Sandbraking. A Technique for Landing Large Payloads on Mars Using the Sands of Phobos

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The basis of a novel braking technique by using the Phobos sands for landing large payloads on Mars is outlined. Here consideration is given to the utilization of the Phobos or Deimos regolith as material for aerobraking by discharging a load of sand at certain distance in front of the spacecraft during the descent manoeuver. Although immediately after getting rid the load of sand in front of the spacecraft they have a null relative velocity with the spacecraft, however, because the stronger atmospheric drag acting on the tiny particles of sand they will be promptly decelerated. As a result, the particles of sand will impact onto the front of the spacecraft with a velocity close to the terminal velocity of the spacecraft itself. By using a pusher-disc -or akin damping system, in front of the spacecraft the momentum exchange from the sand collisions will result in a braking force acting on the spacecraft. Due to the very small delta-v budget required to lift material from the surface of Phobos or Deimos to their transfer orbits, then a small amount of dedicated rocket chemical propellant brought from Earth could be transformed into a huge amount of sand lifted from the surface of Phobos of Deimos to their transfer orbits. The large thrust generated by the Sandbraking makes this technique propitious for landing of planetary bodies struggling against gravity.

Keywords. *planetary spacecraft descent, Mars manned missions, Phobos scenario*

I. INTRODUCTION

Mars atmosphere is less than 1% that that of Earth which imposes a formidable challenge for landing the size of spacecraft needed for human missions. So far, robotic spacecraft have been small enough to enable some success from taking advantage of the weak atmospheric drag for slowdown the spacecraft. However, for human mission to Mars or heavy cargo transportation, traditional solutions used so far as parachutes, airbags or thrusters are not any longer an option. It is believed by most aerospace engineers that the 1-ton payload limit of the current braking technology has been almost attained with the Mars Science Laboratory Curiosity. By aforementioned, it is urged to seek out new alternative solutions for braking and landing large payloads on Mars.

Today, perhaps the only alternative method is the Low-Density Supersonic Decelerator or LDSD which essentially is a bag inflated very quickly with gas rockets called the Supersonic Inflatable Aerodynamic Decelerator (SIAD) to create atmospheric drag in order to decelerate the vehicle before deploying a large supersonic parachute, [1], [2]. Nevertheless, such a sophisticated and expensive device -if works, probably may only be used for very limited early scientific missions but not for a massive and continuous heavy cargo transportation required for human settlements.

A. Sandbraking: and ad hoc braking technology for Mars

The technique proposed here is basically taking advantage of the almost infinite reservoir of regolith existent on Phobos and Deimos -and so far with any technological purpose. We called properly this technique as *sandbraking*, [3].

Although there may be several ways to apply this technique, however, for the sake of illustration, the most general scheme is perhaps as depicted in Fig. 1. Referring to this figure, let us assume that a spacecraft is initially starting its journey from Earth to Mars **(1)**. On the other hand, there is a permanent outpost on the surface of Phobos **(2)** where sand is continuously transported from the surface of Phobos to a sand-station orbiting at Phobos- transfer orbit **(3)**. Now, after months of journey when the spacecraft is approaching the red planet and before starting its entry manoeuver into the atmosphere of Mars, the spacecraft makes a rendezvous manoeuver at the sand-station **(4)** where the spacecraft is loaded with the sand which finally will be used during the descent manoeuver on the red planet.**(5)**.

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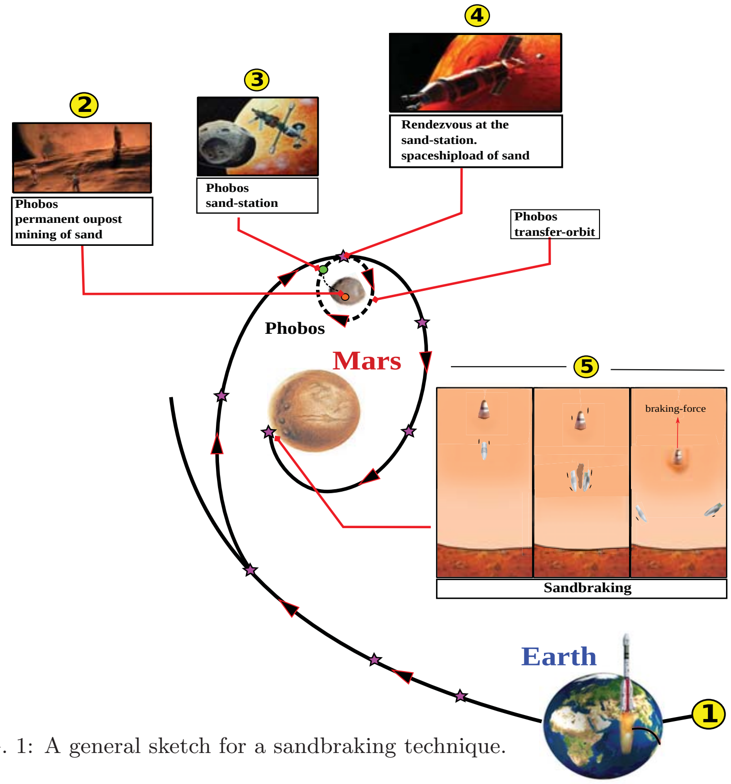

