

In addition, large deviations from the average surface potential are expected due to topography and/or compositional differences, resulting in strong local electric fields, Fig. 2.

* Corresponding author at: Space Research Institute, Moscow 117997, Profsojuznaja 84/32, Russia. Tel.: +1 495 333 2045.

E-mail address: zakharov@iki.rssi.ru (A. Zakharov).

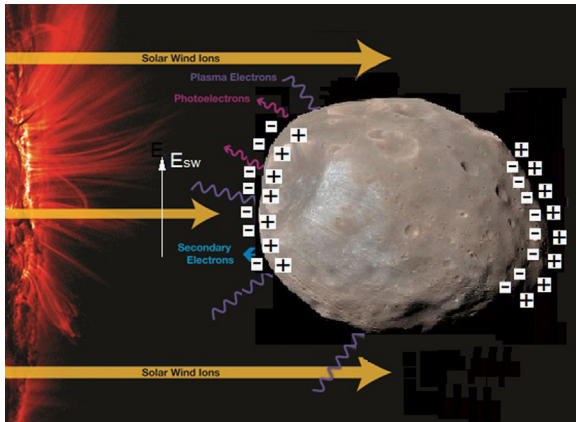


Fig. 1. Global electric fields arise near the surface under the action of the solar UV radiation and the solar wind plasma flow (this fig. is adapted from Stubbs et al., 2011 for the Phobos case).

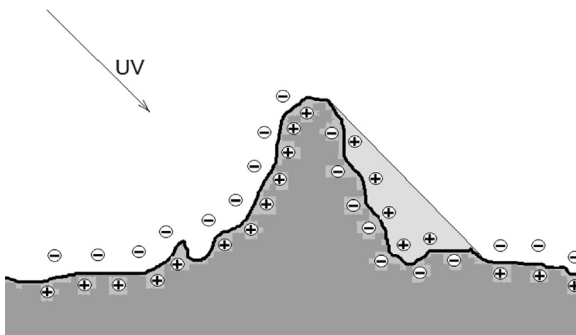


Fig. 2. Local electric fields can arise at topographical features (rocks) of the surface at the illuminated side of Phobos/Deimos.

These fields might be strong enough to overcome surface forces (adhesion and cohesion) and gravity for small charged dust particles, possibly resulting in electrostatic dust transport or levitated dust clouds. This assumes that the resistivity of the regolith at the surface is high enough to allow potentials and fields to build up faster than conduction currents could neutralize them. If the resistivity of the unlit regolith on Phobos and Deimos is similar to the resistivity of known meteorites or the lunar soil, it can be considered as an effective insulator (Duba and Boland, 1984; Lee, 1996).

Following the approach developed for asteroids (Lee, 1996), and taking into account the parameters of the solar wind at the Martian orbit (1.59 AU), the expected value of the electric field near the Phobos/Deimos sun-exposed surface may reach several volts per meter, depending on the angle of the solar illumination. If the electrostatic force, $F_e = qE$, exceeds the surface cohesive forces, F_c , plus the gravity $F_q = m_a g$ (m_a —mass of the dust grain, g —the gravitational acceleration due to the Phobos/Deimos), $F_e \sim F_q + F_c$, grains will leave the surface and may possibly levitate within the dusty plasma sheath (Criswell, 1971, Stubbs et al., 2006). As on the Moon (Reasoner and Burke, 1972), this plasma sheath is formed near the surfaces of Phobos and Deimos, due to the interaction of the solar wind and UV radiation with the regolith. The thickness of the sheath is approximately equal to the Debye length of the photoelectron plasma near the surface, what according to estimations is about several tens centimeters. If the mass of a grain is small enough, F_e exceed F_q , and grains may accelerate along the electric field through the dusty plasma sheath, possibly leaving this region and follow ballistic trajectories, or even escape from Phobos/Deimos.

