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ON THE DUST/GAS TORI OF PHOBOS AND DEIMOS

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Abstract. The dust and gas environment in the vicinity of the orbit of the Phobos moon is assessed using both theoretical methods and observations from previous missions to Mars. It is found that a stable ring of dust particles with radii $\approx 100 \mu m$ could exist with a normal optical depth close to the upper limit determined from the Viking Orbiter 1 mission. The presence of a gas ring with neutral number density substantially higher than the hot atomic oxygen background is possible only if the Phobos moon maintains a certain level of outgassing with $Q_{gas} > 10^{23}$ molec. s^{-1}. The narrow width ($\approx$ 400 km) and the strong plasma perturbations sometimes observed by the Phobos 2 spacecraft at crossings of the orbit of the Phobos moon are still a puzzle to be investigated by further data analysis.

1. Introduction

After orbital insertion at Mars, the Phobos 2 spacecraft had executed 5 elliptical orbits before its circularization into an orbit at 6000 km altitude. During the phase of elliptical orbits, different regions of the Martain magnetosphere and its solar wind interaction were explored with a full set of plasma instruments. A lot of new information concerning the physical properties of the bow shock, the plasma boundaries (i.e., the magnetopause and planetopause), and the ionospheric plasma outflow have been obtained [*Riedler et al.*, 1989; *Lundin et al.*, 1989; *Rosenbauer et al.*, 1989; *Shutte et al*, 1989]. At the same time, several interesting events of plasma disturbances were detected as the spacecraft crossed the orbit of the Phobos moon. In one of the more well-defined events, large-amplitude magnetic field fluctuations, variations in the plasma flow velocity, and the appearance of a suprathermal electron burst were observed [see *Dubinin et al.*, 1989]. In these episodes which have a characteristic dimension of several hundred km, the spacecraft was usually much farther away from the Phobos moon, the plasma effect of a ring of gas and/or particulate material in Phobos moon's orbit thus could be the basic cause. This is indeed an attractive idea in view of the fact that the possible existence of such a Phobos gas/dust torus surrounding Mars has been postulated before [*Soter*, 1971; *Ip*, 1988]. The origin of the dust ring can be attributed to meteoroid bombardment on the satellite surface. The key point is that [*Soter*, 1971], with an ejection velocity of a few to a few tens m s^{-1}, the fragments from the satellite surface could continue to move in near-circular orbits around the central planet. We refer the reader to detailed discussions on the dust ring dynamics by Dobrovoskis and *Burns* [1980], *Davis et al.* [1981] and *Banaszkiewicz and Ip* [1989].

As for the gas ring, in addition to meteoroid impact, intrinsic outgassing and accretional interaction with the hot oxygen corona of Mars could also contribute. In this report, in order to facilitate further analyses of these so-called Phobos torus events, we shall make some quantitative estimates of the dust and gas contents to be expected in the vicinities of Phobos and Deimos.

2. Dust Rings

A most direct way to detect planetary rings is naturally via imaging experiments. Under favorable geometry, even a ring of very tenuous structure can be observed. A good example is the Jovian ring which has a normal optical depth of $\tau_\perp \approx 3 \times 10^{-5}$ [*Smith et al.*, 1979]. When the ring was viewed in a nearly edge-on orientation, its brightness would be significantly enhanced because of the large increase of the optical depth along the line-of-sight, i.e., $\tau_{||} = \tau_\perp$ (H/h) where H is the radial width of the ring and h the vertical thickness. In the case of the Jovian ring, H $\approx$ 6300 km and h < 30 km, thus $\tau_{||} > 6.3 \times 10^{-3}$.

For micron-sized dust particles, their strong forward-scattering effect when observed at small phase angle will permit further increase in their brightness. Such an observational condition was approximately reached in the late phase (ca. 1980) of the Viking Orbiter 1 (VO-1) mission during which the VO-1 orbit was in the equatorial plane of Mars and the phase angle was at 28° when viewed from apoapsis. A sequence of pictures was taken within ± 350 km from the equatorial plane inside the orbit of Phobos. A search for satellites and rings was performed by *Duxbury* and *Ocampo* [1988] using these images. Their result suggests that no evidence of rings or other small satellites was found. A conservative upper limit of 50 m can be set for the radius of small satellites in this region; furthermore, a ring with a brightness equal to the Jovian ring would have been detected in the VO-1 images.

