

# Effect of charging of aerosols in the lower atmosphere of Mars during the dust storm of 2001

Marykutty Michael, Sachchida Nand Tripathi\*

*Department of Civil Engineering, Indian Institute of Technology, Kanpur 208016, UP, India*

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## Abstract

Aerosols are very important in the Martian climate system. Aerosols get charged by the attachment of ions in the atmosphere. Charging of aerosols reduces the conductivity of the atmosphere as the very mobile ions are lost during the ion-aerosol attachment. During a dust storm the dust opacity increases and more ion-aerosol attachment process occurs and consequently conductivity reduces further. It was found that with the background aerosols (dust opacity  $\sim 0.2$ ), the conductivity close to the surface of Mars was reduced by a factor of 5, but during the dust storm (opacity  $\sim 5$ ) of 2001 the conductivity decreased by about 2 orders of magnitude.

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## 1. Introduction

Aerosols in the atmosphere of Mars is a topic of considerable interest since their effect on the climate has been recognized (Hess, 1973; Pollack et al., 1979). Mineral dust and particles of condensate origin have been identified in the atmosphere of Mars (Clancy et al., 1996). The aerosols interact with both visible and infrared radiation and modify atmospheric heating rates (Gierasch and Goody, 1968; Kahn et al., 1992), which is responsible for the atmospheric circulation and the transport of dust. The Martian dust storm, which engulfs the planet in a matter of weeks, is the best example for this transport. As Mars is being observed continuously (HST and Mars orbiters), it is clear that the dust movement is one of the most active aspects of Mars' meteorology. Ubiquitous but seasonally varying background dust is equally important for the climate system of Mars.

Planet-encircling or global dust storms are developed when two or more regional storms combine to form larger storms. Such storms persist for longer periods lifting large amount of dust into the large-scale atmospheric circulation

and spreading dust over large stretches of the planet (Zurek, 1982; Martin and Zurek, 1993). Global storms alter the planet's total heat balance and promote variations in seasonal frost formation and dissipation, and greatly affect the distribution of water vapor. Wind action during the dust storm can produce systematic regional and global movements of dust and sediments from place to place. This leads to the visible appearance of surface features as they become coated with dust or a layer of dust is removed by the wind. E.g. dark features with relatively low albedo, during dust storms, have a higher albedo with dust deposition. Mountain peaks and craters show a noticeable change in the albedo during the passage of dust (Martin and Zurek, 1993). This provides strong clues to the direction and the strength of the wind. In addition to these effects, during storms, the dust opacity increases; this means the dust concentration increases and subsequently affects the atmospheric conductivity.

The relative variation of atmospheric conductivity with the dust opacity of Mars is discussed in the present study. The conductivity of the atmosphere depends on the highly mobile ions (Borucki et al., 1982). When ions get attached to the aerosol particles the charge carrier becomes immobile and the conductivity decreases (Borucki et al., 2006; Whitten et al., 2007). The initiation and evolution of

\*Corresponding author. Tel.: +91 9792138924.

E-mail address: [snt@iitk.ac.in](mailto:snt@iitk.ac.in) (S.N. Tripathi).

Table 1  
The maximum number of charges on aerosol produced at each altitude

Altitude (km)	Maximum aerosol charges	
	Positive charges	Negative charges
0	36	–36
10	32	–32
20	23	–23
40	8	–8
60	3	–3
70	2	–2

the planet-encircling dust storm on Mars, which occurred in 2001 have been observed in detail by the Thermal Emission Spectrometer (TES) onboard the Mars Global Surveyor (Smith et al., 2002). The variation in dust opacity during the storm has been observed by Cantor (2007) and the corresponding variation in the ion loss due to the aerosol charging and atmospheric conductivity is discussed in the present work. In the following sections the ion-aerosol characteristics, physics of ion-aerosol attachment, model for the charging of aerosols and the effect on atmospheric conductivity are discussed.