The dynamics of dust grains near the surface due the electrostatic fields may be considered as a source of the small dust grains population ($< 1 \mu\text{m}$) in the Phobos/Deimos tori (see the next chapter). Besides, the dynamics of dust grains near the surface connected with periodically changes of the Sun angle and peculiarity of the surface topography may form areas on the surface with different characteristics of reflectivity in the IR spectra. The such inhomogeneous color features (red and blue) on the surface of Phobos. Such inhomogeneity in color tinges where detected by IR–vis spectrometer mounted at the Phobos-2 spacecraft (Ksanfomality et al., 1991). Clearly, more theoretical work is needed to understand electrostatic dust transport and its consequences on Phobos and Deimos.

The observations of dust dynamics due to electrostatic processes were made on the lunar surface by the onboard television systems on the *Surveyor* 1, 5, 6, and 7 and *Lunakhod* 2 spacecraft imaging the horizon glow (e.g. Rennilson and Criswell, 1974), several other observations by Apollo 16, 17 (e.g. Berg et al., 1976), and the Clementine spacecraft (Zook et al., 1995). These observations indicate the occurrence of transient bright clouds extending from and above the lunar surface (a review of observations of dust levitation on the Moon presented Colwell et al., 2007).

3. The dust belts of the Martian moons

An existence of dust rings near Phobos/Deimos orbits has been predicted more than 40 years ago (Soter, 1971) and discussed in several theoretical works (Ip and Banaszekiewicz, 1991; Banaszekiewicz and Ip, 1991; Kholshchikov et al., 1993; Ishimoto and Mukai, 1994; Juhasz and Horanyi, 1995; Krivov and Hamilton, 1997). It was suggested that due to their continuous hypervelocity (the average velocity at the Mars' orbit is about 15 km/s) bombardment by interplanetary micrometeoroids ($10^{-18} \text{g} < m < 10^2 \text{g}$) the surface dust grains may be ejected from the moons at velocities larger than their escape velocity (about 10 m/s for Phobos and about 6 m/s for Deimos), but smaller than the orbital speed of the moons ($V_{Ph} = 2.1 \text{ km/s}$ for Phobos and $V_D = 1.35 \text{ km/s}$ for Deimos), and should form a dust torus along the orbit of their source moons. These studies have shown that the motion of the ejected submicron-sized grains can be significantly influenced by the solar radiation and Lorentz forces (Horányi et al., 1991). Grains with the size larger than $1 \mu\text{m}$ are controlled mainly by the solar radiation pressure and gravity, including perturbations due to the oblateness of Mars (Krivov and Hamilton, 1997). The distribution of dust grains in the rings, their dynamics, sinks, sources, and their lifetimes strongly depend on the grain size (e.g. Krivov et al., 2006). One of the main parameters, that define the dynamics of dust grains at Mars, is the ratio, β , of solar radiation force to the gravity (Ishimoto and Mukai, 1994). The relatively large grains (grain radius larger than $\sim 10 \mu\text{m}$ for which $\beta < 0.01$) are concentrated in a toroidal belt along the satellite's orbits. The main perturbation acting on these particles is the solar radiation pressure that causes periodic oscillations of their eccentricities. The major loss mechanism is reaccretion to their parent moon. The lifetime for this population strongly depends on their size and vary from hundreds of years (for size $\sim 10 \mu\text{m}$) to as short as about one year (for about 1mm and larger). For grains in the size in the range of about 1–10 μm the solar radiation pressure causes the amplitude of eccentricity oscillations to be large enough for the dust grains to reach the Martian surface in less than 1 year. This dust population does not form a stable disk. The dynamics of the very small, submicron sized grains (less than $1 \mu\text{m}$, for which $\beta > 0.01$), may lead to dust populations not only due to bombardment by interplanetary micrometeoroids, but also as a result of acceleration in the near surface electrostatic field. The submicron sized dust particles are strongly affected by electromagnetic forces. The trajectories as well as the lifetimes of these particles are strongly influenced by the interplanetary plasma parameters, especially by high-speed solar wind

streams which can rapidly remove small dust particles from the vicinity of Mars and have been suggested that these particles to form an extended “halo” around Mars (Juhász et al., 1993, Krivov 1994). Fig. 3 presents the ring structure for particles with different masses near Phobos and Deimos (Isimoto et al., 1997).