FIG. 1: A general sketch for a sandbraking technique.

II. STATEMENT OF THE CORE IDEA

To begin with, at least two aspects must be initially assessed for any candidate as braking technique, namely: (a) the power efficiency to produce thrust; and (b) the total momentum exchange. Before proceeding with calculations, it is important to realize that from pure momentum-exchange considerations, sand impacting against the spacecraft with a velocity v will have practically the same equivalent than the same load of sand being ejected with the same velocity, i.e., the colliding velocity could be observed as an exhaust velocity and viceversa.

For rocket-like engines, the power, P, needed to run the engine is simply given by:

$$P = \frac{\dot{m}v^2}{2} \tag{1}$$

where $\dot{m}$ is the propellant mass flow rate for a chemical propellant, or from our previous discussion the colliding mass flow rate of sand; and v is the actual exhaust velocity of the propellant or the colliding velocity of sand particles.
From momentum considerations the thrust generated, T, is given by

$$T = \dot{m}v \tag{2}$$

Then by dividing Eq.(2) by Eq.(1), we obtain the thrust produced per unity of power as

$$\frac{T}{P} = \frac{2}{v} \tag{3}$$

Hence the thrust produced per power needed is proportional to the inverse of the exhausts velocity, with higher velocities needing higher power for the same thrust, causing less energy efficiency per unit thrust. Therefore, sand colliding against the spacecraft with a typical velocity close to the terminal velocity of the spacecraft (around 60 m/s) will be around 60 times more efficient producing thrust than a retrorocket with a chemical propellant with an exhaust velocity around 3000 m/s.

Let us now to evaluate a comparison between the total momentum exchange from sandbraking and a retrorocket. To do this, let us assume that a mass of fuel-propellant brought from Earth, say, m_f which was initially intended to be used for a retrorocket during the descent maneuver is instead now used to lift sands from Phobos to its transfer orbit.

One important point with *sandbraking* is that because Phobos and even more Deimos have a very small escape velocities -around 11.39 m/s and 0.003 m/s, respectively., which are much lower than the exhaust velocity of conventional chemical propellant -around 3000 m/s, then in contrast to Earth, the mass payload which can be lifted from their surfaces is much larger than the fuel needed. The mass of payload (including the dry mass) which can be lifted from the surface of a body is given as first approximation by the well-known rocket equation

