EPSC Abstracts
Vol. 11, EPSC2017-117-1, 2017
European Planetary Science Congress 2017

A Tentative Mechanism for Dust Vertical Transport at Extreme Altitudes from the Collapse of Supersaturated Tropospheric Cavities on Mars with Particular Reference to March 2012 Event

Francisco J. Arias(1)
(1) Department of Fluid Mechanics, University of Catalonia,
ESEIAAT C/ Colom 11, 08222 Barcelona, Spain

Abstract

Consideration is given to the formation and collapse of supersaturated tropospheric cavities on Mars for dust vertical transport at extreme altitudes as a tentative mechanism explaining the martian march-2012 plume. It will be shown that if, during the night-time radiative cooling is exacerbated by suspended dust surrounding a tropospheric parcel and then impeding heat flow from the surface into the parcel and if, additionally the parcel itself is devoid of condensation nuclei (dust aerosol on Mars) a supersaturated cavity might be generated. Then, with the first rays of sunlight in the morning -and the beginning of the daily dust activity, any dust incursion into the cavity driven by local winds, could trigger the condensation of the parcel and the subsequent vigorous prompt collapse of the cavity. Utilizing a simplified geometrical model, it is shown that the collapse and rebound of such tropospheric cavities could provide enough energy to lift dust well into the thermosphere and then a possible explanation to the extremely high-altitude plumes seen on Mars. The proposed hypothesis seems consistent with the high-altitude plume seen at Mars 2012 at Cimmeria region -and still unresolved, occurred at the Martian terminator (the day-night boundary) when the atmosphere could be coldest because has been without the heat of the sun for the longest time and the beginning of the dust activity driven by solar heating. Finally the possibility that the local strong magnetic field in Cimmeria region may have played a role in triggering the formation of the hypothesized supersaturated tropospheric cavity or *"magnetocavity"* was also discussed.

Introduction

On 12 March 2012, amateur planetary observers reported an unusual small protrusion seen at sunrise of Mars within the Terra Cimmeria region at roughly 45^o south, $195\ ^o$ west. The protrusion became more prominent over the following days until March 23rd. In 2015 a thorough research report undertaken by the Prof. Sanchez-Lavega research group at the Universidad del Pais Vasco, Spain, estimated the height of these plumes as 200 to 250 km above the surface of Mars,[1]. Since then, concern has been raised in the scientific planetary community because according with the general circulation model (GCM) for Mars, [2], clouds should not exist this high in Mars´s atmosphere. The mystery about what happened on 2012 is still unresolved.
From photometric measurements, two possible scenarios were explored in that report in order to explain the event. These two scenarios are as follows:

In the first scenario the observed plume is formed by particle of CO_2-ice, H_2O-ice or dust reflecting solar radiation with a best fit for CO_2-ice, H_2O-ice particles with effective radii of $0.1^{+0.1}_{-0.04}\mu$m. However, according with the general circulation model (GCM) for Mars, H_2O condensation at the relevant altitudes requires either anomalous temperature drop $>$ 50 K or an unusual increase in the H_2O mixing ratio to complete saturation above 140 km. For CO_2 condensation the situation is even worse, requiring temperature drop of 100 K above 125 km. (see Fig. 1). In addition, explaining the plume as formed by dust would require a strong vertical transport up to at least 180 km above the surface. There is only a known mechanism -so far, able to provide the required vigorous updrafts which is driven by dry convection under high insolation called *rocket dust storms*, [3],

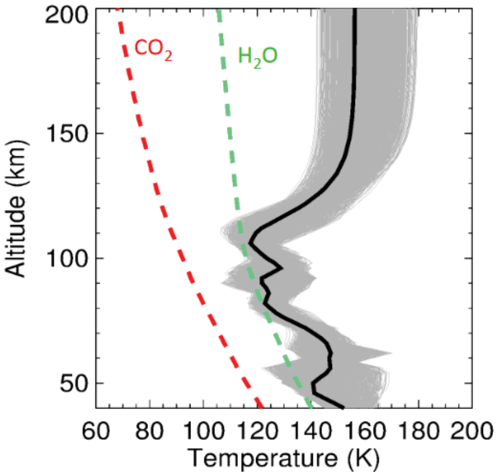

Figure 1: Atmospheric temperature profile and water and carbon dioxide condensation temperatures on Mars. From Sanchez et al,[1].

however, the fact that the plume was observed at the Martian terminator makes the *rocket dust storm* mechanism difficult to support.