According to the dust rings models developed by Krivov and Hamilton (1997) the distribution of grains in the Phobos and Deimos dust belts is non-uniform and depends on the size of the grains as well as the Martian season. The Phobos torus is shifted toward the Sun, whereas the Deimos torus is displaced away from the Sun in any season. The Phobos dust belt is oblate, while the Deimos torus, in contrast, is highly extended in the vertical direction (Hamilton, 1996). Fig. 4 presents an example configuration of the Deimos torus formed 17- μm particles (Krivov and Hamilton (1997)).

Further development of the dust belt model was made by Makuch et al. (2005) with consideration of the Poynting–Robertson drag, and by Krivov et al. (2006) using the modulation of the radiation pressure force due to the orbital eccentricity e_M of Mars. Inclusion of e_M (0.093) has only a small influence on the particles ejected from Deimos, but a rather significant effect for the grains ejected from Phobos. The lifetime of these grains depend on their mass and the solar longitude at the moment of their ejection. The lifetimes of grains in this case are determined mainly by collisions with the moons.

The orbital dynamics of dust around Mars is rather well understood and, according to the existing models, a rather stable part of the rings must consist of particles in the range from a few till 50 μm (Juhász et al., 1993). Submicron-sized grains form a time-dependent and non-uniform dust halo around Mars.

Attempts to directly observe the dust rings of the Martian have been made by several authors. Duxbury and Ocampo (1988) have analyzed images taken from the Viking 1 Orbiter to search for satellites and ring of Mars. Their result were negative. Observation made by HST

(Showalter et al., 2006) also gave negative results. However, these observations set an upper limit of the optical depth shown in Fig. 5. Optical depth of dust belts were estimated made by Krivov et al. (2006) based on models of the dust belts due to micrometeoroid impacts, assuming typical micrometeoroid particles with mass $m=10^{-5}$ g, impact speed $v_{\text{imp}}=15$ km/s, and flux $F_{\text{imp}}=10^{-16}$ $\text{g cm}^{-2} \text{s}^{-1}$. One of the critical parameter in these estimates is the production rate Y from the surface, which remains poorly defined. Taking into account that the plausible range of the production rate is $Y\sim(3-7)\times 10^2$, Krivov et al. (2006) got number of secondary particles from Phobos and Deimos is 10^5-10^6 s^{-1} and concluded that the optical depth of the Deimos belt is an order of magnitude below, while the Phobos ring could be two orders of magnitude below the observation limit set by HST (Krivov et al., 2006).

Another study to find evidence for the hypothetical Martian dust belts or outgassing / dust escape from the Martian moons by Fanale and Salvail (1989) is based on the disturbance of the solar wind moving through charged dust particles near the orbits of Phobos and Deimos. The discussion whether or not small celestial bodies such as magnetized asteroids, weakly outgassing planetary moons or clouds/trails of charged dust can interact with the solar wind to produce observable effects, was initiated with a theoretical investigation by Greenstadt (1971). He predicted that a sufficiently magnetized asteroid might create interplanetary magnetic field perturbations that spacecraft magnetometers might detect. Observations by the Galileo spacecraft during its encounters with asteroids Gaspra and Ida were interpreted in terms of solar wind interaction with a magnetic dipole field (Kivelson et al., 1993; Baumgärtel et al., 1994, 1997; Wang and Kivelson, 1996).