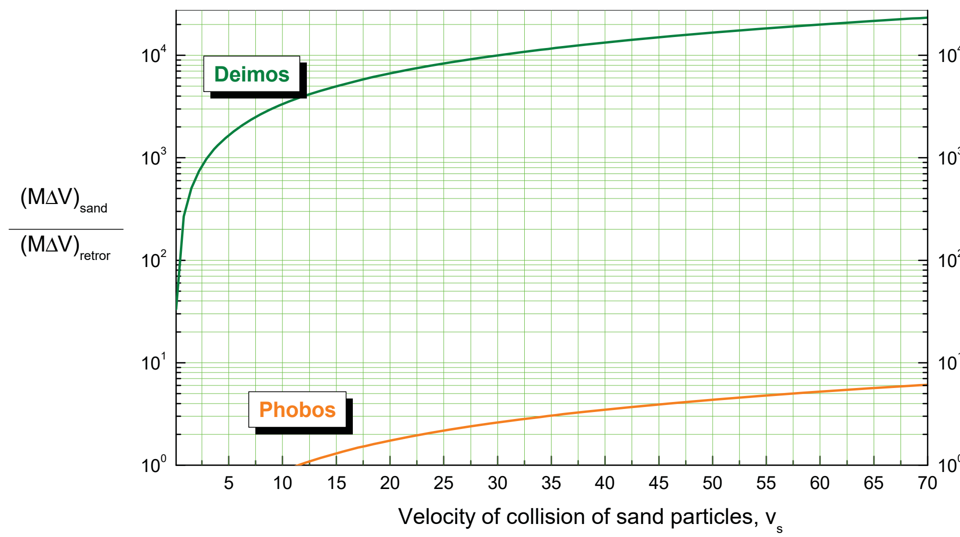

FIG. 2: The total momentum exchange ratio between using sandbraking technique and a chemical retrorocket for Phobos and Deimos as function of the collide velocity of the sand particles from Eq.(6)

$$m_s = m_f \left[e^{\frac{v_e}{c}} - 1 \right]^{-1} \tag{4}$$

where m_s is the mass of payload ., v_e the escape velocity of the celestial body., m_f and c the mass of fuel-propellant and its exhaust velocity, respectively. It is easy to see that, for Phobos or Deimos $v_e \ll c$ then the mass of sand lifted per mass of propellant used is largely amplified. In other words, this translates that a small amount of chemical propellant brought from Earth can be transformed into several orders of magnitude larger amount of sand from Phobos or Deimos, of course, with the penalty of degrading the high exhaust velocity of the chemical propellant to a very low collisional velocity of the sand which must be considered in the momentum exchange. Therefore the combined effect of both: gain in mass and loss of velocity will result in the net gain or loss of the total momentum exchange.

Let us call the total mass of the spacecraft as M and ΔV its total velocity change, then the total momentum exchange of the spacecraft, $M\Delta V$ is given by

$$M\Delta V = mv \tag{5}$$

where m is the total mass of fuel exhausted (or sand in *sandbraking* technique), and v either the exhaust velocity of the propellant (or the colliding velocity in *sandbraking* technique) and then by using Eq.(4) the ratio between the *sandbraking* technique and the retrorocket yields

$$\frac{(M\Delta V)_{sandbraking}}{(M\Delta V)_{retrorocket}} \approx \left[e^{\frac{v_e}{c}} - 1 \right]^{-1} \cdot \frac{v_s}{c} \tag{6}$$

where v_e is the escape velocity of Phobos (or Deimos); c is the exhaust velocity of the chemical propellant; v_s the velocity at which the particles of sand collide onto the front of the spacecraft (close to the terminal velocity of the spacecraft). To obtain some idea of the values given by Eq.(6), we assume some typical value of the parameters: $v_e = 11.39$ m/s for Phobos and $v_e = 0.003$ m/s for Deimos; $c = 3800$ m/s for a LOX-H_2 liquid rocket propellant. The resulting curves are shown in Fig. 2 as function of the collision velocity of sand particles. It is seen that, if we consider typical velocities of collision of sand particles close to the terminal velocity of the spacecraft for Mars which after using the parachute are around 40 m/s-to-60 m/s we obtain that sandbraking for Phobos could give us above 5 times more momentum exchange than using the same chemical fuel as retrorocket. The case for Deimos is even much more notorious.

III. AERODYNAMIC EFFICIENCY

In preceding section it was considered that all the load of sand collide against the spacecraft and also following a straight line. Of course, this is not the case, aerodynamic phenomena called advection will reduce unavoidably the effective amount of sand colliding against the spacecraft as well as their total momentum exchange after collision (by modifying the angle of impact).

Because the aerodynamic advection of particles with the fluid streamlines (apparent atmospheric motion from the spacecraft framework), only a fraction of the sand released will actually hit the pusher-plate or damping system of the spacecraft. Indeed, if the particle of sand has zero inertia it would be swept aside by the atmospheric stream flow around the pusher-plate and a col-

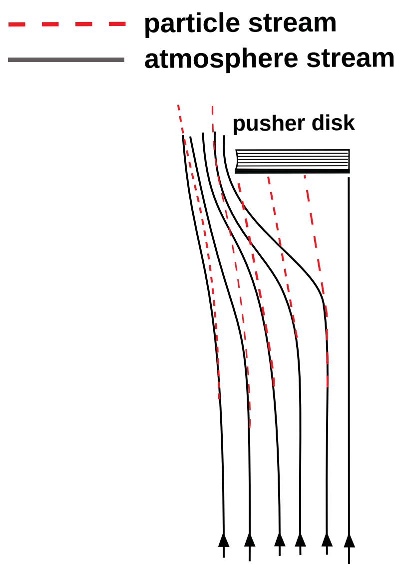

FIG. 3: Atmospheric (solid lines) and particle (dotted lines) flow around a pusher disk in front of the spacecraft.

