AN ANALYTICAL MODEL FOR THE REGOLITH EVOLUTION OF SMALL BODIES IN THE SOLAR SYSTEM.

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I - INTRODUCTION

The meteoritic bombardment of the Moon has triggered the growth and the dynamical evolution of a regolith, i.e., the superficial layer of dust grains and rock fragments that constitutes the lunar surface, and which is about 5 meter-thick on lunar maria. In this paper we extrapolate a model of lunar regolith evolution (1,2) to a test body with a radius, $R_s \sim 10$km, injected either in the asteroidal belt or in orbit around Mars. In this way we simulate the regolith evolution of both small asteroids and the Martian satellites, Phobos and Deimos. In two companion papers (3), we then show how these theoretical predictions when constrained with various types of experimental observations give clues about the early history of the Martian satellites and the origin of gas-rich meteorites.

II - PRELIMINARY REMARKS

All models of regolith evolution so far reported in the litterature including ours(2,4) rely on a few basic functions, which are the meteoritic mass spectrum, $\phi(m>m_o) = Am_o^{-\gamma}$, the production rate of impact crater with a radius, r, $N(r>r_o) = Kr_o^{-\delta}$, and the radius and depth of a crater, $r = Bm^{-\lambda}$ and $D = Cm^{-\lambda'}$. In these expressions, A, B, K, C, γ, δ, λ,λ' are considered as constant within a given range of mass.

In this short paper we can neither derive in detail the mathematical formulation nor rigorously justify all the assumptions used in our computations. The space environment of a small body such as an asteroid is different from that of the Moon. One of the major problem for regolith "evolutionists" is to estimate the corresponding values of both $\phi(m)$ and N(r), which are still very poorly known beyond the Earth's orbit. On the other hand the values of the crater shape parameters (r and D), are considered as much more reliable as a result of extensive laboratory simulation experiments dealing with the physics of impact phenomena.

Our simple analytical model of regolith evolution differ from the models previously reported. In fact this model, purposely based on the physic of impact phenomena, is intended to make regolith predictions as much independent as possible from the absolute values of $\phi(m)$ and N(r). For example the only major assumption used in our derivation of the regolith thickness, Δ_e and Δ_f, (see below) is that in the meteorite mass range $\gtrsim 10^{-2}$g (which plays the major role in the growth and the "gardening" of a regolith) $\phi(m)$ can be represented by a power law spectrum in a given mass range. When an absolute evaluation of $\phi(m)$ was required for evaluating regolith growth rates for example, we considered that the variation of the asteroidal component of the meteoritic flux with the heliocentric distance can be raisonably inferred from the work of Hartmann (5). Consequently $\phi(m)$ is about 1.3 and 10 times higher near Mars and the asteroids, respectively, than on the Moon.

In addition to the effects expected from a different space environment the regolith evolution of a small body differs from that of the Moon with regard to the following points ; i. the acceleration of gravity ($g_s \sim 1 cm.s^{-2}$) is much smaller than on the Moon. Consequently most of the material ejected upon meteoritic impact has a velocity exceeding the escape velocity, and this mass will be lost for the formation of a regolith, i.i. In addition, the small value of g_s triggers a drastic change in the extent and thickness of the blanket of material ejected from the crater interior, whereas both the radius and the depth of the craters are only slightly affected in a predictable way ; i.i.i. it is generally assumed that the lifetime of a small body via fragmentation by a large meteorite producing a crater with a critical radius, r_f, markedly decreases with R_s. This in turn should limit the integrated duration of the meteoritic bombardment of the surface and consequently the growth of a regolith.

III - THE DYNAMICAL EVOLUTION OF ASTEROIDAL REGOLITH

Let us consider a regolith with a thickness, Δ, which is spread on the constituent bed rocks of a small asteroid with a radius, $R_s \sim 10$km. Only the craters that penetrate through the bed rocks contribute to the formation of "fresh" regolith material. In addition, there is a critical radius, $r_c = R_s^2/R_M$ (the subscripts s and M will constantly refer to the small body and the Moon, respectively), such as 50% of the excavated material is ejected with a speed exceeding the escape velocity. The regolith will then only grow when the r_c-craters will inject an amount of bed rock material larger than that of regolith material lost to space. It can be shown that this condition implies that Δ reaches an equilibrium thickness, Δ_e, such as $(r_c-4\Delta_e)^3/r_c^3 \sim 0.5$. Finally,

$$\Delta_e \sim 0.005\ R_s^2/R_M. \tag{I}$$

This expression of Δ_e, which is independent of any assumption on $\phi(m)$, shows that a regolith can be formed on small asteroids, as $\Delta_e \sim 2$m, when $R_s \sim 10$km. This general prediction, that we already derived 3 years ago (6), is in good agreement with both the more complex "model dependent" computations of Housen et al (4) relevant to larger asteroids and the telescopic observations of several asteroids showing in particular a negative branch in their polarization curves (7).