The first observation of unusual solar wind disturbances far downstream in the wake of Deimos was made by the Mars-5 spacecraft (Bogdanov, 1981). It was concluded that the observed effect can be due to the possible outgassing from the Martian

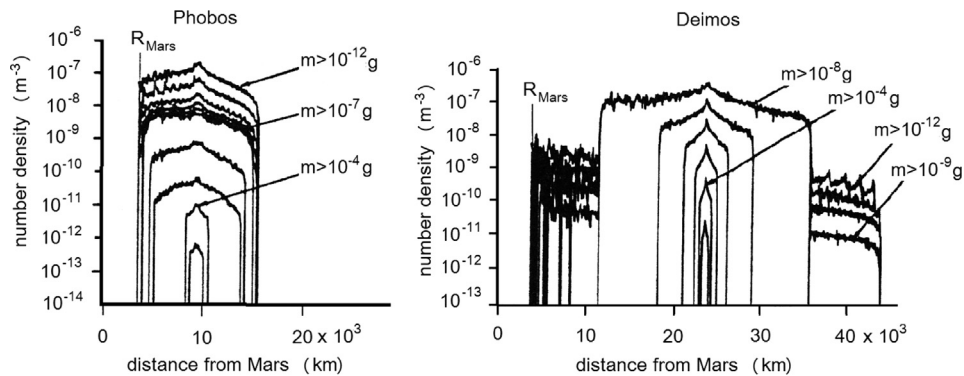


Fig. 3. Phobos and Deimos ring structure for the dust particles with different masses (Isimoto et al., 1997). For $\rho=2 \text{ g cm}^{-3}$ $m > 10^{-12} \text{ g}$ equivalently $a > 0,8 \mu\text{m}$, $m > 10^{-9} \text{ g}$ equivalently $a > 8 \mu\text{m}$, $m > 10^{-8} \text{ g}$ equivalently $a > 17 \mu\text{m}$, $m > 10^{-7} \text{ g}$ equivalently $a > 34 \mu\text{m}$, $m > 10^{-4} \text{ g}$ equivalently $a > 340 \mu\text{m}$.

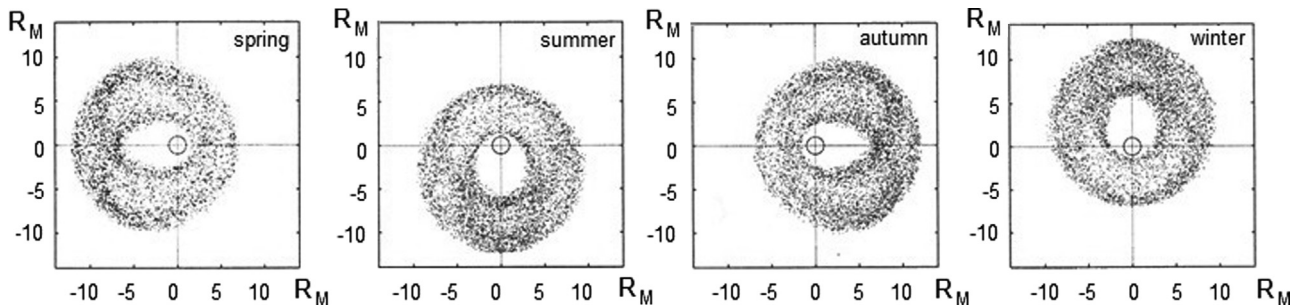


Fig. 4. XY projection of the torus formed by 17- μm particles originated from Deimos. The torus is shown for four Martian seasons. The coordinate system is centered on Mars, with the X axis directed toward the Martian spring equinox. The unit of distance is Mars radius. (Krivov and Hamilton (1997)).