In the second scenario, it was conjectured the possibility whether the observed plume might be attributable to an aurora, where it is known the existence of strong magnetic field anomalies in the crust at Terra Cimmeria region, and where actually Mars aurora activity have been observed in the past. This hypotheses seems to be in agreement with the meridional extent of the plume above 500 km as well as its variability. However, quantitative estimates of the required aurora intensity defy such a hypotheses and additionally requiring an exceptional influx of energetic particles over days from the Sun, although the solar activity in march 2012 was not unusually high. As was concluded in that research report, both explanations, defy our current understanding of Mars´s upper atmosphere.

In this paper, we will explore a possible mechanism which may rescue the first scenario by providing a source of energy able to lift material from the troposphere well into the thermosphere of Mars but contrary to the *rocket dust storm* mechanism it does not require high insolation but rather high insulation.

1 Formation and collapse of supersaturated tropospheric cavities

1.1 Formation

To begin with, let us consider a certain tropospheric parcel as schematically depicted in Fig. 2-left. This tropospheric parcel is placed just at the top of a dense dust cloud which is -after a local dust storm, gravitationally settling down during the night. The presence of this dense suspended dust cloud between the parcel and the surface translates into an overcooling of the parcel because the dust is impeding the input of heat from the surface and then exacerbating the loss of heat of the parcel.

The magnitude of this overcooling will depend mostly on the optical opacity of the suspended dust below the parcel which can be as large as $\tau = 5$, [4]. In anyway, it is suffice to point out for our descriptive purpose that from the available data registered by Viking landings for several years on the Martian surface, with the arrival of dust storms temperature drops down by 10 to 15 ^{o} K, [5], which referring to Fig. 1, it is within the required overcooling required for condensation of H_2O or CO_2 at the troposphere (< 50 Km).

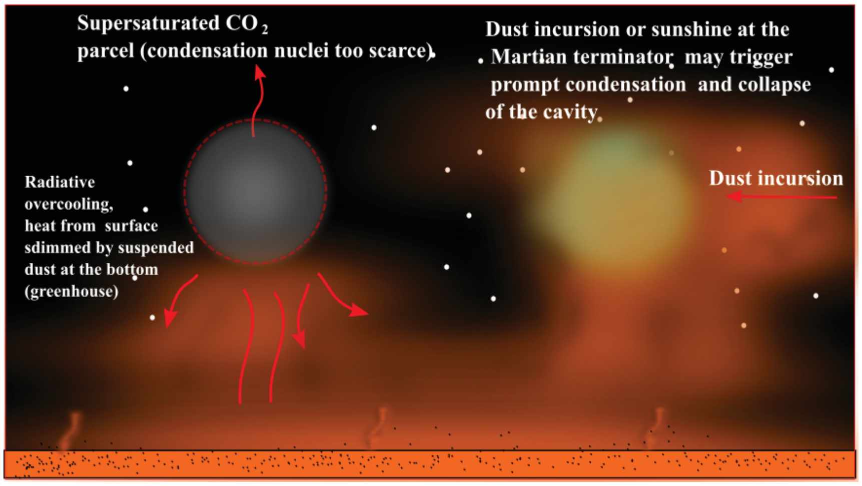

Figure 2: Pictorially sketch of the possible mechanism for the formation of supersaturated tropospheric cavities and collapse on Mars.

Now, if the parcel is devoid of condensation nuclei (dust aerosol on Mars) high supersaturation is possible. This spesaturation has been already observed on Mars from the relatively recent data sent back by the SPICAM spectrometer on board ESA´s Mars Express spacecraft which revealed that the planet´s atmosphere could be supersaturated with water vapor at altitudes of up to 50 km above the surface (troposphere),[6], with extremely high levels of supersaturation -up to 10 times greater than those found on Earth. Once this unstable supersaturated parcel is generated and with the first rays of sunlight in the morning -and the beginning of the daily dust activity, any dust incursion (from the beginning of daily dust activity) might trigger the condensation of the parcel and the formation of a cavity with its subsequent vigorous prompt collapse as schematically depicted in Fig. 2-right.