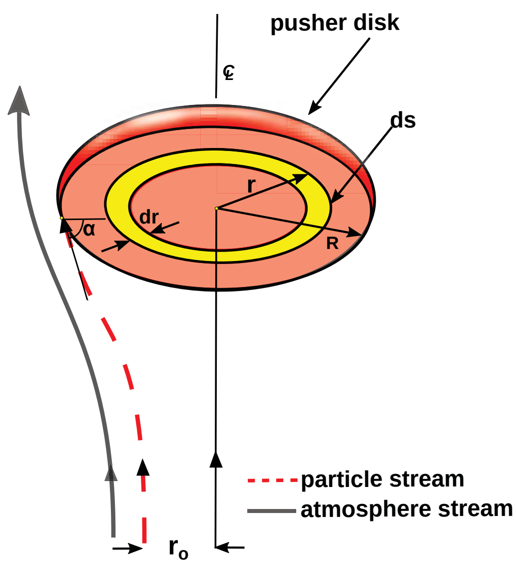

FIG. 4: Physical model

lision would no occur. Fig. 3 is a sketch of the atmospheric (solid lines) and particle (dotted lines) pattern around the pusher or damping disk. In this figure, because the aerodynamic force, particles will tend to follow the streamlines of the fluid (atmosphere) around the spacecraft and then will avoid collision. Only particles inside a certain effective region will collide. Who determines if a particle collision will occur in the pusher-plate is the relative importance of the inertial force and the aerodynamic force. This relative importance is given by the Stokes number which for spherical particles is given by, [4]

$$\mathbf{Stk} = \frac{\rho_p d_p^2 u_t}{18\mu_g R} \tag{7}$$

where ρ_p and d_p, are the density and the diameter of particles, respectively; μ_g the dynamic viscosity of the gas flow (atmosphere); u_t and R the terminal velocity of the vehicle and the radius o the pusher-plate, respectively. A particle with a low Stokes number follows fluid streamlines (perfect advection), while a particle with a large Stokes number is dominated by its inertia and continues along its initial trajectory. Then our efficiency is higher as higher is the Stokes number, i.e., by increasing the size of the particles as much as possible. Fig. 4 is the physical model we will use for determination of the collision efficiency.
From Fig. 4, there are two key parameters that we need for calculation of the collison efficiency: (1) the fraction of particles passing the projected area of the pusher plate that actually hit the plate, which is defined as

$$\eta = \frac{r_o^2}{R^2} \tag{8}$$

and (2) the particle angle of impacts α.

In view of several uncertainties, the ram pressure exerted on the pusher-plate by the stream of particles of sand hitting the pusher-plate at a relative velocity u_r and with an angle α can be estimated as first approximation by using the simplest Newton's sine squared law. Therefore this pressure is given by

$$p_p(r) \approx \rho_s u_r^2 \eta \sin^2\alpha \tag{9}$$

where ρ_s is the mass-concentration of the load of sand at the moment is released in front of the spacecraft; u_r the relative velocity between the sand particles and the spacecraft equal to the difference between their terminal velocities.

The *inertial impact pressure force* on the circular inertial disk is obtained by integrating the pressure expression of Eq.(9) over the disk. Thus, the pressure force is

$$F_p = \rho_s u_r^2 \eta \int_0^R 2\pi r \sin^2\alpha dr$$

$$F_p = 2\pi \rho_s u_r^2 \eta \int_0^R r \sin^2\alpha dr \tag{10}$$

It is convenient to define a variable as $x = \frac{r}{R}$ and thus Eq.(10) becomes

