COMPUTER SIMULATION OF REGOLITH VERTICAL STRUCTURE AND EXPOSURE AGE OF SMALL SATELLITES OF PLANETS

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Abstract. The simulation has shown that the regolith layers several hundred meters thick can be formed on the small satellites of planets of Phobos and Deimos type providing that almost all the material lost at meteorite impacts return to the satellite. The existence of a global layer on Deimos that filled the craters for the depth of about 5 m can be explained by the crater presence of diameter of about 4 km and the age of less than 350 Myr on its hemisphere almost unstudied. Dust belts with dust concentration by 3 orders greater than round the Earth can exist in the region of satellite orbits.

1. Introduction

The model of soil impact reworking on atmosphereless cosmic bodies (ACB) described by Evsyukov (1987a, b; 1990) was decided to be extended for the occasion of small satellites of planets for which the returning of a considerable part of the material lost before at impact events may be essential (Soter, 1971). The main aim of calculations was to investigate the regolith vertical structure on such bodies – the thickness of sedimentary layers and their exposure age, i.e. the time of soil particles staying outside the satellite and in the regolith uppermost layer (about 2 cm thick). The structural and chemical changes of regolith grains affected by protone and other types of irradiation are determined by the exposure age. Phobos and Deimos, satellites of Mars, as well as the Moon studied most carefully served as standards to check the calculation results.

2. The Model of ACB Surface Section

The model should involve as great size range of craters under formation as possible the number of which increases by about 3 orders with decreasing diameter by one order. At the same time the resources of ES-1052 computer used allow to simulate separately the formation of only about 1000 craters. Under these terms the following model of ACB surface section was realized.

A surface section was represented by 3 matrices with 10 by 10 elements, the centers of which coincide and elements sizes are 10 and 100 times less while approaching the center. It allowed to take into account separately the formation of craters on the corresponding matrices, the diameters of which differ in 3 orders. Besides that the formation range of craters by 1 or 2 orders less than the basic ones for the given matrix was taken into account at the average. In the central

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area the ejecta from all the craters were considered. The formation of craters of diameters of 1 km, 100 and 10 m was simulated separately but of diameters of 1 m and 10 cm – at the average (in the central area).

The regolith vertical structure was represented by 50 layers on each matrix. An impact on any matrix element destroyed a certain number of layers filled with material, but the ejecta from the nearby craters and sedimentation of material lost by a satellite before filled the layers with the material again. Each layer was characterized by the thickness h, the degree of crystallinity z, and the exposure age T_e.

3. The Model of Crater Formation

The crater size distribution was set by the power law $\lg N = A - k \lg D$, where N is a cumulative number of craters (their density) of a diameter larger than D (in meters) on the given area (usually 10^6 km^2), A and k are distribution constants (Morris and Shoemaker, 1968). The distribution shown graphically consists of two linear parts with different slope indices. For larger craters starting with some D_c the slope index is close to -3, to be more exact it is determined by the distribution of the impactors energy (Woronow *et al.*, 1982). This is unsaturated crater distribution. For smaller craters the slope index is close to -2 (saturated distribution). The critical diameter D_c changes on the Moon from several meters for younger mare regions (the average D_c on the mare surfaces is equal to 10–20 m) to 1 km for the oldest continental ones (Florensky *et al.*, 1975). It is possible that on Phobos and Deimos the diameter D_c reaches even greater values (Thomas and Veverka, 1980). While making calculations the standard value $k = 3$ was accepted for the crater production function. The craters shape was accepted as a spherical segment with the depth-diameter ratio equal to 0.2. The thickness of the ejecta blanket h outside the crater should depend only on the distance r to the center of the crater (Basilevsky *et al.*, 1983): $h = 0.05D\,(2r/D)^{-3}$. The calculation was made up to $r = 5D$ and it was assumed that the volume of the ejecta blanket is equal to the volume of the crater formed.