The proposed mechanism would be analogous to the well know superheated explosions -also known as steam explosions, where a region initially devoid of condensation nuclei explode vigorously if incursion of condensation nuclei occurs disrupting the metastable state. Here is the same, but instead superheating and explosion, we have supersaturation and implosion.

1.2 Collapse and rebound

Immediately after condensation, the cavity will collapse owing to the surrounding pressure. The collapse will continue and the material inside will be progressively compacted as the collapse progresses until at a certain critical density (of the mixture CO_2-ice, H_2O-ice particles and dust) is attained. At this density, the collapse is stopped and the rebound stage starts. An schematic picture of the collapse and rebound stages is given in Fig. 3.

For the sake of analysis and with the purpose to obtain a first estimate of the energy released from such an event, let us assume a spherical cavity small enough in comparison with the surrounding atmosphere and then making allowable the assumption of an infinite mass of homogeneous incompressible atmosphere with pressure and density calculated at the location where the cavity is formed. With this configuration the infalling velocity of the cavity as function of the contraction ratio is given by the generalized Rayleigh equation, [7], as

$$u^2(t) = \frac{2p}{3\rho}\left(\frac{R_o^3}{R^3(t)} - 1\right) \tag{1}$$

where u is the infalling velocity of the cavity at time t after collapse starts, p and ρ the surrounding atmospheric pressure and density., respectively. R the radius of the boundary cavity at time t, and R_o the ini-

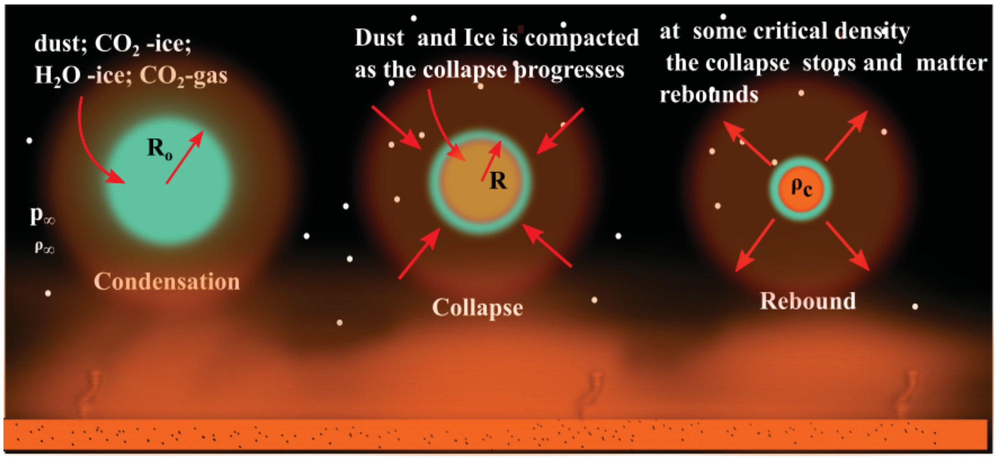

Figure 3: Pictorially sketch of the collapse and rebound phase.

tial value of R, i.e., the initial radius of the cavity at the moment the collapse starts or $t = 0$. On the other hand the whole kinetic energy at time t of the motion is given by

$$E_k = \frac{4\pi}{3} p \left(R_o^3 - R^3(t) \right) \tag{2}$$

As the collapse progresses, the material inside the cavity (mixture CO_2-ice, H_2O-ice particles and dust) attain a certain critical density at which the collapse is stopped followed by a rebound phase. If the critical radius at which the critical density ρ_c is attained is called as R_c, then from Eq.(2) the maximum energy available is

$$E_k = \frac{4\pi}{3} p \left(R_o^3 - R_c^3 \right) \tag{3}$$

where by balance of mass inside the cavity we have

$$\frac{R_o}{R} \approx \left[\frac{\rho_c}{\rho} \right]^{\frac{1}{3}} \tag{4}$$

If we assume that the critical density ρ_c is the maximum density of a compacted solid-ice core, then with $\rho_c \approx 10^3$ kg m^{-3} and the density of troposphere on $\rho \approx 10^{-3}$ kg m^{-3}, then $\frac{R_o}{R} \approx 100$.