$$F_p = 2\pi R^2 \rho_s u_r^2 \eta \Gamma \tag{11}$$

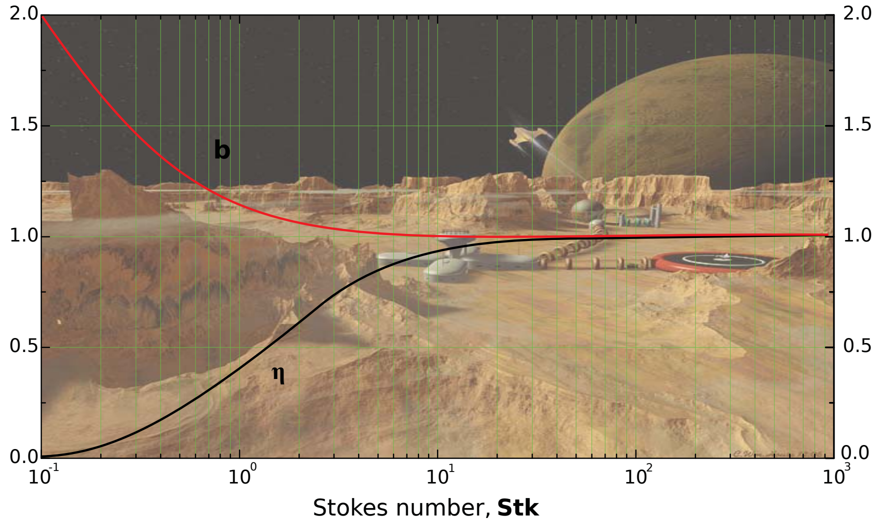

FIG. 5: Plot of b and η as a function of the Stokes number

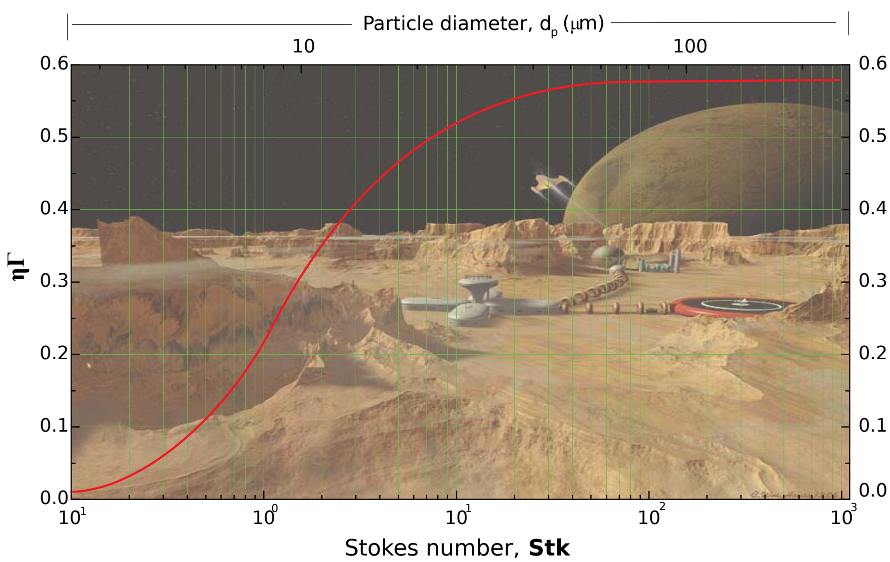

FIG. 6: Plot of product $\eta\Gamma$ as a function of the Stokes number (bottom axis of abscissa) and the diameter of particle (top axis of abscissa)

with the integral factor Γ defined as

$$\Gamma = \int_0^1 x \sin^2 \alpha dx \tag{12}$$

The parameter α is easily calculated by using computational tools. From computational fluid dynamic (CFD) simulations, it was found that this particle angle of impact α follows a profile relationship similar than that found for impaction of particles on a circular cylinder in crossflow , [5]

$$\alpha = \frac{\pi}{2}\left[1 - \left(\frac{r}{R}\right)^{\frac{1}{b}}\right]^b \tag{13}$$

where

$$b = 1.0 + \frac{\beta_1}{\mathbf{Stk}} + \frac{\beta_2}{\mathbf{Stk}^2} + \frac{\beta_3}{\mathbf{Stk}^3} \tag{14}$$

and $\beta_1 = 0.1722$, $\beta_2 = -0.0210$, and $\beta_3 = 0.00142$.

The curves for the collision efficiency η and b are shown in Fig. 5 as function of the Stokes number. Figure 6 is a plot of $\eta\Gamma$ as a function of the Stokes number. In this figure, the diameter of the particle for the Stokes number (top axis of abscissa) was calculated from the Stokes number, Eq.(7) and assuming a density of the particle of sand $\rho_p = 3$ g/cm^3; $\mu_g = 1.37 \times 10^{-7}$ Pa(s); with a plausible pusher-plate radius of $R = 5$ m, and a terminal velocity of $u_t = 65$ m/s.