As mentioned before, the continuous bombardment of the surfaces of Phobos and Deimos by interplanetary meteorids could lead to the formation of dust rings in the vicinities of these Martian moons. Figure 1 illustrates the estimated time scales (t_m) of surface impacts for meteoroids of different masses [see *Fechtig et al.*, 1981, for details]. It can be seen that while the bombardment of mm-sized particles (m $< 10^{-3}$ g) may be considered as being continuous ($t_m < 1$ sec), meteoroids of larger masses (m > 1 g) would hit Phobos and Deimos rather infrequently, i.e., $t_m >$ a few days.

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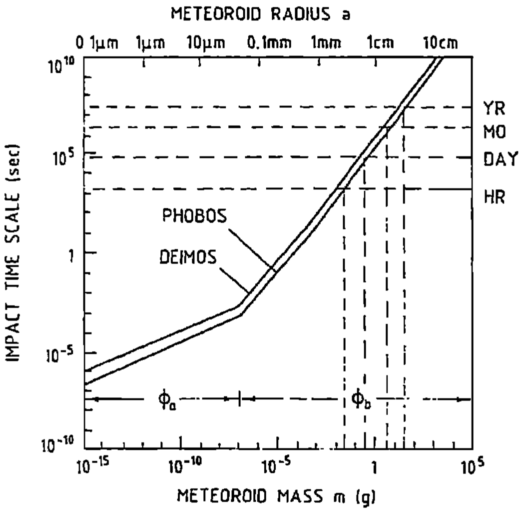

Fig. 1. The meteoroid impact time scales at Phobos and Deimos for meteoroids of different sizes.

In fact, between the Viking mission and the Phobos mission, the Phobos moon would have been hit by a large object with m ≈ a few hundred g only once. In the few months after the arrival of the Phobos 2 spacecraft at Mars, the satellite would have been hit by a 10-g meteoroid. Such a "large" impact event would certainly lead to the injection of a discrete dust cloud into planeto-centric orbits superimposed on a steady background of dust ring particles from continuous micrometeoroid impacts. According to *Davis et al.* [1981], the velocity distribution of the ejecta should follow a very steep velocity dependence, i.e., the ejecta flux in the velocity range (v, v+Δv) should be $I_{ej}(v) \ \alpha \ v^{-13/4}\Delta v$. If the lower limit of the ejecta velocity is assumed to be 0.1 V_{es} where $V_{es} \approx$ (5-10 m/s) is the surface escape velocity, the percentage of the escaping mass flux should be about 5×10^{-3} of the total ejecta flux. *Banaszkiewicz and Ip* [1989] estimated that the ratio of the total ejecta mass to the projectile mass is on the order of 7×10^3. In other words, we have $(M_{ej}/m)_{escape} \approx$ 35.

In our present work, we assume that the ejecta all have their radii (a) at about 100 μm radius as the Keplerian motion of smaller particles is unstable due to the perturbation effect from interaction with the interplanetary medium [*Horanyi et al.* 1989]. From Figure 1, we find that the impact freqeuncy of 100 μm-radius particles at Phobos' surface is about 10^2 hits s^{-1}; the resultant ejecta flux is thus $F_{ej}(100\mu m) \approx 1.8 \times 10^3 - 3.5 \times 10^3$ particles s^{-1}.