The part of the ejecta volume the satellite looses at an impact was calculated according to the data of O'Keefe and Ahrens (1977) for the meteorite impact velocity that is 15 km s^{-1}.

The relation between the energy of the impactor and the volume of the crater formed for the craters in the 'strength-scaling' regime is taken from Basilevsky *et al.* (1983), the material density of ACB is supposed to be equal to 3 g cm^{-3}.

To determine the soil maturity, 3% of the ejecta volume were assumed to melt and turn into glass (Basilevsky *et al.*, 1983) (parameter $V_m = 0.03$). Parameter z characterizes the part of crystalline component in soil, i.e., the degree of maturity.

Parameter K_l characterizing the part of the ejecta volume in the blanketing area changed within the limits from 0.05 to 1 what corresponds to ACB of diameter from 1 to 3500 km (lunar sizes) (Evsyukov, 1987b). This parameter was a factor in the formula for the thickness of the ejecta layer. Parameter K_r characterizes the part of the material lost by satellite which after orbiting the planet for some period of time, ΔT_e, sediments on the satellite surface and forms the layer of a uniform thickness.

The interval between two successive impacts forming in the model separate craters of a minimal diameter was selected as the unit time (u.t.) of the exposure time T_e. As it was shown in Woronow *et al.* (1982), the craters density and size distribution at $D > 8$ km are similar on Mercury, Moon and Mars and are unsaturated. Perhaps the terrestrial planets were bombarded by two body populations: one of them is responsible for the postaccretionary period of intensive bombardment on the early stages of a planet surface formation during the first 0.9 Byr (1 Byr = 10^9 yr), the other is responsible mainly for the crater formation in the postmare lunar period lasted 3.5 Byr. At the constant density of the meteorite flux the value D_c is proportional to time and reaches a value of 10 m during the postmare period. The meteorite flux density in the premare period was essentially higher and D_c on the lunar continent reached a value of 1 km, that is 100 times more than on the lunar maria. This period was 4 times shorter than the postmare one and the meteorite flux density is 400 times higher. That's why the unit time selected in the model for the abovementioned crater sizes (and for reaching the value of D_c of about 100 m at the end of the calculations) makes up on the average about 90 thousand years in the premare period and about 35 Myr in the postmare period.

In the model the linear scale is not fixed and only the ratio between crater sizes and the thickness of the ejecta layers is preserved. While changing the crater sizes we must change the layers thickness, the value of D_c and the unit time proportionally. If $D_c \approx 1$ km the diameters of separate craters make up 100 m, 1 km and 10 km, and the unit time makes up about 0.9 Myr in the premare period and about 350 Myr in the postmare one.

4. The Main Results of Calculations

4.1. Mass balance

First of all the mass balance was checked. At $K_r = 1$, in other words when all the material lost by satellite returns to it in due course, the mass balance appeared to be practically full in spite of satellite size. The numerical estimation of thickness of the layer lost by satellite owing to the soil impact reworking can be presented as $h_l = 2.8D_c(1 - K_l) \times (1 - K_r)$ at arbitrary values of K_l, K_r and D_c, i.e. for the satellites of Phobos and Deimos type (K_l is about 0.6) at $D_c = 100$ m and $K_r = 0.2$ the thickness of the layer lost reaches 60 m and at $D_c = 1$ km is greater by one order.

4.2. Degree of soil maturity

Soil maturity at the chosen values $V_m = 0.03$ and $k = 3$ appeared to be very insignificant. At $K_l = 1$ and $K_r = 1$ the degree of crystallinity z reached the value of about 0.8, similar to the Moon (Evsyukov, 1987a). With decreasing the parameter K_l the value z somewhat increased even at $K_r = 1$ and made up about 0.9. At $K_r = 0.2$ the value z is about 0.95. The calculation of the soil maturity under the optimum conditions, when $k > 3.3$ (Evsyukov, 1987b) were not carried out but according to the obtained data the soil maturity on small satellites of planets even at $K_r = 1$ proceeds slower than on the large bodies. The reason is that the material ejected at impacts is outside the satellite during some time and is not exposed to the impact reworking.