Referring to Fig. 6, it is seen that, for sand particles larger than 100 μm the total efficiency tends asymptotically to $\eta\Gamma \approx 0.6$. Although there is not available experimental data on the size of the regolith grain of Phobos or Deimos, however, by using remote measurements of the thermal inertia it was found that small airless bodies in the Solar System (diameter less than ~100 km) are covered by relatively coarse regolith grains with typical particle sizes in the millimeter to centimeter regime, [6]. Therefore, it seems allowable to assume a conservative figure of $\approx 60\%$ for the *sandbraking* efficiency in the collision.

A. Braking power

In this section some preliminary calculations are performed on the capability of the proposed technique for braking the spacecraft. In order to centre ideas, Fig. 7 is depicting a possible two-stages strategy to carry out the release of the load of sand. Referring to Fig. 7 we have: **(1)** the load of sand is detached inside a tank from the spacecraft. **(2)** at certain distance in front of the spacecraft a signal is sent by the spacecraft and then the tank release the load of sand. This distance is programmed by the space engineer to be enough to allow that the sand attain its own terminal velocity and then impact against the pusher-plate of the spacecraft with the maximum relative velocity allowable which is the difference between the terminal velocity of the spacecraft and the sand **(3)**. Finally the sand collide against the pusher-disc exchanging momentum. With this rather simplified picture we can now proceed to perform some calculations.

To begin with, the force acting on the pusher-plate by de collision of sand particles is given by Eq.(11)

$$F = 2\dot{m}_s u_r \eta\Gamma \tag{15}$$

where $\dot{m}_s$ is the mass flow rate of particles colliding against the pusher plate ($\dot{m}_s = \pi R^2 \rho_s u_r$). The deceleration experienced by the spacecraft with mass M

$$2\dot{m}_s u_r \eta\Gamma \sim -M\frac{\Delta u}{\Delta t} \tag{16}$$

where Δu is the total variation of velocity of the spacecraft during a braking time Δt. On the other hand, taking into account that the total load of sand is given by

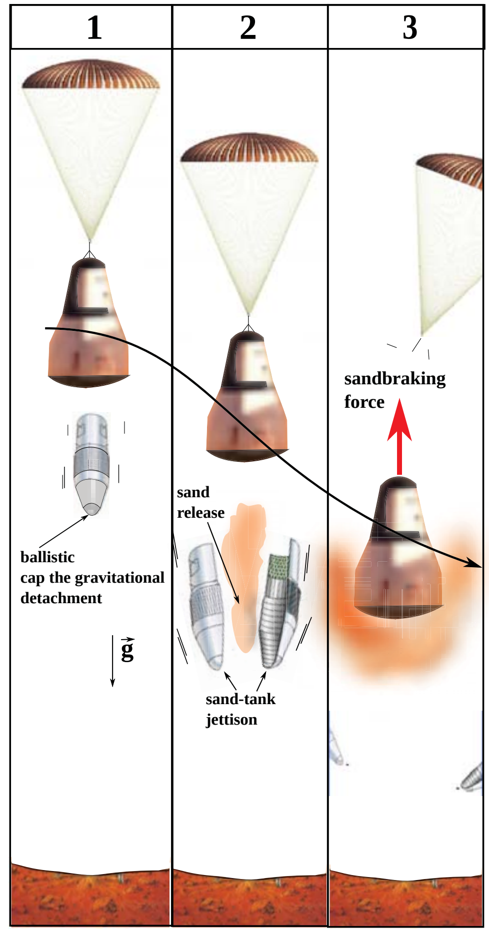

FIG. 7: Sandbraking. The load of sand can be decoupled from the spacecraft by using a tank with a ballistic cap. Once the container is released by, say,opening a clamping ring gravity will separate the load form the spacecraft. The tank will open later by pressure or programmed signal sent by the spacecraft

$$m_s \simeq \dot{m}_s \Delta t \tag{17}$$

inserting Eq.(17) into Eq.(16), the total variation of the velocity of the spacecraft Δu yields

$$\frac{\Delta u}{u_r} = -\frac{2m_s}{M}\eta\Gamma \tag{18}$$

However, this result is misleading. It is easy to see that, by using a load of sand also we are increasing the initial terminal velocity of the spacecraft and therefore this must be considered in the final velocity in comparison with no using sand. This fact cannot be neglected because the load of sand could exceed the mass of the spacecraft itself.