In order to know how fast the surrounding material will be accelerated when the inside material is rebound, we could use the Gurney equations by analogy with material ejected by explosive detonations surrounding initially the explosive. This equation determines how fast fragments surrounding explosives are released into the surrounding and is given by the generalized expression [8]

$$v^2 = u^2 \left[\frac{M}{C} + \frac{3}{5} \right]^{-1} \tag{5}$$

where v is the velocity of accelerated material surrounding the cavity after implosion-rebound; C is the mass contained in the cavity; M the mass of the accelerated sheet of material.

Inserting Eq.(1) into Eq.(5) one obtains

$$v^2 = \frac{2p}{3\rho} \left[\frac{R_o^3}{R^3} - 1 \right] \left[\frac{M}{C} + \frac{3}{5} \right]^{-1} \tag{6}$$

In order to obtain some rough idea or upper limit of the maximum altitude H_{max} attainable by the accelerated material, we can equal the kinetic energy with the potential energy yielding

$$H_{max} < \frac{v^2}{2g} \tag{7}$$

where g is the gravity acceleration which in view of several uncertainties we will take as the surface gravity. By inserting Eq.(6) into Eq.(7), we obtain

$$H_{max} < \frac{p}{3g\rho} \left[\frac{R_o^3}{R^3} - 1 \right] \left[\frac{M}{C} + \frac{3}{5} \right]^{-1} \tag{8}$$

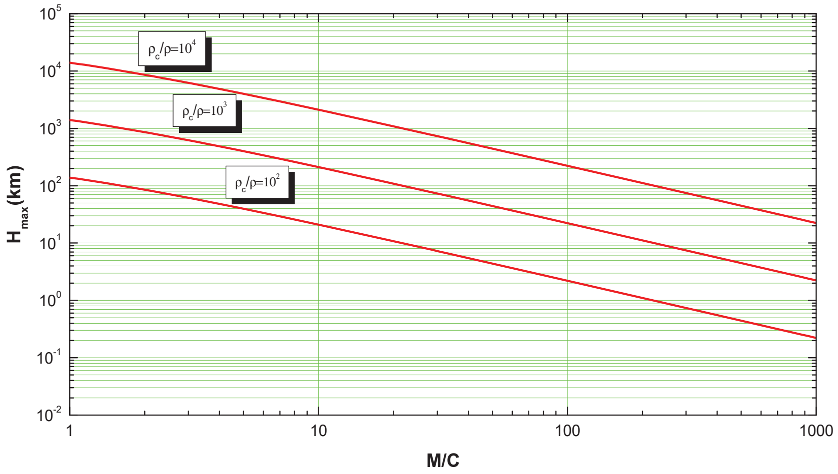

Figure 4: The maximum altitude upper limit as a function of the contraction ratio from Eq.(10).

and taking into account Eq.(4) we get

$$H_{max} < \frac{p}{3g\rho}\left[\frac{\rho_c}{\rho}-1\right]\left[\frac{M}{C}+\frac{3}{5}\right]^{-1} \tag{9}$$

Eq.(9) may be simplified further by considering the relation of ideal gases $\frac{p}{\rho} = \frac{\bar{R}T}{\bar{m}}$ where T is the temperature,$\bar{R}$ the gas constant and $\bar{m}$ the molecular mass of the atmosphere. Thus we obtain

$$H_{max} < \frac{\bar{R}T}{3g\bar{m}}\left[\frac{\rho_c}{\rho}-1\right]\left[\frac{M}{C}+\frac{3}{5}\right]^{-1} \tag{10}$$

• **Discussion**

To obtain some idea of the shape of the curves predicted by Eq.(10), we assume some typical values of the parameters: $T = 130$ K; $\bar{m} = 43 \times 10^{-3}$ kg/mol; $g = 3.7$ m s^{-2}. The resulting curves are shown in Fig. 4. It is seen, that with a maximum theoretical value of $\frac{\rho_c}{\rho} =< 10^5$ (if it is is assumed as critical density the density of a solid ice core), there is enough energy to lift material well into thermosphere and even ionosphere. For example, with $\frac{\rho_c}{\rho} < 10^4$ the implosion will be able to lift 100 times the mass of the condensate cavity up to a height of 100 km or thereabouts. Although admittedly this is an idealized calculation where in reality with such high velocities and pressures there would be thermal effects -which had been neglected in the calculation, and also the assumed atmospheric incompressibility is not longer appropriated, nonetheless, it is shown that the conjectured mechanism is potentially able to lift material at high altitudes.