## 2. Ion-aerosol characteristics

To calculate the aerosol charging and ionic conductivity of the atmosphere it is necessary to choose a standard atmosphere. The density and temperature determine the mobility and the mean free path which in turn are essential in calculating the attachment coefficients and subsequently the conductivity. The Mars Pathfinder data for the northern summer neutral atmosphere were obtained from Magalhaes et al. (1999).

Whitten et al. (1971) carried out a detailed study of the lower ionosphere of Mars considering the ionization by cosmic rays and solar radiation in an ion-neutral model and calculated the concentration of ions and electrons below 80 km. The detailed study of the lower atmosphere of Mars by Molina-Cuberos et al. (2001) has shown that the galactic cosmic rays are the major ionization agent during the night-time. Galactic cosmic rays come from interstellar medium and as they approach the sun they encounter the solar wind and the magnetic field associated with it. Therefore, the cosmic rays lose some of their energy and would not reach Earth (or Mars). In times of higher solar activity this effect is stronger and fewer cosmic rays reach the Earth or Mars. Therefore, Cosmic ray flux is minimum during the period of maximum solar activity.

Molina-Cuberos et al. (2001) have calculated the cosmic ray ionization rates of CO<sub>2</sub>, N<sub>2</sub> and Ar. The maximum ion concentration occurs at the surface. Hydrated hydronium ions H<sub>3</sub>O<sup>+</sup>(H<sub>2</sub>O)<sub>n</sub> (*n*, varies from 1 to 4) are the most abundant positive ions for all altitudes below 70 km. CO<sub>2</sub><sup>+</sup>CO<sub>2</sub> becomes important at altitudes higher than 65 km. The most abundant negative ion is CO<sub>3</sub><sup>-</sup>(H<sub>2</sub>O)<sub>2</sub>.

In the present study the most abundant positive ion considered is H<sub>3</sub>O<sup>+</sup>(H<sub>2</sub>O)<sub>4</sub> and the most abundant negative ion is CO<sub>3</sub><sup>-</sup>(H<sub>2</sub>O)<sub>2</sub>.

Recently, O'Brien (private communication) has calculated the ion production rates at different altitudes in the Mars atmosphere corresponding to different solar activities. The ion production rate for the minimum solar activity is used in the present work. The variation of atmospheric conductivity by varying the ion production rates corresponding to the different solar activities has been described in Michael et al. (2007) and the maximum variation in conductivity was found to be about a factor of two. The electron concentration is negligible during the night-time lower atmosphere of Mars (Molina-Cuberos et al., 2001). During the day-time solar UV radiation of energy <6 eV reaches the lower atmosphere and knocks out electrons from aerosols (Grard, 1995). Therefore, this model can only be used for the night-time atmosphere. The details of the model developed for the day-time atmosphere and the results thereof are provided in Michael et al. (2008)

The density and the size of the aerosols were estimated by Chassefiere et al. (1995) from the solar occultation measurements performed by the Auguste instrument onboard Phobos 2 spacecraft. According to Chassefiere et al. (1995) the densities and the effective radii of particles close to the surface are 2.26 cm<sup>-3</sup>, and 1.9 μm, respectively. Chassefiere et al. (1995) estimated the optical depth to be 0.1–0.3. The present study considered monodisperse particles and used profiles of density and effective radii from Chassefiere et al. (1995).

