Solar Panel Obscuration in the Dusty Atmosphere of Mars

M. K. Mazumder[1], A. S. Biris[1], S. Trigwell[1], R. A. Sims[1], C. I. Calle[2], and C. R. Buhler[2]

[1]University of Arkansas at Little Rock, Applied Science Department, ETAS 575, Little Rock, AR 72204, mkmazumder@ualr.edu.

[2]Electrostatics and Materials Physics Laboratory, YA-C2-T, NASA Kennedy Space Center, FL, 32899, Charles.Buhler-1@ksc.nasa.gov.

***Abstract*— There are strong indications that dust is of great importance on Mars. Dust appears to have both long-term effects on the surface geologic evolution as well as on the aeolian processes in the present climate conditions. Early spacecraft missions [1] confirmed hypotheses from telescopic work that changes observed in the planet's surface markings are caused by wind-driven redistribution of dust. Suspended dust is known to alter the atmospheric thermal structure and circulation as well as to obscure our ability for remote observation of the planet's surface, especially during the occasional development of larger, planet-encircling dust storms which occur on average once every three Martian years. Because of the possible high electrostatic charge of the dust and its strong adhesion properties, its deposition onto life support equipment could damage or degrade equipment, reducing the mission duration and endangering personnel. The inhalation of electrostatically charged airborne dust is also a health hazard to astronauts inside the habitat. In this paper, we discuss the obscuration of solar panels by: (1) a dust cloud over the panels, causing extinction of light reaching the solar cells even when the panels are relatively clean; (2) extinction of light due to dust deposition on the surface of the panel in a relatively clear sky; and (3) extinction caused by both high density particle cloud and a significant dust deposition on panels, conditions expected in dust storms on Mars. Electrostatic adhesion of charged particles on the panel surface is analyzed as a function of charge and size distributions to analyze possible dust removal processes.**

I. INTRODUCTION

The atmosphere of Mars contains significant amounts of suspended dust, and in Martian dust storms with a wide range of particles (submicrometer to 50µm in diameter) are a serious problem to solar cells, spacecraft, and spacesuits [2,3]. The dust may also possess a high electrostatic charge due to tribo-charging by contact with other particles or materials, or photoionization by the intense UV radiation. The settling of this dust, especially during a Martian dust storm, can have a significant effect on the efficiency of solar panels, due to the settled dust impeding the sunlight from the cells. Results from the Materials Adherence Experiment (MAE) on the Mars Pathfinder mission measured an obscuration of the solar arrays due to dust deposition at a rate of about 0.28% per day [4] with an estimate that settling dust may cause degradation in performance of a solar panel of between 22% and 89% over the course of two years [1].

Given the high charge the Mars dust can acquire due both the tribocharging and UV radiation, they can adhere very strongly to the solar panels or the life support equipment, reducing their efficiency and life time. This paper analyzes the mechanisms that are responsible for the dust deposition on the solar panels, the obscuration of these solar panels, the charge the dust acquired during the tribocharging process against different materials, how fast this charge may decay.

II. OBSCURATION OF THE SOLAR PANELS

The obscuration of solar panels depends upon the particle size, shape and refractive index, distribution of dust cloud, deposition mechanisms involved, and the orientation of dust deposits on the panel. Three cases of obscuration of solar panels by Mars dust are considered:

(1) A dust cloud over the panels, causing extinction of light reaching the solar cells even when the panels are relatively clean; (2) Extinction of light due to dust deposition on the surface of the panel in a relatively clear sky; and (3) Extinction caused by both high density particle cloud and a significant dust deposition on panels, conditions typically found in dust storms on Mars.

For a parallel beam of light, normally incident on a solar panel, the extinction ratio of the intensity of the transmitted beam (I) to that of the incident beam (I_o) can be written as [5]:

$$\left(I/I_o\right) = e^{-N_o A_p Q_{ext} L}, \tag{1}$$

where N_o is the number of monodispersed aerosol particles per unit volume of the aerosol cloud, A_p is the projected area of each particle towards the incident beam, Q_{ext} is the extinction efficiency of individual particles, and L is the path length of the incident beam through the aerosol cloud.