The collisional destruction life time t_c for a 100-μm radius dust particle at 1 AU has been computed to be 3×10^5 years (Grün, et al., 1985). The average number density (n_r) of the ring dust particles can be obtained via a steady-state balance of the particle production rate from surface ejection at Phobos (or Deimos) with the collisional destruction rate, i.e., $F_{ej}(100\mu m)t_c = n_r V_r$, where V_r is the spatial volume of the dust torus. For a ring width H and a vertical thickness h, we have $n_r = F_{ej}t_c/(2\pi$ R H h). With R ≈ 9000 km, H ≈ 400 km, the surface number density is $n_r h \approx 0.15$ or $n_r \approx 1.5 \times 10^{-7}$ if $h \approx 10$ km. The corresponding value of normal optical depth would be $\tau_\perp \approx \pi n_r h a^2 \approx 4.4 \times 10^{-5}$ which is very close to the upper limit derived by the VO-1 observations [*Duxbury and Ocampo*, 1988]. If the Poynting-Robertson effect is important in causing inward radial drift of the ring particles [*Banaszkiewicz and Ip*, 1989], we expect the effective ring width (H_{eff}) to be larger than 400 km. The maximum value is $H_{eff} \approx 6000$ km, the normal optical depth would be reduced to be 6.6×10^{-6} in this case. The total mass contained in the dust ring or dust disc will be on the order of 2.5×10^{11} g. This means that the sporatic ejection of dust clouds as a result of "large" meteoroid impact events should not significantly upset the long-term mass balance.

3. Gas Rings

The O_2^+ ion is an important constituent in the upper ionosphere of Mars. Just like Venus electron dissociative recombination of O_2^+ near and above the planetary exobase would allow the production of exothermic ($\Delta E \approx 1$ eV) atomic oxygen forming a hot oxygen corona [*see Ip*, 1988; *Nagy and Cravens*, 1988 and references therein]. In the following we shall make use of the oxygen density profile described in *Ip* [1988] as it yields the maximum number density ($n* \approx 200$ cm^{-3}) at Phobos' orbit.

In the presence of a hot oxygen corona, the dust ring from Phobos would introduce quite interesting effects. The most immediate process is that the dust particles will accrete the oxygen atoms via collisions. Atoms so attached will later be released with a velocity (V_a) determined by the surface temperature (T_r) of the ring particles, i.e., $V_a = (2kT_r/m*)^{\frac{1}{2}}$ where $m*$ is the mass of the oxygen atom. With $T_r \approx 245K$, $V_a \approx 0.5$ km s^{-1}. In comparison, the orbital velocity (V_o) of the Phobos moon is 2 km s^{-1}; most of the released oxygen atoms should be confined in planeto-centric orbits. On the other hand, hydrogen atoms which are accreted by the dust grains would tend to escape from the system as a result of their much larger value of $V_a(\approx 2$ km $s^{-1})$.

Assuming a 100% efficiency, we can express the total ring accretion rate as

$$\dot{N} = n^*.V^*.(\pi n_r a^2).(2\pi RHh) \qquad (1)$$

where V^* is the average impact velocity between the hot oxygen atoms and the ring particles. With $V^* \approx 3$ km s^{-1}, R ≈ 9000 km, $H \approx 400$ km, $h \approx 10$ km, a ≈ 100μm and $n^* \approx 200$ cm^{-3}, we find $\dot{N} \approx 6 \times 10^{20}$ atoms s^{-1}. If the ionization time scale is set to be $t_i \approx 3 \times 10^6$ sec, a balance between supply and loss would lead to the presence of a gas torus with an average number density of 4 atoms cm^{-3} if the circular cross section of the torus has a radius of $R_T = (V_a/V_o)R$. If the velocity dispersion of the reemitted gas is taken into consideration, a central peak with a half-width of 300 km should appear in the gas distribution. Figure 2 shows the radial variation of the number density of the hot oxygen corona in the equatorial plane, the recycled gas from dust ring accretion, and the gas particles from possible surface outgassing of the Phobos moon. The model calculations show that a peak density of about 20 atoms cm^{-3} may be expected. The enhancement in the oxygen atom number density from gas-dust ring interaction is hence quite small. Only for an optical depth (i.e., $\tau_\perp \approx 10^{-3}$) much larger than the VO-1 limit would the gas ring density obtained this way be $\approx 2 \times 10^3$ atoms cm^{-3}. The neutral gas distribution