2 The possible role of the magnetic field: *magnetocavities*

At it was mentioned in introduction, it is known the existence of strong magnetic field anomalies in the crust at Terra Cimmeria region, which is given place to the aurora hypothesis for explanation of the March 2012 event.

It is interesting to investigate if the magnetic field at Cimmeria region could play some role within the framework of our proposed mechanism., i.e, in the formation of supersaturated tropospheric cavities. Although cavities could be formed in a number of different ways which can lead to the basic condition, i.e., supersaturation by overcooling, however it could be true that if it is demonstrated that magnetic fields can play some role in the formation of such cavities this will be more completeness to the proposed hypothesis, and in fact, will be possibly the only hypothesis which can merge all the accounts known on the March 2012-event. Fig. 5 shows an illustrative sketch of what we are seeking to investigate in this section. In this picture, we want to know if it is possible that in someway the local magnetic could

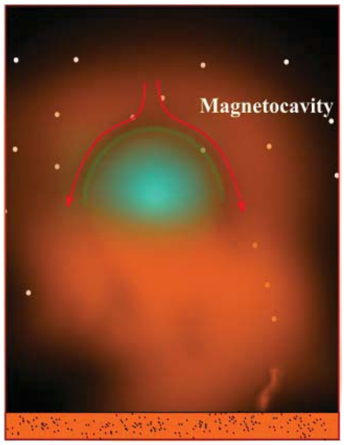

Figure 5: Possible formation of supersaturated cavity induced by the local magnetic field at Cimmeria region.

manage a certain place devoid of dust (allowing high supersaturation).

First of all, it is required that dust particles are electrically charged and then permitting it to respond to the imposed local magnetic field.
It is known that bipolar charging of dust particles (by tribocharging or friction charging process) are generated from dust atmospheric activity on Mars, [9]; [10]; [11]-[13]., and it had been hypothesized that the smaller, or finer, particles tribocharge oppositely to the larger size particles, [14]; [15]; [16];[17] and additionally the particle-size dependence of the charge polarity of particles of dust has been experimentally demonstrated [18].

Now, assuming a bipolar charged dust particles, we need to know if the magnetic energy density (at that region) must be comparable to the kinetic energy density of the charged particles of dust, or putting another way, that the dynamic ram pressure from the dust particles be equal to the magnetic pressure from the Mars's local magnetic field. Taking into account that the low-pressure Martian troposphere gives it a high electrical conductivity -the high electrical conductivity of the atmosphere of Mars could result in an atmospheric electric circuit as proposed by some researchers [19], then the magnetic pressure p_m is given by

$$p_m = \frac{B^2}{\mu_o} \tag{11}$$

and then condition for affecting significatively dust particles yields

$$\left(\frac{\rho_d u_t^2}{2}\right)_d \leq \left(\frac{B^2}{\mu_o}\right) \tag{12}$$

where ρ_d is the charged dust density, u_t the dust settling or terminal velocity, B the magnetic strength at that region and μ_o the vacuum permeability.

If its is assumed spherical dust particles, then the settling velocity is approximately given by

$$u_t^2 = \frac{2\rho_p r_p g}{3\rho_\infty C_d} \tag{13}$$

where ρ_p and r_p are the density and the radius of the particle, respectively., ρ_∞ the atmospheric density through which the particles is falling, C_d is the drag coefficient., and g the acceleration due to gravity. Since the gravitational field varies with distance as $\frac{1}{a^2}$ where a is the radial distance to the center of the planet. Then Eq.(13) becomes.

$$u_t^2 = \frac{2\rho_p r_p g_o a_o^2}{3\rho_\infty C_d a^2} \tag{14}$$

Where g_o is the gravitational acceleration at the surface and a_o the radius of the planet. Finally, the density of the dust is given by