A. Extinction due to dust cloud

The extinction efficiency Q_{ext} of a particle is the sum of its scattering efficiency (Q_s) and the absorption efficiency (Q_a), and it varies from 0 to 5 depending upon the particle size parameter α (α=πd/λ), the particle shape, and the complex reflective index m ($m=m_o-m_o ai$), where $i=(-1)^{1/2}$. A monodisperse aerosol containing spherical particles of diameter d and absorption coefficient a is assumed covering the solar panel exposed to the radiation of monochromatic radiation of wavelength λ.

Since the particle cloud density N_o is likely to be a function of height (L) above the surface of the solar panel, it is possible to express extinction ratio (Equation 1) with respect to the total number of particles suspended in a vertical column (assuming noon conditions at Mars) over a unit area (1cm^2 in cgs unit) of the solar panel. Letting $N=N_oL$=total number of particles suspended over 1cm^2 area, Equation 1 can be re-written:

$$\left(I/I_o\right) = e^{-NA_pQ_{ext}}, \tag{2}$$

where N is the number of particles suspended per unit area in the direction parallel to the incident beam and normal to the plane of the panel. Since the product NA_pQ_{ext} is dimensionless, it can be expressed as "optical depth" (OD), by:

$$OD = -NA_pQ_{ext}. \tag{3}$$

Experimental data from the Mars Path Finder (MPF) [1] showed that OD is approximately equal to 0.5 after the first 50 to 60 sols, i.e.:

$$OD = -NA_pQ_{ext} = 0.5 \text{ after 50 sols (sols=a day in Mars).} \tag{4}$$

A sol is equivalent to 24 hours 37 minutes on earth. MPF data also show that the particle diameter is approximately 1.6μm, therefore:

$$\alpha = \frac{\pi d}{\lambda} = \frac{\pi x\, 1.6}{0.52} = 9.7, \tag{5}$$

assuming λ=0.52μm. For a value of α greater than or equal to 20 for absorbing particles, Q_{ext} approaches its limiting value of 2. For α between 2 and 20, Q_{ext} oscillates around 2.0 with maximum value approaching 5.0. For irregular particles in the range 1 to 4 μm in equivalent projected area diameter, maxima and minima are close to 2.0. Based on the MPF data, the Tomasko model suggests: Q_{ext}=2.5. For a spherical particle of diameter d=1.6μm,

$$A_p = \pi r^2 = \pi(0.8 \text{ x } 10^{-4})^2 cm^2 = 2.01 \text{ x } 10^{-8} cm^2. \tag{6}$$

From Equation (4),

$$N = 0.5/(2.01 \text{ x } 10^{-8} \text{ x } 2.5) = 9.95 \text{ x } 10^6 \text{ particles}/cm^2. \tag{7}$$

Therefore, the imaginary vertical column over the unit surface area (1cm^2) contains approximately 10 million particles of 1.6 μm diameter. In the above calculations, a monodispersed aerosol cloud of particles with diameters of 1.6

μm was assumed. In actual conditions on Mars, the aerosol cloud will be polydispersed and the extinction coefficient should be expressed as:

$$\text{Extinction coefficient } \sigma_i = \sum_i \frac{\pi (N_o)_i \, d_i^2 (Q_{ext})_i}{4} \tag{8}$$

$$\text{and optical depth } OD = \sum_i N_i (A_p)_i (Q_{ext})_i \,. \tag{9}$$

Where $(N_o)_i$ and N_i are number concentrations with diameters d_i and extinction coefficient $(Q_{ext})_i$. When $\alpha \geq 20$, Q_{ext} approaches 2.0. For a constant mass concentration of suspended particles, the maximum extinction occurs for particles with diameters in the range 0.4-1.0μm, where Q_{ext} approaches 5.