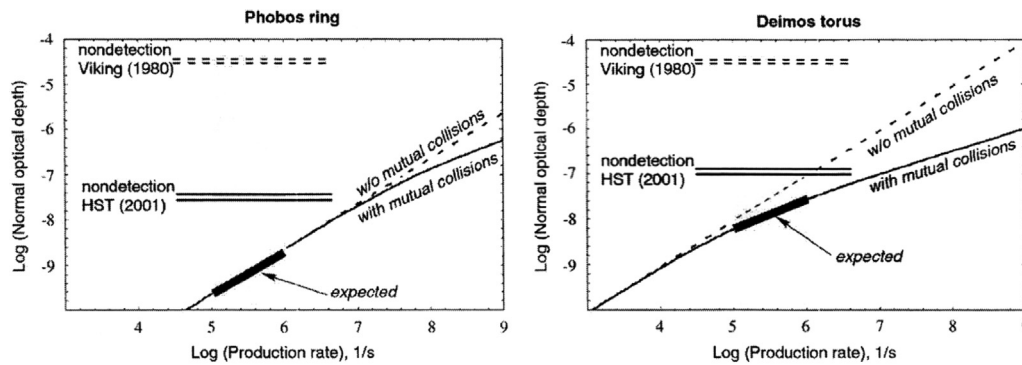


Fig. 5. Expected normal optical depth of the Phobos (left) and Deimos (right) dust tori (marked curve) as a function of the production rate of particles that make the largest contribution to the optical depth (20–30 μm for Phobos and 10–15 μm for Deimos) (Krivov et al., 2006). Horizontal double dashed and double solid lines mark upper limits of the optical depth set by observations with the Viking Orbiter 1 cameras in 1980 (Duxbury and Ocampo, 1988) and Hubble Space Telescope in 2001 (Showalter et al., 2006).

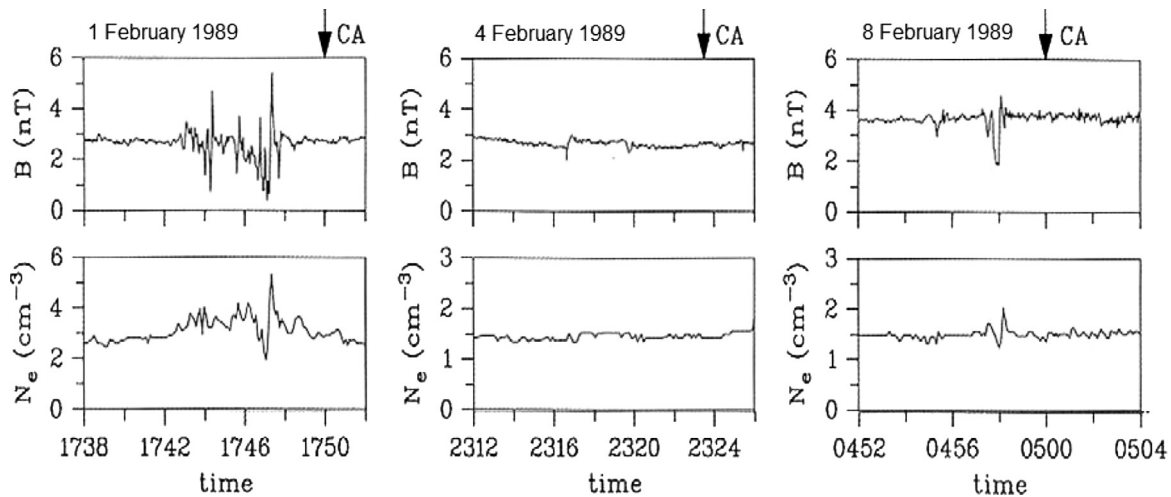


Fig. 6. The Phobos events observed by the Phobos-2 spacecraft during the first three elliptical orbits (February 1, 4, 8, 1989) just before crossing the Phobos orbit by the magnetometer MAGMA, and the electron and ion spectrometer ASPERA, mounted at the Phobos-2 spacecraft. The strength of the magnetic field (top) and the number density of electrons (bottom). (Dubinin et al., 1990).

moon. Due to outgassing the presence of a heavy ion population, with enhanced densities near the orbit of Phobos, may give rise to ion-ion beam instabilities, similar to those which are believed to operate in the solar wind interaction with cometary atmospheres (e.g. Tsurutani, 1991).