## 3. Physics of ion-aerosol attachment

There are three types of theories for ion-aerosol attachment depending on the comparative size of the aerosol particles with the ionic mean free path (Yair and Levin, 1989). Ion diffusion to surface of particles occurs when the particles are larger than the ionic mean free path. Here ions are trapped by image force. Free molecular theory uses a kinetic approach when particles are much smaller than the ionic mean free path. Here the attachment occurs via 3-body trapping (similar to the ion–ion recombination). Transition regime theory is used when the size of the particles and the ionic mean free path become comparable. In this regime a combination of the above two mechanisms are used. As the Martian atmosphere is very tenuous, the aerosols are smaller than the ionic mean free path and therefore the free molecular theory is applicable here. Ionic mean free path is calculated using the following relation (Loeb, 1960).

$$\mu = 0.75 \frac{e\lambda}{M\bar{v}} \left( 1 + \frac{M}{m} \right)^{1/2} \quad (1)$$

where  $\mu$  is the ionic mobility,  $e$  is the electronic charge,  $\lambda$  is the mean free path,  $m$  is the mass of the ion,  $M$  is the mass of the gas (CO<sub>2</sub>), and  $\bar{v}$  is the average thermal velocity of

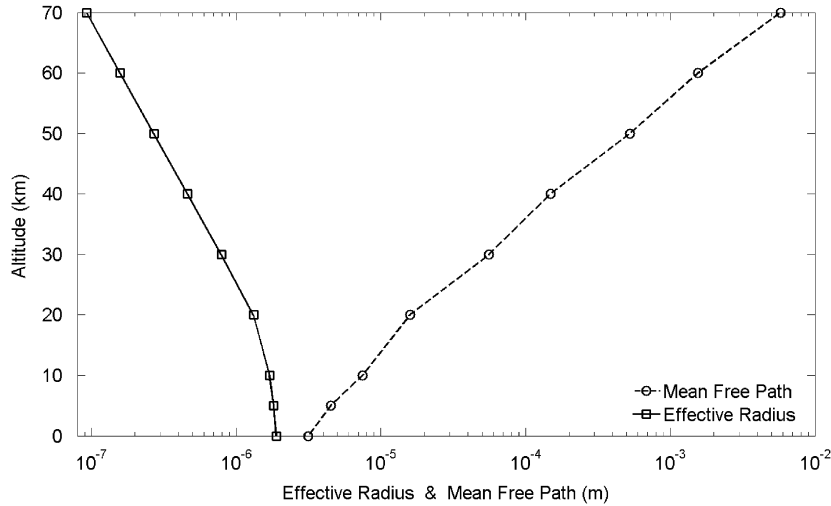


Fig. 1. Altitude profile of mean free path and effective radius of the aerosols.

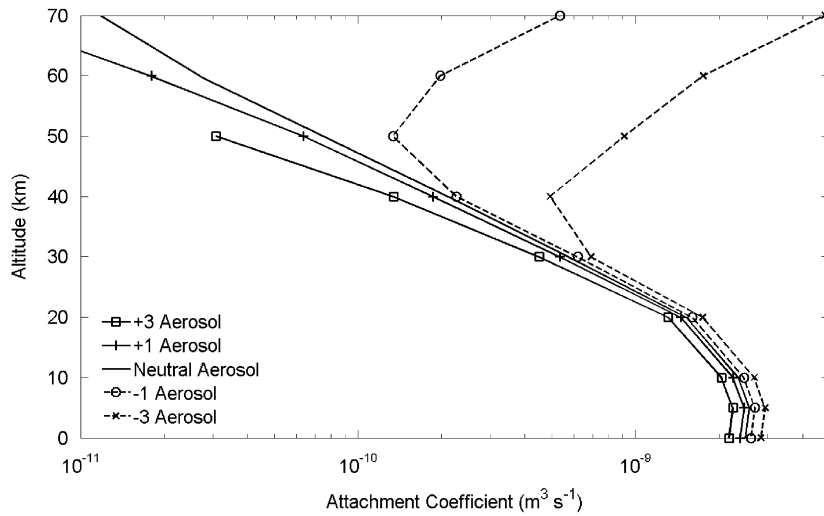


Fig. 2. The altitude profile of the attachment coefficients of positive ions to aerosols.

the molecule. Fig. 1 presents the altitude profile of the comparison between the mean free path and the effective radius of the aerosols.