4.3. Exposure age of soil

The time variations of the exposure age T_e of the regolith uppermost layer when $K_r = 1$ and 0.2, $K_l = 0.05$, 0.6 and 1 (for satellite diameters $D_s = 1$, 10 and 3500 km) and when the time of the material return to satellite ΔT_e is equal to 2 u.t. are shown in Figure 1. The time increasing of parameter T_e has a saturation character. The exposure age increases also with the increasing of parameter K_r and with the decreasing of parameter K_l; i.e., if $\Delta T_e = 2$ u.t. the essential contribution into T_e is made by the staying of the satellite material ejected at impacts on the circumplanetary orbit. In the same figure there are two time scales T of the surface impact reworking – i.e., in fact, of an absolute age, meant to reach the values of D_c of about 100 m and 1 km at the end of the calculations. The most part of the calculations is related to the premare lunar period when D_c increment of 1 m has occurred for about 1 Myr. The last D_c increment of 10 m ($T =$ 0.9–4.4 Byr) with the rate of 1 m per about 350 Myr relates to the postmare period on the second scale T.

Two scales of an exposure age T_e calculated for the premare period correspond with the mentioned scales of an absolute age T. The age-limits T_e about 0.6 and 6 Myr correspondingly (at ΔT_e of about 0.2 and 2 Myr) were registered. During the postmare period the critical diameter D_c on the lunar mare surface increased from 0 to 10 m which the T_e increment of about 2 u.t. or 70 Myr (at $\Delta t_e = 2$ u.t.) corresponds to on the first scale. The exposure age of the continental surface should be approximately similar as the contribution of the pre-mare impact reworking of soil into T_e increment is insignificant.

The duration of the satellite material staying on the circumplanetary orbit ΔT_e does not depend on the intensivity of the meteorite bombardment but is determined by a great number of parameters affecting the movement of dust particles before they come into a collision with a satellite (Soter, 1971). It was decided to vary it while specifying ΔT_e as 0.01, 2 and 8 u.t. The results are represented in Figure 2.

Value $\Delta T_e = 0.01$ u.t. corresponds to the situation when the determining factor