Solar wind plasma and magnetic field disturbances were also observed by the Phobos-2 spacecraft during crossing the Phobos orbit (Dubinin et al., 1990). Fig. 6 presents plots of the magnetic field (upper plots) and the density of electrons (lower plots) during crossing of the vicinity of Phobos by the Phobos-2 spacecraft at the first three elliptical orbits on February 1, 4 and 8, 1989. The most prominent increase of the electron number densities within a few tens of seconds are accompanied by simultaneous drops in the magnitude of the magnetic field were seen on February 1, 1989. The dimension of these diamagnetic plasma clouds along the spacecraft orbit, what were called “Phobos effects”, is about 50–100 km. The “Phobos effects” were considered in detail by Baumgartel et al. (1966,1968). It was concluded that the strongly localized magnetic field and plasma variations observed by the spacecraft near the closest approach to the orbit of Phobos were the signature of crossing of the dispersed fast mode Mach cone, originating from the positively charged dust torus along the moon’s orbit (Baumgartel et al., 1966).

These events near the crossings of the Phobos orbit have been suggested as indirect evidence for the presence of either a gas ring or a dust torus along the Phobos orbit (Dubinin et al., 1990; Baumgartel et al., 1966,1968).

More than thousand events in both the energy flux and the IMF magnitude in the Martian environment observed by the Mars Global Surveyor were identified for study. Their distribution was examined relative to Phobos and its orbits (Oieroset et al., 2010). However, these authors concluded that among several interpretations of reasons of observed solar wind disturbances there is no evidence for solar wind disturbances to be connected to the Martian moons, and they find no evidence for a gas/dust torus along their orbits.

Also, the disturbances of the solar wind in the vicinity of Mars observed by the ASPERA-3 ion spectrometer on board Mars Express did not indicate either a clear relation with the Martian moons (Futaana et al., 2009). However, detailed analyses of the most prominent event on July 23, 2008 during the Mars Express closest approach to Phobos arrived at a conclusion that the observed disturbances were induced by the backscattering of solar wind protons from the surface of Phobos.

4. Summary

In summary we conclude that there is a good theoretical understanding of the behavior of the dynamics of dust particles near the moons Phobos and Deimos. There are predictions for dust rings near their orbits based on detailed estimates for the sources and sinks of the dust particles as well as their lifetimes. However, there is no compelling observational evidence for the predicted dust torus,

around Phobos or Deimos orbits, and there are no observations yet of dust dynamics near their surfaces. Naturally, in order to detect the motion of dust near the surfaces of these moons, and their dust tori we need measurements using a complementary set of sensitive instruments, including impact dust detectors, electric field sensors, and optical cameras in future missions to Mars and its moons.

Acknowledgments

The work was supported by International Space Science Institute and the Program 22 of the Presidium of the Russian academy of sciences. We are grateful to J. Oberst for inspiration of this paper and E. Dubinin for helpful remarks.