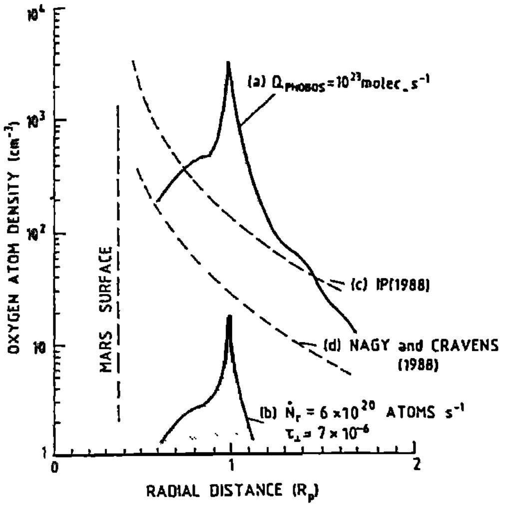

Fig. 2. A comparison of the neutral gas densities from different sources in the Martian exospheric environment: (a) a gas ring from Phobos outgassing with a production rate of $Q_{gas} \approx 10^{23}$ molec. s^{-1}; (b) a gas ring from accretion of the hot oxygen atoms by the dust ring (the normal optical depth of the dust ring is $\tau_\perp \approx 4 \times 10^{-5}$); (c) the hot oxygen corona model from Ip (1988); (d) the hot oxygen corona model from Nagy and Cravens (1988).

associated with a hypothetical outgassing effect from Phobos with a gas production rate of 10^{23} molec. s^{-1} is depicted in Figure 2. In this situation, a peak density of about 4×10^3 particles cm^{-3} will be possible. It is interesting to note that a recent study by *Fanale and Salvail* [1989] showed that an escape rate of such magnitude at present may be possible via subsurface sublimation of water ice contained in the Phobos moon.

It should be noted also that an additional source is from collisional interaction of the dust ring with the tailward plasma flow of heavy ions. For an ion flux of $10^6 - 10^7$ ions cm^{-2} s^{-1} [*Lundin et al.*, 1989], the ring accretion rate could be as much as 10^{20} ions s^{-1} for a nominal value of $\tau_\perp \approx 4 \times 10^{-5}$. In this way, a narrow ring of O_2 molecules can be formed.

4. Plasma effects

The perturbations on the solar wind flow from the gas/dust ring could arise in several ways. First of all, ionization of the neutral gas and the subsequent pickup process could lead to plasma turbulences as observed in the comas of comets Giacobini-Zinner and Halley. The basic idea is that the newborn exospheric ions would have a ring-beam like pitch-angle distribution which is unstable to plasma instabilities [*Wu and Davidson*, 1972; *Sagdeev et al.* 1986]. Note that in the case of comet Halley a significant level of magnetic field fluctuations was observed at cometocentric distances as far away as 2×10^6 km at which point the neutral gas number density $n_g \lesssim 10$ cm^{-3}. At Mars, the number density of the hot oxygen corona reaches 10 cm^{-3} at about 15000 km altitude. However, since the scale length of the Martian hot oxygen corona is much smaller than that of the cometary coma, the plasma turbulences should not have time to grow to similar magnitudes. Indeed, no special magnetic field disturbances (except for the "Phobos torus events") have been reported.

After creation, an exospheric ion will be accelerated into cycloidal motion by the interplanetary electric field $\underline{E} = -\underline{V}_{sw} \times \underline{B}_o$ where $\underline{V}_{sw}$ is the solar wind velocity and B_o the interplanetary magnetic field. Because of the difference in the gyroradii and the opposite sense of gyrations, the new ions and their photoelectrons will consititute a so-called pick-up current in the mass-loading region [*Ip and Axford*, 1980; *Goertz*, 1980]. If $\dot{n}_i$ is the exospheric ion production rate, the corresponding pick-up current can be expressed as

$$j_\perp = m_i \dot{n}_i c^2 E / B_o^2. \tag{2}$$

Such current flow, in principle, can generate field-aligned propogation of MHD perturbations [*Gurevich et al.*, 1978]. The magnitude of the perturbation field (ΔB) can be estimated by the following expression,

$$\Delta B \approx 4\pi j_\perp \Delta s / c \tag{3}$$

where Δs is the length scale of the magnetic perturbations. Combining Eqs.(2) and (3) we have eventually,