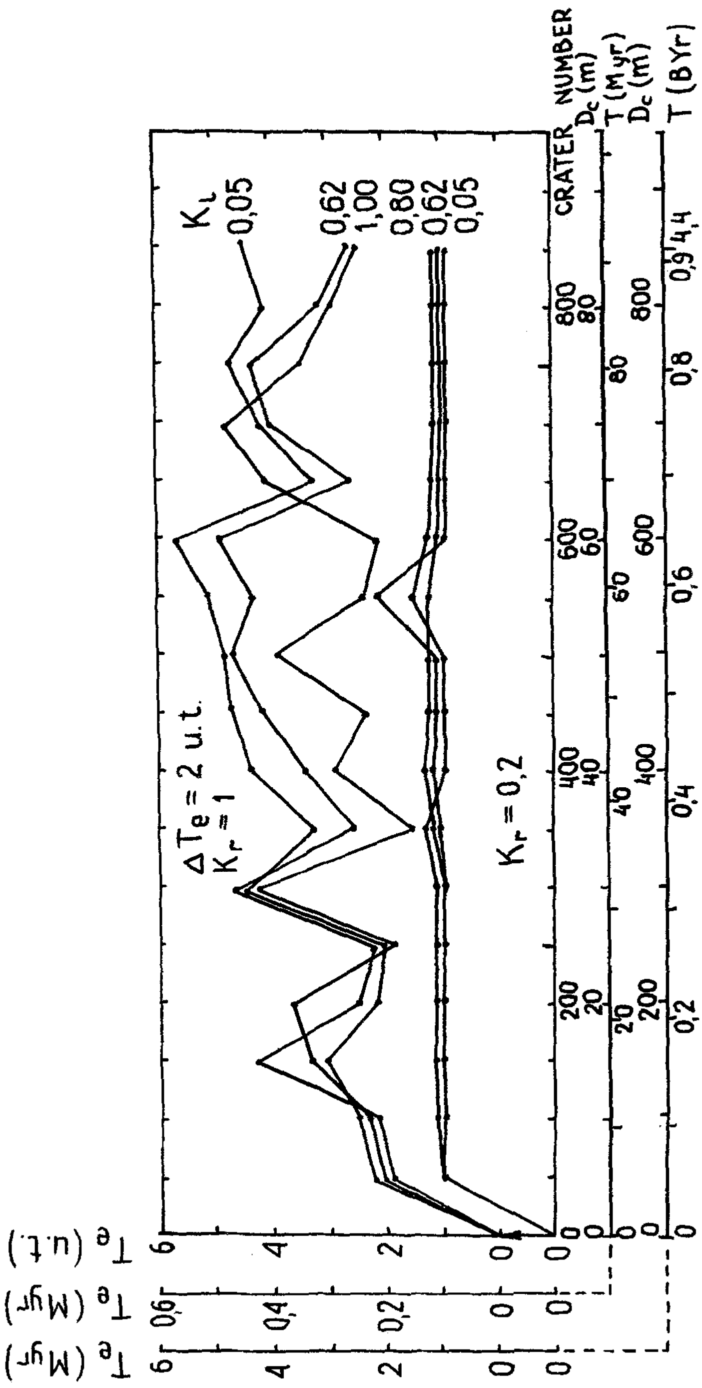

Fig. 1. The time variations of the exposure age T_e of the regolith uppermost layer. Scales description is given in the text.

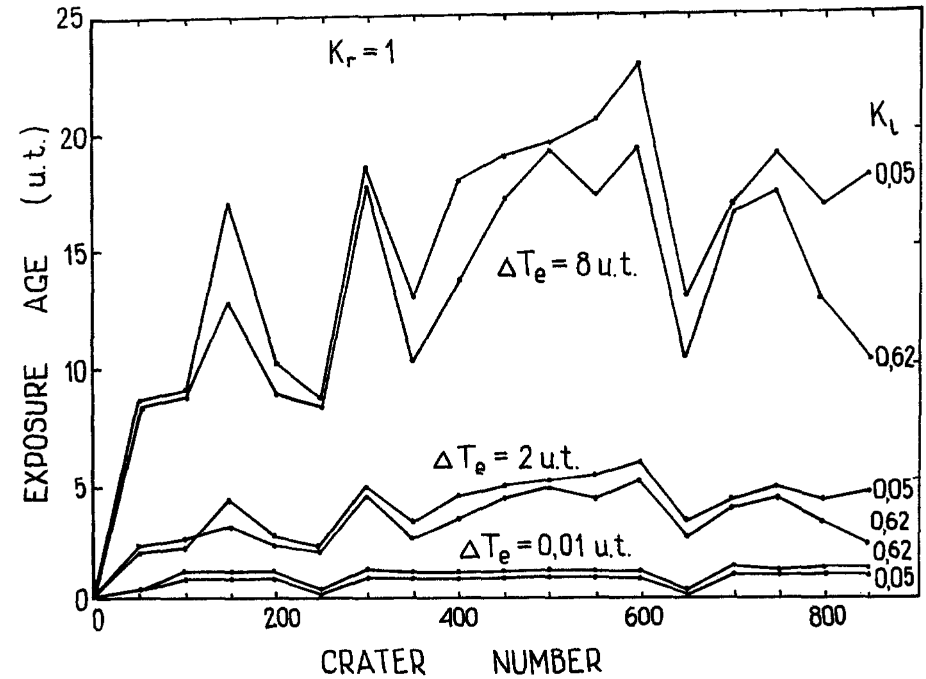

Fig. 2. The influence of the duration of the satellite material staying on the circumplanetary orbit ΔT_e on the exposure age of satellite uppermost layer.

for the increment of the regolith grains exposure age is their staying in the surface uppermost layer exposed to the different types of radiation and the intensive vertical stirring. For the other values of ΔT_e the increment of T_e takes place mainly on account of the material staying outside the satellite.