The study of the rate at which the ions attach to aerosols requires the ion-aerosol attachment coefficient. The continual impingement of ions on particles gives rise to a statistical charge distribution on particles which can be expressed in terms of the ion-aerosol attachment coefficients. Hoppel and Frick (1986) have developed a theory, which can be applied to aerosol particles with radii comparable to or smaller than the ionic mean free path. In the present work the method developed by Hoppel and Frick (1986) is used to calculate the attachment coefficients of ions to the aerosols and the application of the theory in the atmospheres of various planets and satellites is discussed in Tripathi and Michael (2008) and Tripathi et al. (2008). The altitude profile of the attachment coefficients of positive ions to aerosols charged  $-3$ ,  $-1$ ,  $0$ ,  $+1$  and  $+3$  are presented in Fig. 2. At the surface of the

terrestrial atmosphere the typical value of the attachment coefficient of the aerosol is  $\sim 10^{-11} \text{ m}^3 \text{ s}^{-1}$ .

#### 4. Numerical model for charging of aerosols

Concentrations of ions and aerosols can be found from the three-level probabilistic master equations. These constitute a set of  $2p + 3$  simultaneous differential equations,  $p$  being the maximum number of elementary charges allowed on a particle (Yair and Levin, 1989). The ion and aerosol balance equations are the following.

$$\frac{dn^+}{dt} = q - \alpha n^+ n^- - n^+ \sum_i (\beta_1^{(i)} N^i) \quad (2)$$

$$\frac{dn^-}{dt} = q - \alpha n^+ n^- - n^- \sum_i (\beta_2^{(i)} N^i) \quad (3)$$

$$\frac{dN^i}{dt} = \beta_1^{(i-1)} n^+ N^{(i-1)} + \beta_2^{(i+1)} n^- N^{(i+1)} - \beta_1^{(i)} n^+ N^{(i)} - \beta_2^{(i)} n^- N^{(i)} \quad (4)$$

here,  $\alpha$  is the ion–ion recombination coefficient,  $q$  is the ion production rate,  $\beta_j^i$  is the attachment coefficient for ions of polarity  $j$  (1 for positive and 2 for negative) to particles with charge  $i$  and  $N^i$  is the density of particles of charge  $i$ . The value of  $q$  ranges from  $5.03 \times 10^6$  to  $6.9 \times 10^3 \text{ m}^{-3} \text{ s}^{-1}$  in the altitude region from 0 to 70 km.  $\alpha$  is about  $10^{-13} \text{ m}^3 \text{ s}^{-1}$ . The elementary charges on the aerosols are allowed to vary between plus and minus 100 and therefore there are 203 simultaneous differential equations for each altitude. The differential equations are solved using the 4th order Runge–Kutta method. This approach is used to solve the set of equations at 10 km altitude intervals using the charge conservation as a validation on the calculations.

After the steady state is achieved the conductivity of the atmosphere at the corresponding altitudes, with the given values of  $n^+$ ,  $n^-$ ,  $N$ ,  $q$ ,  $\alpha$ , and  $\beta$ , is calculated as

$$\sigma = e \left( \sum_i n_{i+} K_{i+} + \sum_i n_{i-} K_{i-} \right) \quad (5)$$

where,  $e$  is the electronic charge,  $n$  is the number density of ions and  $K$  is the corresponding mobility.

### 5. Results and discussion

Currently, the simultaneous differential equations for the concentrations are solved for ions and aerosols. The charging of the aerosols depends on the ion–aerosol attachment coefficients and ion–ion recombination coefficients. As the attachment coefficients and the recombination coefficients are functions of altitude, the rate of charging of the aerosols also differs accordingly. The positive and negative ionic concentrations are considered equal  $(q/\alpha)^{0.5}$ , initially. All aerosol particles are neutral at  $t = 0$ ; the calculations then consider the acquisition of

charge by ion–aerosol attachment, neglecting any aerosol–aerosol charge exchange.