B. Extinction of light due to dust deposition on the surface of the panel in a relatively clear sky

For a monolayer of dust particles deposited on the surface of the solar panel, the extinction of light can be calculated as:

$$(I/I_o) = e^{-NA_pQ_{ext}}\,, \tag{10}$$

where N is the number of deposited particles per unit area. Extinction due both to Aerosol Cloud and Dust deposition: the resultant extinction of light can be approximated by summation, first calculating the light intensity incident on the deposited layer of dust then by calculating the intensity of the transmitted light passing through the dust layer to the panel. At a high cloud density, multiple scattering effects will have to be considered.

C. Dust Deposition on Solar Panels

Particle deposition on the panel surface is caused primarily by five deposition mechanisms: (1) gravitational settling, (2) deposition by diffusion, (3) electrostatic deposition, and (4) inertial and diffusive deposition from turbulent flow.

The gravitational settling velocity V_{TS} can be written as:

$$V_{TS} = \frac{\rho_p d^2 C_C}{18\eta} g = \tau_p g\,, \tag{11}$$

where ρ_p is the particle bulk density, η is the viscosity, C_C is the Cunningham Slip Correction factor, and τ_p is the relaxation time of the particles. Since acceleration due to gravity (g) for Mars is 0.38 x 1g on Earth, the settling velocity on Mars is reduced by a factor of 0.38, but increased by the ratio of C_C(Mars)/C_C(Earth) for the same particle size. For a particle diameter d, expressed in μm, and atmospheric pressure P expressed in absolute pressure kPa:

$$C_C = 1 + \frac{1}{Pd}[15.6 + 7.0e^{(-0.059Pd)}]\,. \tag{12}$$

For 1.6 μm diameter particles, C_C = 1.93 at P = 0.5 kPa (5mb), and V_{TS} (Mars) = 7.3 V_{TS} (Earth). The settling velocity from Stokes' Law can be estimated:

$$V_{TS}(d = 1.6\mu m) = 0.145 cm/s \text{, on Mars surface.}$$

In tranquil (non-turbulent) settling of dust on Mars, particles of 1.6 μm diameter will settle on a horizontal surface from a maximum height of 12.78km in a sol. Landis' model [1], suggests that approximately 30,000 particles settle per sol per square centimeter.

The rate of deposition due to diffusion of particles per unit area of surface for a time period (t) can be expressed:

$$J = N_o (D/\pi t)^{\frac{1}{2}}, \tag{13}$$

where D is the diffusion constant, given by:

$$D = kTC_C / 3\pi\eta d, \tag{14}$$

where k is the Boltzmann constant and T is the absolute temperature. D is independent of the density of the particles. Assuming T= 233k and Cc=9.7, the diffusion constant is approximately 8.8 times greater than that of particles of the same diameter on Earth's surface.

Equations (11) and (14) show that the deposition rate for 1.6 μm diameter particles will be 3.35 times higher on Mars surface for both gravitational settling and diffusion compared to the deposition rate for similar cases on Earth. The deposition rate due to gravity increases as d^2 for settling, but for diffusion, it increases inversely as particle diameter d decreases. However, since Q_{ext} decreases rapidly when d decreases from 2.0 to 0, the obscuration caused by particles smaller than 0.2μm can be neglected in the case of polydispersed aerosol containing larger particles. In this model, extinction is dominated by particles with diameters greater than 0.4 μm. For a given set of atmospheric conditions, there is a particle diameter for which the deposition rates due to gravity and diffusion become equal, and for Mars, it appears that the critical diameter is between 0.3 and 0.5μm. Since fine particles in the range of 0.3 to 1.0μm will have a relatively large value of Q_{ext}(close to 5), they may play a significant role in attenuating the incident solar energy. MPF data show that the majority of the suspended dust particles are in the range of 1 to 2 μm in diameter.