Taking into account that the terminal velocity is proportional to the mass as

$$u_t \sim \sqrt{M} \tag{19}$$

Then, by increasing the initial mass of the spacecraft from M to $M + m_s$ i.e., by adding the load of sand, the original terminal velocity u_{to} (without load of sand) will be proportionally increased as

$$u_t = u_{to}\sqrt{1 + \frac{m_s}{M}} \tag{20}$$

and then, Eq.(18) becomes

$$\frac{\Delta u}{u_{to}} \simeq \left[\sqrt{1 + \frac{m_s}{M}} - 1\right] - \frac{2m_s}{M}\frac{u_r}{u_{to}}\eta\Gamma \tag{21}$$

Because the stronger atmospheric drag acting on the tiny particles of sand in comparison with the spacecraft, If it is allowable to assume that relative velocity u_r is approximately equal to the terminal velocity of the spacecraft, i.e., $u_r \simeq u_{to}\sqrt{1 + \frac{m_s}{M}}$, Eq.(21) simplifies to

$$\frac{u_f}{u_{to}} = \left[1 - \frac{2m_s\eta\Gamma}{M}\right]\left[\sqrt{1 + \frac{m_s}{M}}\right] \tag{22}$$

where u_f is the final velocity of the spacecraft immediately after braking. Therefore, $\frac{u_f}{u_{to}}$ is the comparison between the velocity without using *sandbraking* (u_{to}) and using *sandbraking* (u_f). The curve predicted by Eq.(22) is shown in Fig. 8 with a rather conservative low $\eta\Gamma = 0.3$ much lower than the expected form Fig. 6 which is around 0.5-to-0.6. It is seen that the *sandbraking* technique can reduce substantially the velocity of the spacecraft.

B. Deceleration and damping system

In order to maximize *sandbraking* the large load of sand must be released at once (See Fig. 7) and hit the spacecraft during a very short time. Therefore the crew could be subject to forces which can be larger than the limit that humans can comfortably withstand -typically about 2 to 4 g, and then a certain damping system behind the pusher-plate will be necessary to smooth the instantaneous deceleration. This damping system could be as depicted in Fig. 9. A first roughly estimation of the deceleration involved can be inferred as follows:

First, the force of the sand hitting the pusher-disc is given Eq.(11)

$$F_p = 2\pi R^2 \rho_s u_r^2 \eta\Gamma \tag{23}$$

Then, if the total mass of the spacecraft is M, a rough estimation of its deceleration is given by

$$a = \frac{2\pi R^2 \rho_s u_r^2 \eta\Gamma}{M} \tag{24}$$

If it is allowable to assume that the load of sand with mass m_s is initially contained in a cylindrical tank with a volume V_p with a cross section approximately equal to the pusher plate, i.e., πR^2, and a length L, i.e., $V_p = \pi R^2 L$ and $m_s = V_p \rho_s$, then Eq.(24) can be rewritten as

$$a \approx \frac{2\eta\Gamma u_r^2}{L}\frac{m_s}{M} \tag{25}$$

• Discussion

To obtain some idea of the values given by Eq.(25), we assume some possible value of the parameters: using a $\eta\Gamma \approx 0.3$ as before; $u_r \approx 40$ m/s; and with a realistic length of the tank around 20 m. Finally, for practical considerations, let us take a mass of the sand twofold than of the spacecraft , i.e., $\frac{m_s}{M} = 2$. With these values we obtain something like 10 g´s, which give us a rough idea of the magnitude of deceleration experienced during *sandbraking*.

IV. SUMMARY OF RESULTS AND CONCLUSIONS

The basis of a novel braking technique called *sandbraking* by using the Phobos or Deimos sands for landing large payloads on Mars was outlined.

Some interesting conclusions are raised by this preliminary work as follows:

(a) It is possible to obtain an atmospheric drag enhancement by *sandbraking* with substantial reduction of the terminal velocity of the spacecraft by using a sand load with a mass similar than the mass of the spacecraft.

(b) Propellant requirements for transporting the sand from an outpost on Phobos to its transfer orbit are very reduced due to its very low delta-v budget.

(c) The very low delta-v budget of Phobos and Deimos translates into the capability of lifting very large amount of sand form theor surfaces to their transfer-orbits by using a small amount of chemical rocket fuel.

(d) Besides the use of a pusher-plate in front of the spacecraft for momentum exchange, also a certain damping system will be necessary to smooth the instantaneous deceleration to a level that humans can comfortably withstand.

(e) Additional R&D is required in order to explore all the possibilities of this braking technique.

