Dust at the Martian moons and in the circummartian space

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A B S T R A C T

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 impact dust detectors, electric field sensors, and optical cameras in future missions to Mars and its moons.

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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.
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 μm) 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 (Ksanfomalite 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 Banaszkiewicz, 1991; Banaszkiewicz and Ip, 1991; Kolišhevnikov et al., 1993; Ishimoto and Mukai, 1994; Juhasz and Horányi, 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 g < m < 10⁻⁹ 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 (Vₚₘ = 2.1 km/s for Phobos and V₉ᵋ = 1.35 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 μm 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 ~10 μm for which β < 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 ~10 μm) 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 μm, for which β > 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.
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 microns to a few millimeters. The lifetime of these grains depends 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.

Fig. 3. Phobos and Deimos ring structure for the dust particles with different masses (Isimoto et al., 1997). For $\rho = 2 \, \text{g cm}^{-3}$, $m > 10^{-12}$ g equivalently $a > 0.8 \, \mu\text{m}$, $m > 10^{-9}$ g equivalently $a > 8 \, \mu\text{m}$, $m > 10^{-8}$ g equivalently $a > 17 \, \mu\text{m}$, $m > 10^{-7}$ g equivalently $a > 34 \, \mu\text{m}$, $m > 10^{-6}$ 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)).

Attempts to directly observe the dust rings of the Martian have been made by several authors. Ducru 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 micrometeorite particles with mass $m = 10^{-5}$ g, impact speed $v_{\text{imp}} = 15 \, \text{km/s}$, and flux $F_{\text{imp}} = 10^{-16}$ g cm$^{-2}$ 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 $Y \approx (3-7) \times 10^{2}$, 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
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.

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