References

- Banaszkiewicz, M., Ip, W.-H., 1991. A statistical study of impact ejecta distribution around Phobos and Deimos. *Icarus* 90, 237–253.
- Baumgartel, K., Sauer, K., Bogdanov, A., Dubinin, E., Dougherty, M., 1966. "Phobos-events": signatures of solar wind dust interaction. *Planet Space Sci.* 44 (6), 589–601.
- Baumgartel, K., Sauer, K., Dubinin, E., Tarrasov, V., Dougherty, M., 1968. "Phobos-events"—Signature of solar wind interaction with a gas torus. *Earth Planets Space* 50, 453–462.
- Baumgärtel, K., Sauer, K., Bogdanov, A., 1994. A magnetogidrodynamical model solar wind interaction with asteroid Gaspra. *Science* 263, 653–655.
- Baumgärtel, K., Sauer, K., Story, T.R., McKenzie, J.F., 1997. Solar wind response to a magnetized asteroid: linear theory. *Icarus* 129, 94–105.
- Berg, O.E., Wolf, H., Rhee, J., 1976. Lunar soil movement registered by the Apollo 17 cosmic dust experiment. In: Elsasser, H., Fechtig, H. (Eds.), *Interplanetary Dust and Zodiacal Light*. Springer-Verlag, N.Y., pp. 233–237.
- Bogdanov, A.V., 1981. Mars satellite Deimos interaction with the solar wind and its influence on the flow around Mars. *J. Geophys. Res.* 86, 6926–6932.
- Colwell, J.E., Batiste, S., Horányi, M., Robertson, S., Sture, S., 2007. Lunar surface: Dust dynamics and regolith mechanics. *Rev. Geophys.* 45, 1–26. (Paper number 2005RG000184–RG2006/2007).
- Criswell, D.R., 1973. Horizon glow and the motion of lunar dust. In: Grard, R.J.L. (Ed.), *Photon and Particle Interactions with Surfaces and Space*. Reidel, Dordrecht, pp. 545–556.
- De, B.R., Criswell, D.R., 1977. Intense localized photoelectric charging in the lunar sunset terminator region. 2. Supercharging at the progression of sunset. *J. Geophys. Res.* 82, 1005–1007.
- Duba, A.G., J.N., Boland, 1984. High temperature electrical conductivity of the carbonaceous chondrites Allende and Murchison. In: *Proceedings of the 15th Lunar and Planetary Science Conference*, pp. 232–233. (Abstract).
- Dubinin, E.M., Lundin, R., Pissarenko, N.F., Barabash, S.V., Zakharov, A.V., Koshkin, H., Schwingshuh, K., Yeroshenko, Ye.G., 1990. Indirect evidence for a gas/torus along the Phobos orbit. *Geophys. Res. Lett.* 17, 861–864.
- Duxbury, T.C., Ocampo, A.C., 1988. Mars: Satellite and ring search from Viking. *Icarus* 76, 160–162.
- Fanale, F.P., Salvail, J.R., 1989. Loss water from Phobos. *Geophys. Res. Lett.* 16, 287–290.
- Futaana, Y., Barabash, S., Holmstrom, M., Lundin, R., The ASPERA team, 2009. Solar wind interaction with Phobos: observation of a new type of interaction. *European Planetary Science Congress*, vol. 4, EPSC2009-701, EPSC Abstracts.
- Greenstadt, E.W., 1971. Conditions for magnetic interaction of asteroids with the solar wind. *Icarus* 14, 374–381.
- Hamilton, D.P., 1996. The asymmetric time-variable rings of Mars. *Icarus* 119, 153–172.
- Horányi, M., 1996. Charged dust dynamics in the Solar system. *Annu. Rev. Astron. Astrophys.* 34, 383–418.
- Horányi, M., Tatrallyay, M., Juhasz, A., Lunmann, J.G., 1991. The dynamics of submicron-sized dust particles lost from Phobos. *J. Geophys. Res.* 96 (A7), 11283–11290.
- Ip, W.-H., Banaszkiewicz, M., 1991. On the dust/gas tori of Phobos and Deimos. *Geophys. Res. Lett.* 17 (6), 857.
- Ishimoto, H., Mukai, T., 1994. Phobos dust rings. *Planetary and Space Science* 42 (8), 691–697.
- Isimoto, H., Kimura, H., Nakagawa, N., Mukai, T., 1997. Planned observation of Phobos/Deimos dust rings by Planet-B. *Adv. Space Res.* 19 (1), (1)123–(1)126.
- Juhasz, A., Horányi, M., 1995. Dust torus around Mars. *J. Geophys. Res.* 100, 3277–3284.