$$\Delta B \approx 4\pi m_i \dot{n}_i V_{sw} \Delta S / B_o \tag{4}$$

With $\dot{n}_i \approx 10^{-4} - 10^{-3}$ molec. s^{-1}, $\Delta s > 500$ km, and $B_o \approx 5$ nT we find $\Delta B \approx 0.1 - 1$ nT. While this represents a significant amplitude of magnetic field variations, it is in no way near the large-amplitude fluctuations with $\Delta B / B_o \gtrsim 1$ as observed in one of the "Phobos torus" events [*K. Schwingenschuh, priv. comm.*, 1989]. In conclusion, the detected features could not be readily explained in terms of solar wind - gas torus interaction.

As for the dust ring, if the solar wind flow is nearly tangential to the ring plane, the integrated absorption effect (i.e., $\tau_\parallel$) could amount to about 2×10^{-3} for a nominal ring thickness of $h \approx 10$ km. Only in the case when h is much smaller, i.e., h ≈ 0.1 km, would the resultant solar wind absorption effect ($\tau_\parallel \approx 0.2$) be appreciable. In combination with photoelectron emission, the collisional interaction (and sputtering) of the solar wind plasma with the dust particles would lead to a build up of the surface electrostatic potential (ϕ). For instance, in the sunlight, $\phi \approx 10$ V and $\phi \approx -10$ V in the shadow of the planet. The surface charging of phobos and Deimos could also lead to electrostatic levitation and subsequent ejection of small dust particles (see Ip, 1986). As for the dust ring effect, assuming free-space charging and using the simple formula [*Mendis and Axford*, 1974] relating the total number of electrons (Z_e) to ϕ and the particle radius (a),

$$Z_e = 700 \phi(V) \mathrm{a}(\mu\mathrm{m}) \tag{5}$$

we find that $Z_e \approx 7 \times 10^5$ if a $\approx 100 \mu$m. Hence, even for an extremely low dust density, the corresponding charge density could be quite high ($n_r Z_e \approx 0.2$ *el.*cm^{-3} for h ≈ 10 km and $n_r Z_e \approx 20$ *el.* cm^{-3} if $h \approx 0.1$ km). In comparison, the solar wind plasma density is $n_{sw} \approx 3 - 5$ cm^{-3}. It is thus possible that such charge sheet might introduce interesting electromagnetic effects in the dust ring region [*W.I. Axford, priv. comm;* 1989).

5. Discussion

Our considerations of the dust and gas distributions in the vicinity of the orbit of the Phobos moon suggest that a main dust ring of particles with radii on the order of 100 microns and a normal optical depth of $6 \times 10^{-5} - 6 \times 10^{-6}$ could, in principle, be maintained by meteoroid bombardment. A gas ring of oxygen atoms could be supplied by collisional interaction of the dust ring with the hot oxygen corona and the tailward plasma flow of heavy ions. The nominal number density is very small, however. The gas density could be enhanced in two ways: (a) maintainence of a certain level of surface outgassing from the Phobos moon, or (b) increase of the dust ring content. The first possibility may be tested by direct detection of H_2O vapour and/or OH emission (the required surface density of H_2O is about 2×10^9 molec. cm^{-3}). The second possibility can be examined by analysis of the imaging data from the Phobos mission as was done for the VO-1 observations [cf. *Duxbury and Ocampo*, 1988]. Note that even if the main dust ring is quite tenuous (i.e., $\tau_\perp < 7 \times 10^{-6}$) we still expect the presence of a halo of sub-micron particles generated by meteoroid impact at the Phobos moon and with the ring particles. Because of electrostatic charging, their Keplerian motion around Mars could be highly perturbed. As for the so-called "Phobos torus" events, no clear-cut physical mechanism(s) can yet be identified except for the thin charge sheet effect discussed in Sec. 4. A more quantitative study would be needed to assess this possibility. Finally, we should note that in the later phase of the Phobos mission, the spacecraft stayed very close to the orbit of the Phobos moon; we would therefore expect the detections of similar "Phobos torus" events in these circular orbits. We perhaps could find the ground truth in the corresponding data set.

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