The electrostatic deposition also plays a very important role due to the particles carrying an electrostatic charge, which can be quite high. When a charged particle comes close to a grounded metal conductor or an insulating surface, it experiences electrostatic attractive force due to the image force to dielectrophoretic forces respectively. These forces vary inversely as the square of the distance between the particles and the surface. Therefore, they are effective only when the distance is small, a few mm from the surface. The electrostatic force becomes dominant when the charged particles arrive close to the substrate by other forces, such as gravity, diffusion, and turbulent transport. Once the charged particles are close to the surface, the electrostatic force often changes the microstructural deposition pattern of charged particles, which depends upon both the polarity and magnitude of charge. For particles with unipolar charge distribution, the electrostatic deposition forces (space charge and image forces) are likely to make the dust layer more uniformly deposited on the panel and adhere strongly to the surface, compared to the cases for uncharged powder cloud.

Diffusion and inertial deposition of particles from turbulent flow can occur due to the dust particles being carried by the Mars winds or dust storms. For particles larger than 1μm in diameter, impaction of particles on the panel surface could be one of the dominant mechanisms of deposition in a turbulent gas flow. Inertial impaction occurs in a turbulent gas flow when the particles acquire sufficient lateral velocity in the boundary layer. Both diffusion and inertial deposition will occur during a dust storm. Values of several turbulence parameters, such as the thickness of the boundary layer, the mean gas velocity, and the PSD of particles, are needed to estimate deposition velocity or the rate of particle deposition.

III. Microstructural Pattern of Dust Deposition on Solar Panels

Particle shape, size, and electrostatic charge distributions play a significant role in obscuration of solar radiation reaching the solar cells. If the particles are insulative and are highly charged with one polarity, positive or negative, they will deposit more as a monolayer on the surface of the panel. If we assume that the transparent cover of the solar cells is nonconducting, but the bottom plate of the cells is conducting, then the unipolarly charged particles experience a local repulsive force just before they deposit on the panel. When the particle to panel distance is large, greater than 100d, the particle experiences only the external deposition force, such as gravity or diffusion. When the charged particles are close to the surface, they experience the image force, which can be many times greater than the gravitational force. Until the particles are within a distance of about 10d, they do not experience any repulsive force due to the charged particles previously deposited on the panel. At a distance greater than 10d between the charged particles and the panel, the repulsive and attractive forces caused by the charges of the deposited particle layer on the panel, and their image charges are equal and opposite. However, as the particles approach very close to the panel, the repulsive forces dominate because of their closer proximity to the dust layer charged with the same polarity of charge, compared to their distance from the image charges of the dust layer.

Experimental studies were carried out in which various amounts of charged Mars dust simulant were uniformly deposited over the surface of the solar panels. The dust deposition was investigated by using an optical microscope. As seen in Fig.1, the dust particles form dendritic formations and agglomerations. This can be explained based on the bipolar charge the Mars dust was observed to acquire. A dendritic deposition has the advantage over the uniform deposition that even at relatively large amounts of dust deposited on the surface of the solar panels, there still will be some clear space for the light to reach the panel.

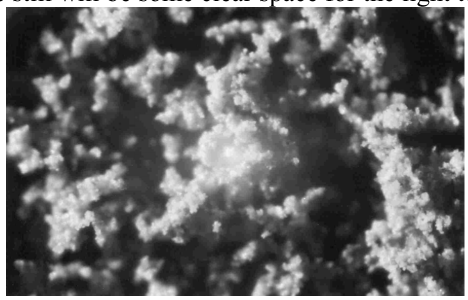

Fig.1. The dendritic formations of Mars dust particles during the deposition on glass slides

IV. EXPERIMENTAL APPROACH

Several hundred grams of JSC Mars-1 simulant dust were ground and successively sieved to obtain approximately 50 grams of dust powder of particle size diameter < 38 µm (400 mesh). The powder was then baked in an oven at 150°C for a week to dry, and then placed in a vacuum until used. Samples of the dust powder were tribocharged by milling respectively in a stainless steel or PTFE lined container, as shown in Figure 2.