Initially the aerosol charging and conductivity were calculated for the background aerosols (dust opacity  $\sim 0.2$ ). Fig. 3 presents the time-dependent positive ion concentrations for altitudes 0, 10, 20, and 40 km. It is evident that more ions are lost at the lower altitudes than at the higher altitudes. The charged aerosols are produced due to the attachment of ions. At the lower altitudes the aerosols get charged to a much higher order than at higher altitudes. There are aerosols which are charged up to 36 (i.e.  $-36$  and  $+36$ ) at 0 km in the atmosphere, but at 70 km the aerosols are charged only up to  $-2$  and  $+2$ . The concentration of the neutral aerosols is the highest and the concentration of charged aerosols decreases rapidly as the charge on the aerosol increases. The number of charges produced at each altitude is presented in Table 1.

Fig. 4 presents the initial and final positive and negative ion concentrations. More ions are lost in the lower altitudes. It is evident that most of the ion–aerosol attachment occurs in the lower altitudes. More than 80% of the ions get attached to aerosols at the surface. For altitudes greater than 40 km the presence of aerosols does not affect the ion concentration.

The atmospheric conductivity depends on the existence of ions, and the resulting conductivity can be expressed in terms of the number densities and mobilities of the individual charged species. The conductivity of the atmosphere in the absence of aerosols is presented in Fig. 5 as the line with crosses. The conductivity peaks at the surface as the ion concentration is maximum at the surface. The attachment of ions to aerosols reduces the conductivity as they become almost immobile by attachment to aerosol particles. Line with triangles in Fig. 5 depicts the effect of aerosols in the conductivity of the atmosphere. It is evident that the conductivity decreases in the presence of aerosols. The background aerosols decrease the conductivity by a factor of 5 at the surface of Mars. The atmosphere of Mars

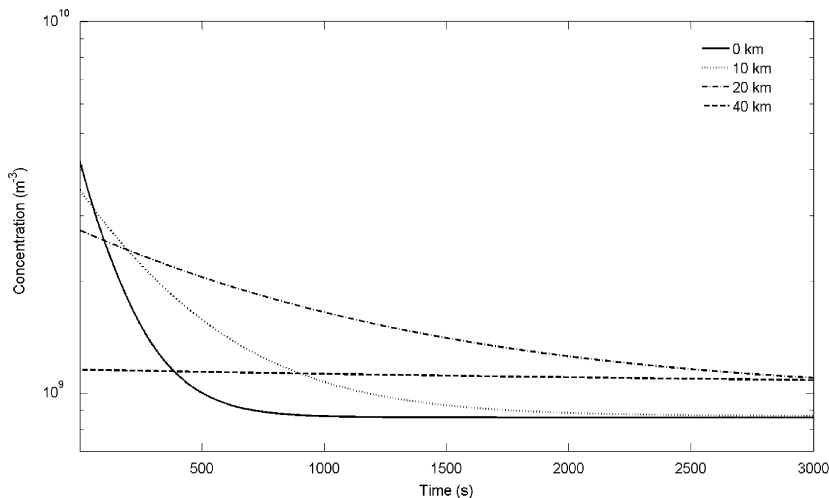


Fig. 3. Time dependent ion concentrations for altitudes 0, 10, 20 and 40 km.