- Juhasz, A., Tatrallyay, M., Gevai, G., 1993. On the density of the dust halo around Mars. *J. Geophys. Res.* 98, 1205–1211.
- Kholshchevnikov, K.V., Krivov, A.V., Sokolov, L.L., Titov, V.B., 1993. The dust torus around Phobos orbit. *Icarus* 105, 351–362.
- Kivelson, M.G., Bargatze, L.F., Khurana, K.K., Southwood, D.J., Walker, R.J., Coleman jr., P.J., 1993. Magnetic field signatures near Galileo's closest approach to Gaspra. *Science* 261, 331–334.
- Krivov, A.V., 1994. On the dust belts of Mars. *Astron. Astrophys.* 291, 657–663.
- Krivov, A.V., Hamilton, D.P., 1997. Martian dust belts: waiting for discover. *Icarus* 128, 335–353.
- Krivov, A.V., Feofilov, A.G., Dikarev, V.V., 2006. Search for the putative dust belts of Mars: the late 2007 opportunity. *Planet. Space Sci.* 54, 871–878.
- Ksanfomalija, L., Murchie, S., Britt, D., Duxbury, T., Fisher, P., Goroshkova, N., Head, J., Kuhrt, E., Moroz, V., Murray, B., Nikitin, G., Petrova, E., Pieters, C., Soufflot, A., Zharkov, A., Zhukov, B., 1991. Phobos: spectrophotometry between 0.3 μm and 0.6 μm and IR-radiometry, special issue: Phobos-Mars mission. *Planetary and Space Science*, 39, pp. 311–327.
- Lee, P., 1996. Dust levitation on asteroids. *Icarus* 124, 181–194.
- Makuch, M., Krivov, A.V., Spahn, F., 2005. Long term dynamical evolution of dusty ejecta from Deimos. *Planet. Space Sci.* 53, 357–369.
- Manka, R.H., 1973. Plasma and potential at the lunar surface. In: Grard, R.J.L. (Ed.), *Photon and Particle Interactions with Surfaces in Space*. Reidel Publishing Co., Dordrecht, Holland, pp. 347–361.
- McCoy, J.E., Criswell, D.R., 1974. Evidence for a high altitude distribution of lunar dust. In: *Proceedings of the 5th Lunar and Space Science Conference*, pp. 2991–3005.
- Oieroset, M., Brain, D.A., Simpson, E., Mitchell, D.L., Phan, T.D., Halekas, J.S., Lin, R.P., Acuna, M.H., 2010. Search for Phobos and Deimos gas/tori using observations from Mars global surveyor MAG/ER. *Icarus* 201, 189–198.
- Reasoner, D.L., Burke, W.J., 1972. Direct observation of the lunar photoelectron layer. *Proc. Lunar Sci. Conf.* 3, 2639–2654.
- Rennilson, J.J., Criswell, D.R., 1974. Surveyor observations of lunar horizon-glow. *The Moon* 10, 121–142.
- Showalter, M.R., Hamilton, D.P., Nicholson, P.D., 2006. A deep search for Martian-dust rings and inner moons using the Hubble Space Telescope. *Planet. Space Sci.* 54, 844–854.
- Soter, S., 1971. The Dust Belts of Mars. Rep. 462, Cornell Center for Radiophysics and Space Research Physics, Ithaca, N.Y..
- Stubbs, T.J., Vondrak, R.R., Farrell, W.M., 2006. A dynamic fountain model for lunar dust. *Adv. Space Res.* 37, 59–60.
- Stubbs, T.J., Glenar, D.A., Farrell, W.M., Wang, Y., Collier, M.R., Zimmermann, M.I., McClanahan, T.P., Vondrak R.R., 25–27 January 2011. Consideration for investigating the Moon's plasma and dust environment with the Russian LUNA landers. Landing site selection for the LUNA-GLOB mission international workshop, Space Research Institute.
- Thomas, P., 1979. Surface features of Phobos and Deimos. *Icarus* 40, 223–243.
- Thomas, P., Veverka, J., 1980. Downslope movement of material on Deimos. *Icarus* 42, 234–250.
- Tsurutani, B.T., 1991. Comets: a laboratory for plasma waves and instabilities, in *Cometary plasma processes*. *Geophys. Monogr.* 61. (AGU).
- Wang, Z., Kivelson, M.G., 1996. Asteroid interaction with solar wind. *J. Geophys. Res.* 101, 24479–24493.
- Whipple, E.C., 1981. Potentials of surfaces in space. *Rep. Prog. Phys.* 44, 1197–1250.
- Zook, H.A., Potter, A.E., Cooper, B.L., 1995. The lunar dust exosphere and Clementine lunar horizon glow. *Lunar Planet. Sci. Conf.* 26, 1577–1578. (Abstract).