$$\rho_d \approx \frac{4\pi r_p^3 \rho_p N_p}{3} \tag{15}$$

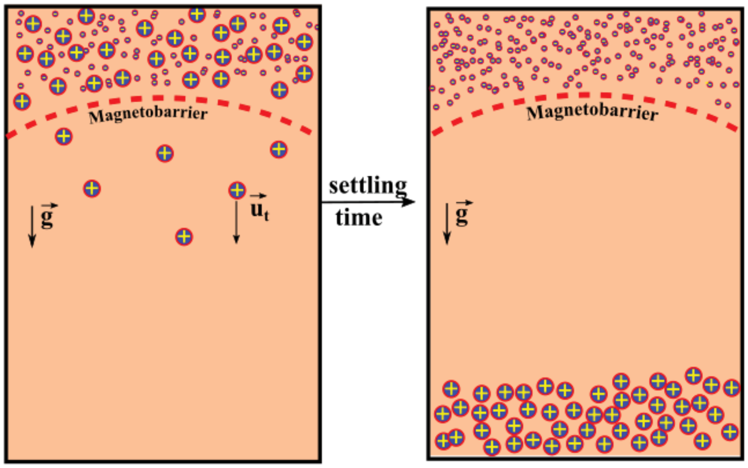

Figure 6: *Magnetobarrier* induced y local magnetic field anomalies acting on charged dust particles on Mars could generate an effective spatial separative mechanism and the formation of cavities or the creation of large local electrostatic fields.

where N_p is the concentration of dust particles per unit of volume. This concentration is as first approximation given as function of the the optical opacity as, [4]

$$N_p = N_o \tau \exp^{-\frac{z}{H}} \tag{16}$$

where $N_o = 6 \times 10^6$ m^{-3} is the number density at the surface when the optical depth $\tau = 1.$, and $H = 10$ km is the atmospheric scale height for Mars. Substituting terms, Eq.(12) becomes

$$B > \frac{2\rho_p a_o r_p^2}{3a}\left[\frac{\pi N_o \tau \exp^{-\frac{z}{H}} g_o \mu_o}{\rho_\infty C_d}\right]^{\frac{1}{2}} \tag{17}$$

According with Eq.(17) there would be some induced *magnetobarrier* for small particles as is schematically depicted in Fig. 6.

• Discussion

Assuming some reasonable values of the parameters: $\rho_p \approx 3 \times 10^3$ kg m^{-3}, [4]; dust suspended at a tropospheric distance of 10 km; and then $\frac{a_o}{a} \approx 0.98$; $N_o = 6 \times 10^6$ m^{-3}; $z = 10$ km and scale height $H = 10$ km, [4]; $g_o = 3.7$ m s^{-2}; $\rho_\infty = 10^{-2}$ kg m^{-3}; and $C_d \sim 0.5$, then we get

$$B > 157 \times \tau^{\frac{1}{2}} r_p^2 \tag{18}$$

with B in (nT); and r_p in (μm).

The resulting curves are shown in Fig. 7. It is seen, that magnetic anomalies on Mars will be able to separate dust particles of a few micrometers from large particles. This mechanism could enhance the formation of cavities devoid of dust. Also it is interesting to see, that the smaller particles will be on the top of the cavity, which means that at the moment of the collapse of the cavity and rebound, small particles will be preferentially propelled to high altitudes. This fact seems consistent with the best fit obtained for the effective radii of particles CO$_2$-ice particles of 0.1μm for the March 2012 event, [1].

NOMENCLATURE

a = distance from center of planet to center of cavity
a_o = radius of the planet
B = magnetic field
C = mass contained in the cavity
C_d = drag coefficient
E_k = kinetic energy
g_o = gravity at surface
g = gravity
H = length scale
H_{max} = maximum permissible altitude
M = mass of the accelerated sheet of material

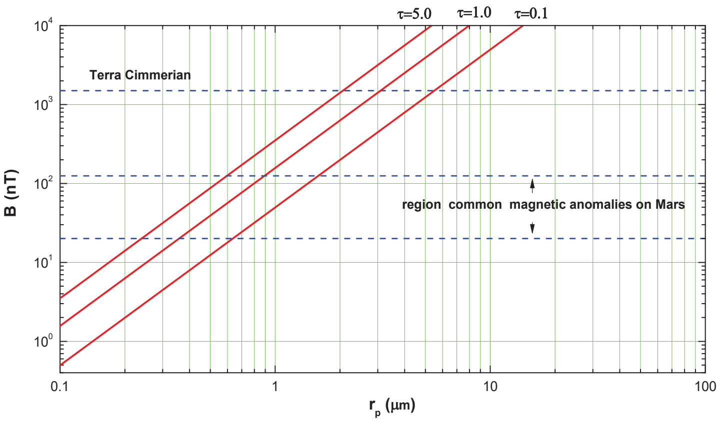

Figure 7: Predicted curves by Eq.(18) for several values of dust storms.