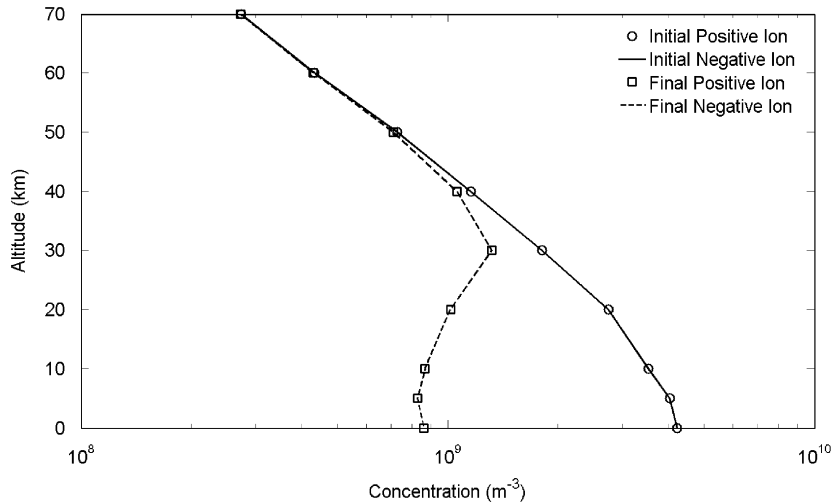


Fig. 4. Initial and final positive and negative ion concentrations.

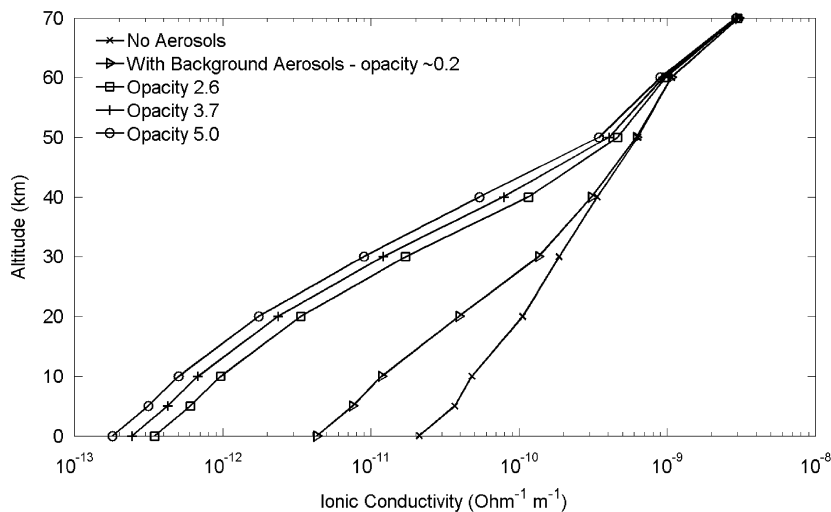


Fig. 5. Altitude profile of ionic conductivity.

is much tenuous than that of the atmosphere of Earth and the pressures close to the surface of Mars is comparable to the Earth's stratosphere at altitudes 35–40 km. After considering the differences and similarities of the two atmospheres, [Grard \(1995\)](#) and [Berthelier et al. \(2000\)](#) suggested the atmospheric conductivity close to the surface of Mars as  $10^{-12}$ – $10^{-10} \Omega^{-1} \text{m}^{-1}$  similar to that of the Earth's stratosphere at an equivalent pressure. The present calculations show that the conductivity of the atmosphere close to the surface is  $\sim 5 \times 10^{-12} \Omega^{-1} \text{m}^{-1}$ , which is within the predicted range. The inferences made in this work will therefore be useful while designing electrical instruments for future missions.

Local and regional dust storms as well as planet-encircling storms are observed on Mars ([Smith et al., 2002](#)). Mars Orbital Camera (MOC) onboard Mars Global Surveyor (MGS) observed the planet-encircling storm in 2001 during the months of June–October ([Cantor, 2007](#)).