For $\Delta T_e = 0.01$ u.t. the average age on the surface is close to 1 u.t. (Figure 2), i.e. in the postmare period it is close to 35 Myr (this very situation is related to Phobos and Deimos). Thickness of a layer, which this age is related to, makes up about 2 cm, as just such layer is completely stirred for specified time. On the Moon the exposure (radiative) age of the surface layer about 20 cm thick is estimated as 500 Myr (Kashkarov *et al.*, 1975), but in the area of the ejecta from the fresh craters of $D \gg 1$ m is determined by the craters age. These values of the exposure age correspond to each other; though for small satellites of planets, even if $K_r = 1$, the exposure age should be less than on the large bodies, as the returning material covers the surface uniformly and refreshes it.

When $\Delta T_e > 1$ u.t., i.e. when the material staying outside the satellite becomes the determining factor, value T_e is roughly proportional to ΔT_e (Figure 2). Value $\Delta T_e = 8$ u.t. corresponds to about 0.7 Myr in the pre-mare period, and about 300 Myr in the post-mare one. The last number must be not real and the first one is considerably lower than the above-mentioned values of T_e. Thus the exposure age is mainly determined by the impact reworking of the surface in the post-mare

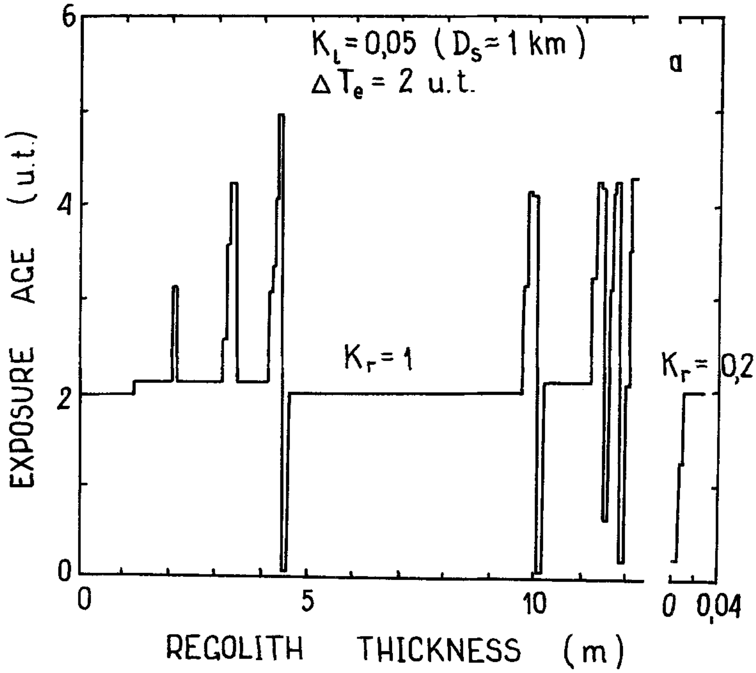

Fig. 3a.