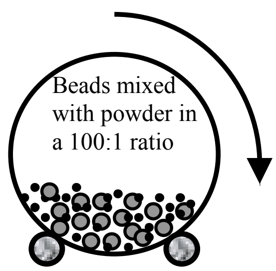

Fig.2. The setup used to charge the Mars dust simulant against different materials

The milling was performed in an environmental chamber, in which the humidity could be controlled to +/- 1% RH. The dust powders were first run at room temperature (23°C) and at a relative humidity of 44%. Each powder sample was milled for 10 minutes. After milling, a tube supplying dry air, was attached to the milling chamber and some of the dust powder was blown off by dry air into a Faraday cup to measure the Q/M. The Faraday cup was removed, and the rest of the dust powder was blown into the charge separator beneath the environmental chamber to determine the relative mass fractions of the charged powder with positive and negative polarities.

V. RESULTS AND DISCUSSIONS

The normalized power output of the solar panel was plotted as a function of the surface mass density of Mars Dust simulant particles on the glass panel (Fig. 3). Assuming that the dust particles are spherical in shape and are deposited as singlets on the glass panel, we can calculate the surface mass density considering the fact that maximum coverage of the panel will not exceed 66% of the panel's surface area by a monolayer of the particles. Since the spherical particles in an ordered monolayer can cover only 66% of the area, 36% of the light should still be transmitted, considering geometrical optics.

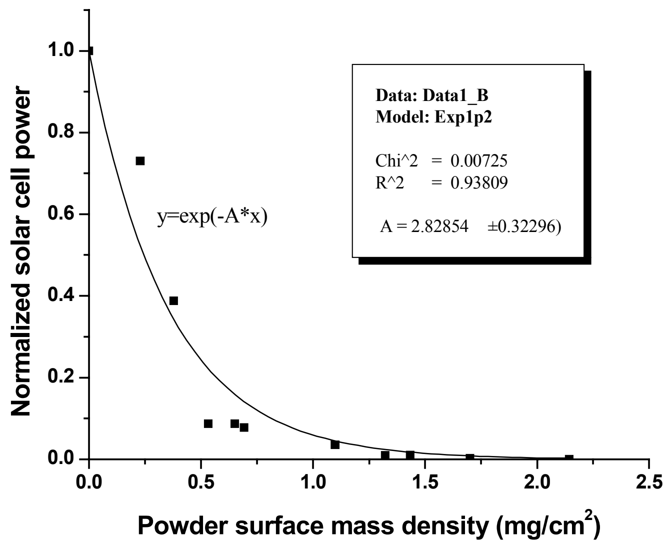

Fig.3. Normalized power output of a solar cell as a function of mass density of Mars dust simulant (<35 μm) deposition on the panel surface.

Once the particles deposit on the solar cells, the adhesion is dependent upon its charge. As seen form the laboratory experiments, the Mars dust simulant charges in contact with different materials. The data for the tribocharging for both the air and CO_2 environments is shown in Figure 4.

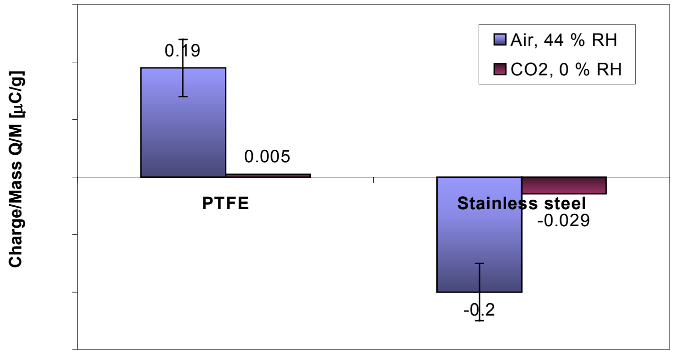

Fig.4. Q/M values of the dust charged against PTFE and stainless steel in air and CO_2

Here it was observed that the simulant dust did charge positive against PTFE and negative against stainless steel in air and CO_2. However, the Q/M for the simulant dust decreased significantly in the dry CO_2 environment. Although the dust charges positively against PTFE and negatively against stainless steel, the individual particles are bipolarly charged as shown by the charge separation data plotted in Fig. 5.