Upon meteoritic impact this limiting thickness will recess toward the interior with a rate, dR_s/dt, which now depends on the absolute value of $\phi(m)$. For R_s values $\lesssim$ a few tens of km, dR_s/dt can be approximated by the following simple expression :

$$dR_s/dt \sim AB^2C \log m_f/m_c \tag{II}$$

where A, B, C, are the constants defined in the previous section and m_f and m_c the mass of a meteorite capable of fragmenting the asteroid and producing a crater with a radius, $r_c = R_s^2/R_M$, respectively.

With the values of $\phi(m)$ derived by Hartmann and by supposing that the intensity of the ancient meteoritic flux is similar to the present day value, we deduce the following scenario for the evolution of asteroidal regolith (In this paper we thus exclude exotic speculations based on the existence of a much more intense meteoritic flux $\gtrsim$ 4 by ago) : for $R_s \sim 10$km the value $\Delta_e \sim 2$m is reached in $\lesssim 100$ my and the regolith subsequently recesses to the interior with a speed of ~ 10 m/by. When R_s increases up to 100km, $\Delta_e \sim 200$m, and dR_s/dt, which has now to be inferred from a formula different from that just quoted for Rs $\lesssim 10$km, decreases to about 2m/by.

In sharp contrast to the lunar regolith, which presents a stratified structure, no stratum should be expected in the regolith of a small asteroid except in the immediate vicinity of a large crater. In fact as a result of the small value of g_s, the ejecta blanket is spread over a distance which is $\sim R_M/R_s$ times greater than on the Moon. Consequently the thickness of the strata varies as R_s^{-2}, and they cannot be observed when R_s 0.3 R_M. The regolith grains of a small asteroid ($R_s \sim 10$km) are thus deposited individually via a "steady rain" and this has profound implications concerning their space weathering (3), when they reside in the most superficial layers of their parent regolith.

IV - THE REGOLITH OF THE MARTIAN SATELLITES

As already pointed out by Pollack (8) the material ejected from a small satellite in orbit around Mars could efficiently be reaccreted,and we thus predict that Δ should be larger than the equilibrium value, $\Delta_e \sim 2$m, evaluated for an asteroid. On the other hand Δ cannot exceed an upper limit, Δ_f, corresponding to the exposure of the satellite surface to the maximum integrated flux of metecrites beyond which the satellite is fragmented by an impact crater with a critical radius, $r_f \sim R_S/2$. With this value of r_f and by imposing that all the ejected material is reaccreted, the value of Δ_f can be obtained first by computing the volume of material accreted per unit of time and per cm^2, $d\Delta/dt$. Then this expression has to be integrated up to the time when an impact crater with a radius, $r_f \sim R_s/2$ is formed. We thus obtain :

$$d\Delta = \int_{4E}^{R_s/2} K. \ .R^{(-\delta-1)\pi/6}.(R-4E)^3 \ dR \qquad \text{(III)}$$

By taking a raisonable range of δ values (>3)this integral can be solved in yielding a value, $\Delta_f \sim R_s/50$, that only slithly depends on δ($\Delta_f = R_s/60$, $R_s/45$ and $R_s/30$ when $\delta = 3.2$, 3.4 (lunar value) and 4.0, respectively) and which happens to be independent of the absolute values of both $\phi(m)$ and $N(r)$.

From more detailed computations we have obtained the following additional predictions concerning the regolith evolution of a small satellite around Mars, which will be used in one of our companion paper (3) : i. the "normal" regolith thickness, $\Delta_o \sim 5$ to 10m, computed by assuming that the satellite surface was exposed during ~ 4 by to a meteoritic flux similar to the present day flux, is both much smaller than $\Delta_f \sim 200$m, and comparable to that observed on lunar maria ; ii. the ejecta blankets are too thin to generate a stratified regolith, and the deposition of material on a Martian satellite can be described by a steady rain operating like on asteroids.

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