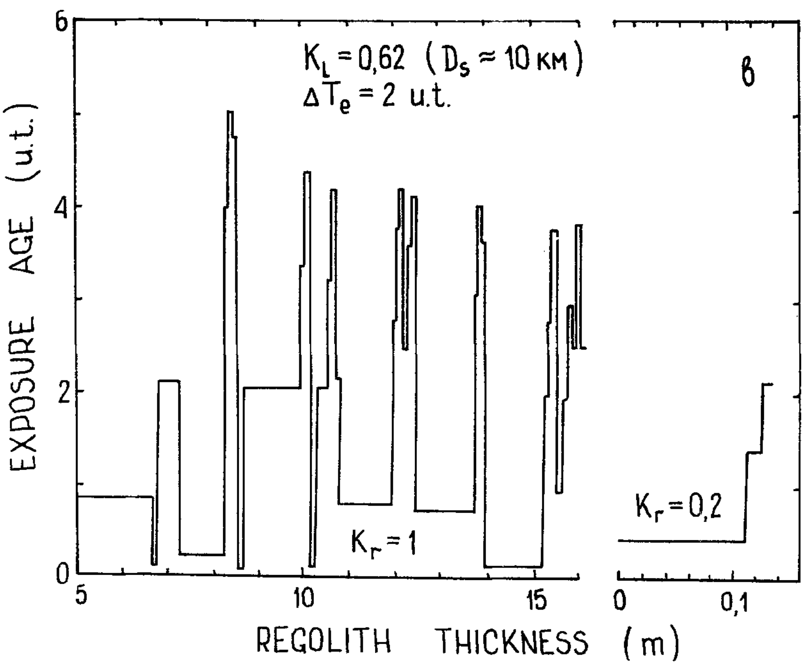

Fig. 3b.

Fig. 3. The vertical regolith structure on satellite after reaching the critical diameter D_c of about 100 m for: (a) satellite diameter D_s of about 1 km; (b) satellite diameter D_s of about 10 km.

period. For the soil uppermost layer about 2 cm thick its estimation is close to 35 Myr at $\Delta T_e \ll 1$ u.t. and is several times higher at $\Delta T_e > 1$ u.t.

4.4. Regolith vertical structure

The typical vertical structure of the regolith on the satellites of diameters D_s of about 1 km (K_l is about 0.05) and 10 km (K_l is about 0.6) for $K_r = 1$ and 0.2 is shown in Figure 3 in the form of dependence $T_e(h)$ after reaching the value D_c of about 100 m and it is accepted that $\Delta T_e = 2$ u.t. If the returning coefficient $K_r = 0.2$ then the total thickness of the regolith ejecta layers is close to 4 cm for $D_s = 1$ km and to 14 cm for D_s of about 10 km. The increasing of D_c to 1 km will increase this thickness by the factor of 10 approximately (for $D_s \gg D_c$, otherwise the satellite will be destroyed). At $K_r = 1$ and D_c of about 100 m the regolith thickness reaches about 15 m in spite of the satellite size and by one order greater at D_c of about 1 km. At $K_r = 1$ and D_c of about 100 m the regolith is formed by the tens of the layers of different thickness. The layers of about 1 m thick are met often enough, the layer of about 5 m thick is registered in one case.

The exposure age of separate layers does not depend on their depth and varies within the range from 0 to 5 u.t. Since the post-mare period, when the unit time is about 35 Myr, makes the main contribution into the exposure age, value T_e for about 2 upper meters of the regolith (ΔD_c is about 10 m) is considerably higher than for the lower layers – about 70 Myr on the average (at $\Delta T_e = 2$ u.t.). The layers having the highest values of T_e are rather thin – about 10 cm.

5. Discussion of the Results

The adduced results of the calculations can be compared with the data for the Martian satellites Phobos and Deimos with their major axes of 27 and 15 km correspondingly (K_l is about 0.6).

The determination of the craters critical diameter on these satellites appeared to be very complicated. The cumulative size-distributions of the craters within the diameter range from 40 m and to the maximum ones (10 km for Phobos, 2.3 km for Deimos) obtained from the whole surface of Phobos and from the hemisphere of Deimos appeared to be very close to the saturated distribution with the slope index $k = 1.9$ (Thomas and Veverka, 1980). D_c cannot be defined with these data. The relative crater density was noted to be 2 times lower in the area of Stickney and the grooves connected with it on Phobos (Thomas and Veverka, 1980). Formally, according to the craters distribution inside the grooves $D_c \approx 0.25$ km at k of about 2.4 is obtained in the field of unsaturated distribution but the deviation from the saturated destribution lay within the limits of measurement error. The considerable deviations from the crater saturated distribution are registered within the range of diameters less than 200 m in the number of small areas on Phobos. The reduction of the crater density with respect to the saturated one increases with the decreasing of the crater diameters and reaches tens of times for the minimum diameters among the studied ones ($D = 10$–20 m). The similar reductions for $D < 25$ m (up to $D = 5$ m) are registered on the only photo of Deimos section with high resolution (Thomas and Veverka, 1980).