$\bar{m}$ = mean molecular mass of atmosphere
N_p = number density of particles per unit volume
p = pressure
r_p = radius of particles
R = actual radius of cavity
$\bar{R}$ = gas constant
R_o = initial radius of cavity
R_c = critical radius of cavity
u = infalling radial velocity of collapsing cavity
u_t = terminal velocity of particles
v = velocity ejected material surrounding the cavity
t = time
T = temperature
z = vertical distance

Greek symbols
ρ = density
ρ_c = critical density
ρ_d = density of dust cloud
ρ_p = density of particles
ρ_∞ = density of atmosphere
τ = optical opacity
μ_o = magnetic permeability of vacuum

subscripts
d = dust; drag
o = reference, surface
p = particle
e = Earth
m = Mars

Acknowledgements

This research was supported by the Spanish Ministry of Economy and Competitiveness under fellowship grant Ramon y Cajal: RYC-2013-13459.

References

[1] Sanchez-Lavega A., Munos G.A., et.al. 2015. An Extremely high-altitud plume seen at Mars´Morning Terminator. Nature Letter, 518. 525-527.

[2] Gonzales-Galindo F., Maatttanen A., Forget F., Spiga A. 2011. The Martian Messosphere as revelaed by CO_2 cloud observations and general circulation modelling. Icarus. 216. 10-22.

[3] Spiga A. et.al. 2012. Rocket dust storms and detached dust layers in the Martian atmosphere, Journal Of Geophysical Research: Planets, Vol. 118, 746.

[4] Haberle R.M., Mckay C.P., Pollack J.B. et.al. 1993. Atmospheric effects on the Utility of Solar Power in Mars. Resources of Near Earth Space, pp. 799-818.

[5] Ehrlich P.R., Sagan C., Kennedy D. The Cold and the Dark: The World After Nuclear War. Norton, 1985.

[6] Maltagliati L., Montmessin F., Fedorova A., Korablev O., Forget F., BertauxJ.L. 2011. Evidence of Water Vapor in Excess of Saturation in the Atmosphere of Mars. 333, 6051, pp. 1868-1871

[7] Rayleigh Lord. 1917. On the pressure developed in a liquid during the Colllapse of a Spherical cavity. Phil. Mag, 34, 94-98

[8] Cooper Paul W. 1996. Acceleration, Formation, and Flight of Fragments. Explosives Engineering. Wiley-VCH. pp. 385-394. ISBN 0-471-18636-8.

[9] Eden, H. F., and B. Vonnegut. 1973. Electric breakdown caused by dust motion in low-pressure atmospheres: Considerations of Mars, Science, 180, 962-963.

[10] Mills A. A. 1997. Dust clouds and frictional generation of glow discharges on Mars,Nature, 268, 614

[11] Erika L. Barth, William M. Farrell, Scot C.R. Rafkin. 2016. E< Icarus. 268, 253-265

[12] Ping Wang., Xiaojing Zheng. 2015. Unsteady saltation on Mars. Icarus, 260, 161-166

[13] Farrell W.M., McLain J.L., Collier M.R., Keller J.W., Delor J.T. 2015. Is the electron avalanche process in a martian dust devil self-quenching?. Icarus, 254, 333-337

[14] Freier G. D. (1960), The electric field of a large dust devil, J. Geophys.Res. 65, 3504.

[15] Crozier W. D. 1964. The electric field of a New Mexico dust devil, J. Geophys. Res.69, 5427-5429.

[16] Stow C. D. (1969), Dust and storm electrification, Weather, 24, 134-139.

[17] Renno N. O., and J. F. Kok. 2008. Electrical activity and dust lifting on Earth, Mars and beyond, Space Sci. Rev. 137, 419-434

[18] Forward K. M., Lacks D.J., Sankaran R.M. 2009. Particle-size dependent bipolar charging of Martian regolith simulant. Geophys. Res., 36, 1-5

[19] Farrell, W. M., and M. D. Desch (2001), Is there a Martian atmospheric electric circuit, J. Geophys. Res., 106(E4), 7591-7595.