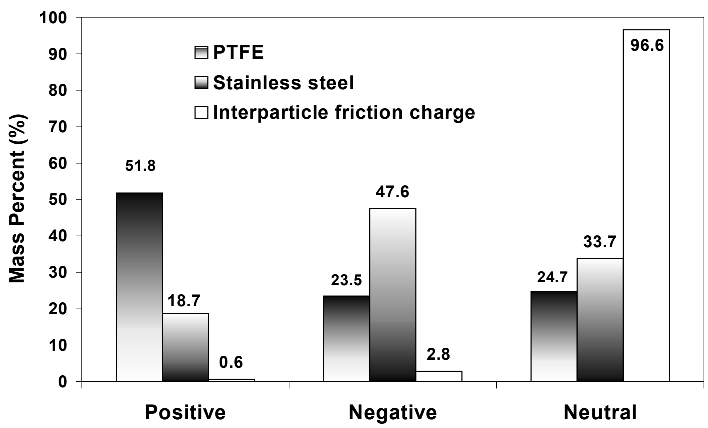

Fig.5. The charge separation data of the Mars dust simulant charged against PTFE, stainless steel and itself

Another important information is related to the charge decay kinetics for the dust. The charge decay plots for two different humidity values are shown in Fig.6.

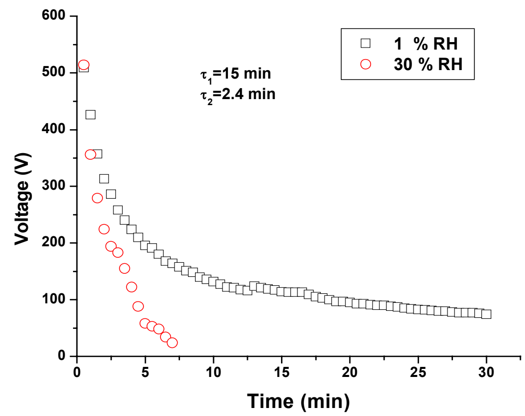

Fig. 6. The charge decay curves for the Mars dust simulant at two different humidity values.

The experimental results show that the charge decay time constant value for 1 % RH is of about 15 minutes, while at 30 % RH it is of approximately 2.4 minutes.

VI. Conclusions

The surface of Mars contains significant dust, which can be visually observed especially during the strong Martian storms. The dust particles can seriously affect future missions, especially by settling and obscuration of solar panels that will be used to power the missions. Due to the dust being highly abrasive, the fine particles can also destroy the joints of the space suits or the mobile parts of the rovers. The dust particles can become highly charged in the turbulent Mars atmosphere due to contact charging or because of the intense UV radiation. The adhesion of the dust on different surfaces is dependent upon the level of charge acquired by the particles.

The obscuration of solar panels depends upon the particle size, shape and refractive index, distribution of dust cloud, deposition mechanisms involved and the orientation of dust deposits on the panel. Three cases of obscuration of solar panels by Mars dust were considered: dust cloud over the panels, causing extinction of light reaching the solar cells even when the panels are relatively clean, extinction of light due to dust deposition on the surface of the panel in a relatively clear sky; and extinction caused by both high density particle cloud and a significant dust deposition on panels, conditions typically found in dust storms on Mars.

It was observed that during its deposition on the solar panels, the Mars dust simulant formed dendrites and agglomerations, which can be explained by the bipolar nature of the charging process. These facts can explain that even at relatively large mass density values of dust deposited on the solar panels, the panels still generate powder.

The net charge to mass ratio of the dust depends upon the material the particles were charged against. Mars dust simulant charged positively against PTFE and negatively against stainless steel. In low humidity environments, it was showed that the dust has a relatively large time decay constant of over 15 minutes.

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