The differences in the craters size-distribution on the Moon and the satellites of Mars can be caused, according to Thomas and Veverka (1980), by the differences in the flux density of the bombarding bodies, as well as in the forces of gravitation and the soil strength. It is shown in Woronow *et al.* (1982) that the densities of meteorite fluxes are similar for all the terrestrial planets. Craters diameters under the gravitation influence can be 2 times larger against the Moon, i.e. the same value $D_c = 1$ km can be reached on Phobos for about 0.4 Byr and not for 0.9 Byr of the pre-mare bombardment (the total age is about 4 Byr). Under the same conditions the Stickney age at D_c of about 0.25 km should be younger than the basic surface age by about 0.3 Byr. The low soil strength on the Martian satellites should also assist in increasing the crater sizes but the numerical estimations of the effect are not carried out.

The typical cumulative density of the craters at saturation makes up 8–10% of the maximum one on the Moon and the Martian satellites (Veverka, 1978; Thomas and Veverka, 1980), what is caused, in general, by the destructive action of the larger craters and partially by the smaller ones. However, with the craters size approach to the maximum one for a cosmic body the main destructive factor disappears and the craters saturated density aims to a maximum one that can be reached. It must decrease the slope index of a function of craters saturated distribution on satellites of Mars up to $k \approx 1$ at $D > 0.5$–1 km. In fact such slope index is not observed and it testifies to the unsaturated craters distribution in the range of specified sizes. The slope index of the craters production function on satellites of Mars may be less than on the Moon, i.e. $k = 2$–2.5 (Thomas and Veverka, 1980; Ivanov, 1989). All this leads to vague estimation of D_c on satellites of Mars. The most probable value of D_c is close to 1 km with the indefinite factor of 2, i.e. close to D_c on the lunar continent.

According to Veverka (1978) the regolith thickness on Phobos reaches about 200 m though the craters do not show any signs of their filling. On Deimos the most part of craters are partially filled with the ejecta up to the depth of about 5 m but it does not exclude the existence of a thicker regolith layer.

The results of the numerical simulation at $K_r = 1$ and $D_c = 1$ km certify the possibility of existence of such thick regolith layer on small satellites of planets but do not demonstrate considerable differences in regolith structure between such bodies as Phobos and Deimos are, if, of course, not to consider the values of K_r to be different enough for them. The low density of small craters detected in some Phobos regions (Thomas and Veverka, 1980) and, probably, typical for the whole Deimos surface (Veverka, 1978) may be connected with the existence of fresh mantle about 5 m thick on Deimos and some tens of meters thick in the separate regions of Phobos. Such mantle is formed on satellites of Mars around the craters of diameter of more than 0.5 km. It is possible that seismic waves arising at strong impacts destroy small craters in a loose regolith. In size range of the craters completely destroyed the unsaturated function of craters production should be observed which is expected to become saturated again at $D < D'_c$ (D'_c is the critical diameter on the refreshed surface). The actual resolution of photographs did not allow to reveal this part of crater size distribution, but while giving a value of $k > 2$ and supposing that the craters with the minimal sizes are new, one can estimate the value D'_c. For all mentioned regions D'_c is less than 1 m. The age estimation of such regios according to D'_c and the crater density of the smallest craters registered gives 0.01–0.1 of the duration of the postmare lunar period, i.e. 35–350 Myr. With the older age of such regions the deviations from the saturated size-distribution of the craters would not be revealed. On Phobos with the surface area of about 1500 km^2 10–20 craters of diameter of 1 km and more should be formed during the postmare lunar period at $k = 3$. On Deimos the number of such craters should be 4 times less. The existence of local areas of small craters destruction can provide it. However, if a sedimentary layer about 5 m thick is assumed to be the global one on Deimos (Veverka, 1978) and formed with the help of ballistic sedimentation of a satellite of the material lost at a strong impact before, it is necessary to suppose the existence of an extremely young crater of diameter of about 4 km on Deimos (the volume of lost material is about 2 km^3). Such crater does not exist on Deimos hemisphere studied. The picture of the other hemisphere was made only once with a bad resolution and at a small phase angle when any details of a profile are undistinctive (Thomas and Veverka, 1980). Nevertheless, it seems to be hardly probable that so large the crater was not revealed on that photo, so the abovementioned blanket on Deimos should be considered local. According to Thomas and Veverka (1980) this possibility cannot be excluded.