NOMENCLATURE

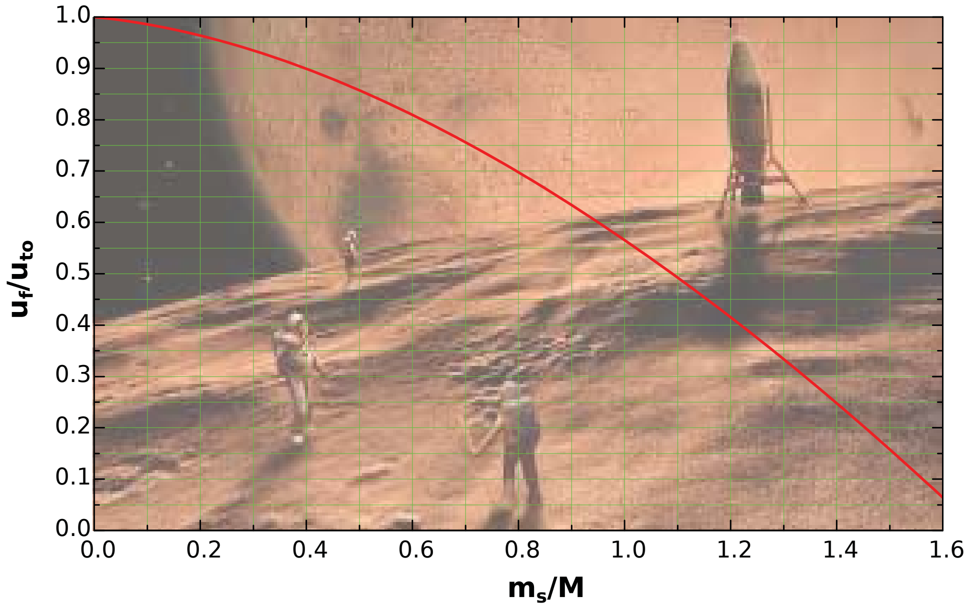

FIG. 8: Spacecraft velocity fraction as function of the load of sand m_s and mass of spacecraft M ratio according with Eq.(22) and using $\eta\Gamma = 0.3$

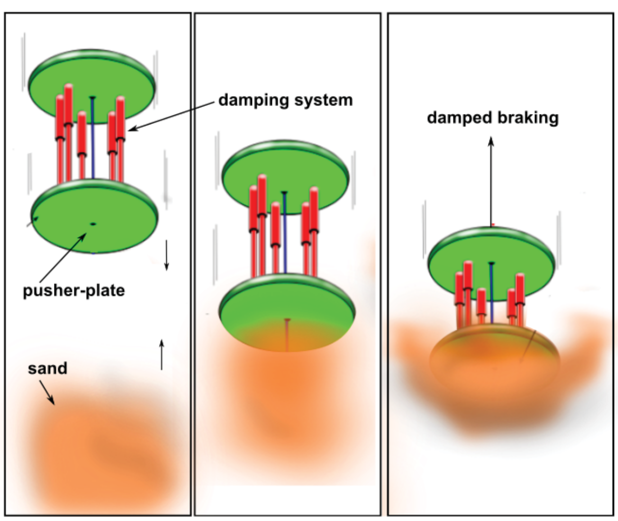

FIG. 9: Possible damping system behind the pusher-plate to smooth the instantaneous deceleration to a level that humans can comfortably withstand.

a = vehicle deceleration
A_p = projected area of the pusher plate.
b = parameter
d_p = particle diameter
g = Earth gravity acceleration
L = length of the cylindrical tank containing the sand
m_s = mass of load of sand
$\dot{m}_s$ = mass sand flow per unit of time
F_p = force of sand particles hitting the pusher-plate
M = mass of the spacecraft (without sand)
p_p = dynamic ram pressure of stream of particles on the pusher-disc
R = pusher-plate radius
r = radial distance pusher-disc
r_o = particle staring position upstream of the pusher-disc
Stk = Stokes number
t = time
T = thrust
Δt = braking time
u = velocity of the spacecraft
Δu = velocity change by braking the spacecraft
x = variable equal to $\frac{r}{R}$

Greek symbols
α = particle angle of impact
β = parameters
η = collision efficiency
Γ = collision parameter, given in Eq.(12)
μ = dynamic viscosity
ρ = density
ρ_p = density of sand particle
ρ_s = density or mass concentration of the load of sand released
μ = dynamic viscosity

subscripts
p = particle

ph = Phobos
g = gas (atmosphere)
s = sand
t = terminal

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