The onset of the storm occurred on 26 June 2001 in southern mid-to-low latitudes in Hellas basin. The expansion of the storm was rapid in all directions. Temporal changes in the dust opacity ( $\tau$ ) were studied by [Cantor \(2007\)](#) during the dust storm of 2001. During the onset and expansion phase of the storm the dust optical depths were estimated to be increasing steadily. In Hellas  $\tau$  reached a maximum of  $\sim 5$  at  $L_s = 199.5^\circ$ . The storm reached Elysium next and the maximum  $\tau$  was estimated as  $\sim 3.7$  at  $L_s = 211.1^\circ$ . Claritas followed with maximum  $\tau$  of  $\sim 3.8$  at  $L_s = 206.6^\circ$ . At the Viking 1 lander site Chryse,  $\tau$  reached a maximum of  $\sim 2.6$  at  $L_s = 194.8^\circ$ . To study the effect of dust storms, the conductivity of the atmosphere with different amounts of dust corresponding to  $\tau = 5.0$ , 3.7 and 2.6 are calculated. The altitude profile of conductivity corresponding to these dust opacities are presented in [Fig. 5](#). It is evident that the atmospheric conductivity decreases with increase in the dust opacity.



This is due to the fact that more ions become immobile by their attachment to dust particles. Higher the dust opacity, higher the dust concentration and therefore higher the ion loss. The effect is highest close to the surface as the aerosol concentration peaks close to the surface. The conductivity reduces by about an order of two at the surface when the dust opacity becomes five. Roldugin and Tinsley (2004) and references therein suggest that the vertical current density decreases when there is a high loading on stratospheric aerosols in the terrestrial atmosphere which supports the conclusions of the present study. Farrell and Desch (2001) suggested that the dust storms (analogous to terrestrial thunderstorms) could act as generators for the global electric circuit of Mars. The surface conductivity assumed in their study is greater than that predicted in the present study during dust storms. But the iron blend in the soil and the possible presence of trace amounts of water in the subsurface region may greatly enhance the subsurface conductivity, and could complete the electric circuit.

Bertheliet et al. (2000) suggests that charge separation and electric-field breakdown are likely to occur in Martian dust storms. The ability of Martian dust particles to become electrically charged was observed by the Mars Pathfinder lander camera which showed dust accumulation on the wheels of the rover (Ferguson et al., 1999). Numerical simulations on the build-up of the electric fields in the Martian atmosphere during dust storms suggest that the charging develop very fast and the breakdown or the glow discharge occurs almost immediately (Melnik and Parrot, 1998). The consequences of the development of a large-scale electric field on Mars are important in several areas like the transport of dust particles, as for micron size particles electrical forces may become comparable to the drag forces and surface material chemistry etc. It has also been suggested that the lightning and electrical discharges may influence the production of those chemical compounds that have been related to speculation regarding life on Mars (Bertheliet et al., 2000).

## 6. Summary

It is generally accepted that the global electric circuit is driven by thunderstorms on Earth. For a global electric circuit to exist on Martian atmosphere, a constant current generator must be present in a finitely conducting atmosphere. Cloud particles exist in the atmosphere of Mars at altitudes about 30 km (Montmessin et al., 2006). Farrel and Desch (2001) have suggested that Mars possesses a global electric circuit driven by dust storms. Therefore, it is important to study the charging of particles and the conductivity of the atmosphere as there could be a driving force for a global electric circuit. The study of the charging of the aerosol particles by the ion attachment is important as it leads to a reduction in the atmospheric conductivity. Martian atmosphere is very tenuous that the ionic mean free path is higher than aerosol size and therefore the ion-attachment follows the free molecular theory. Charge

balance equations have been solved to find the steady state ion and aerosol concentrations. Conductivity of the atmosphere is then calculated as it depends on the concentration and mobility of the positive and negative ions. Maximum ion loss is observed at the surface. It was found that more than 80% of the ions are lost at the surface due to the ion-aerosol attachment with the background aerosols. The conductivity was reduced by about a factor of 5 at the surface due to the presence of the background aerosols. The variation in atmospheric conductivity during the dust storm in 2001 has also been estimated. It was observed by Mars Global Surveyor that the dust opacity reached a maximum of  $\sim 5.0$  during the dust storm of 2001. The conductivity decreased by about 2 orders of magnitude for the maximum dust opacity observed.

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