As for a certain time ΔT_e the satellite material lost at impacts stays on the circumplanetary orbits, it forms an additional dust concentration.

Using the fromula given above for the thickness of a layer lost by a satellite we shall obtain the volume estimation of dust staying outside the satellite: $V_d = 1.8 D_c (1 - K_l) S$, where D_c is the critical diameter which is approached during the time ΔT_e; S is the satellite surface area. For Phobos $S = 1500$ km^2. In the postmare lunar period $D_c = \Delta T_e / 3.5 \times 10^8$ m yr^{-1}. In the surroundings of Phobos orbit $V_d \approx 3 \times \Delta T_e$ m^3, where ΔT_e is expressed by years. About 3 m^3 of dust per year or 10^7 g yr^{-1} are ejected from Phobos surface that is close to the lower limit of this value estimation done by Ivanov (1989).

According to Soter (1971) the mean time of a particle life till a collision with Phobos is equal to ΔT_e (yr) $= 1.5\, v$ (m s^{-1}) $- 7.5$, where v is a particle velocity with respect to Phobos and a volume of a belt occupied by these particles is equal to $V(\text{m}^3) = 1.4 \times 10^{16}\, v^2\, (\text{m s}^{-1})$. While using an inversely proportional distribution of ejecta masses on ejecta velocities (Ivanov, 1989) and restricting the upper velocity limit by the possibility of approaching Deimos orbit we shall obtain a mean mass proportional velocity value of the particles ejected from Phobos: $v = 140$ m s^{-1} with $\Delta T_e \approx 200$ yr and $V \approx 2.6 \times 10^{20}$ m^3 corresponding to it. The total dust volume on Phobos belt is about 600 m^3, the mass m is about 2×10^9 g. The mass transfer through the area fixed with respect to Phobos makes up $mv/V \approx 0.03\ \mathrm{g\,m^{-2}}$ yr, that is by one order greater than an estimation made by Ivanov (1989).

If an average diameter of dust particles is 100 m their concentration in the belt is $\sim 5 \times 10^{-6}\ \mathrm{m^{-3}}$. In the Earth surroundings, according to the data by Hörz *et al.* (1975) a micrometeorite flux for particles with masses of more than 10^{-10} g (with a diameter of more than 10 μm) is about $2 \times 10^{-5}\ \mathrm{m^{-2}\,s^{-1}}$, that for an average particles velocity of $8\ \mathrm{km\,s^{-1}}$ gives their concentration of $\sim 3 \times 10^{-9}\ \mathrm{m^{-3}}$, i.e. by 3 orders lower than in Phobos belt. The influence of separate impacts, that form large craters on Phobos, on dust concentration is unimportant due to small number of such impacts. The volume of dust contained in a belt can be doubled with formation of a crater of $D \approx 30$ m what occurs on Phobos every 5 thousand years. While forming a crater of $D = 4$ km a satellite loses about 2 $\mathrm{km^3}$ of dust and its concentration is 10^6 times more but such events are unique during the whole satellite history.

Optical density of dust belts has an average value of about 10^{-7}, so they could not be revealed with a help of photometric method. The existence of these belts has to be taken into account while planning any cosmic experiments nearby Mars.

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