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Quasi-electrostatic field analysis and simulation of Martian and terrestrial dust devils

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[1] Recent experimental and modeling studies show that large quasi-static electric fields (2–20 kV/m) can be developed in a Martian or terrestrial dust devil as a result of contact electrification and charge separation of dust grains with different sizes and compositions. Electric discharging occurs when the maximum electric field reaches breakdown values (~20 kV/m on Mars and ~3 MV/m on Earth, at surface altitudes). We derive a maximum electric field in a dust devil and develop a two-dimensional (2-D) cylindrically symmetric finite element model for Martian and terrestrial dust devil simulations. Unlike previous models with unlimited field growth, the tribocharging process and the time evolution of the dust devil electric field are self-consistently limited in our model and the saturated maximum electric fields in our simulations are comparable to past measurements. We study the saturated maximum electric fields for dust storms of different size, atmosphere conductivity and time rate of tribocharging. We also discuss the 2-D cylindrical field structures surrounding a dust devil and the conductivity gradient effect to the field growth of large Martian dust storms.

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1. Introduction

[2] Dust devils formed by wind swirling around a column of warm, rising air are common occurrence in dry and desert terrestrial landscapes and are a common feature in the dry and low-pressure Martian atmosphere. The formation and evolution of dust storms is a multiphysical process involving dust particle thermal and kinetic energy evolution, dust grain contact electrification and charge separation [*Toigo et al.*, 2003; *Farrell et al.*, 2003]. Initially, surface air molecules and dust grains absorbing heat from sunlight generate pressure and temperature gradients on the surfaces that form vertical wind or local vortices, and dust grains are lifted from the ground. As the moving dust grains contact with the surface and with each other, they exchange charge via triboelectric (frictional) processes. With the decrease of wind speed and reduced pressure and temperature gradients, the convective-driven dust storms go through a mass stratification process that leads to charge separation due to gravity and air viscosity.

[3] Past in situ measurements suggest that large electric fields (bigger than 4 kV/m where many instruments have saturated and has been recently measured to be near 120 kV/m) exist in terrestrial dust devils [*Crozier*, 1970; *Farrell et al.*, 2004] (see also T. L. Jackson and W. M. Farrell, Electrostatic fields in dust devils: An analog to Mars, submitted to *IEEE Transactions on Geoscience Remote Sensing*, 2005) (hereinafter referred to as Jackson and Farrell, submitted manuscript, 2005). Recent numerical and analytical studies show that the micro-electro-aerodynamical system of a dust devil is an efficient giant electric generator that may trigger Martian electrical discharges and radio emissions [*Melnik and Parrot*, 1998, 1999; *Farrell et al.*, 1999, 2003]. Experimental evidence in a Martian-like lab environment has shown the possibility of electric discharges of Martian dust storms [*Eden and Vonnegut*, 1973], and theoretical and modeling studies have indicated that under some conditions, discharging may occur [*Melnik and Parrot*, 1998; *Farrell et al.*, 2003]. However, many critical issues, such as under what conditions can the field reach breakdown values and whether charge and electric field growth will be saturated before reaching the breakdown, have not been systematically addressed. The two electrical systems, one at the small scale for dust grains, and one at the large scale for the overall dust storm, have not been connected in a way that illuminates the basic physics. On the basis of the findings in previous work, our goal in this paper is to connect these two different pictures by incorporating the charge dissipation of individual dust grains. Specifically, we derive a maximum electric field within a dust devil in simple terms and develop a realistic numerical model to study the electric fields of Martian and terrestrial dust storms, to predict potential electric discharges that may challenge future human explorations on Mars [*Farrell et al.*, 2004; *Beaty et al.*, 2005].

[4] Dust particles are electrified in a dust devil when they collide with each other as a result of differences in sizes and

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contact potentials between compositionally distinct materials [*Melnik and Parrot*, 1998; *Desch and Cuzzi*, 2000]. When two particles of similar composition collide, the smaller grain tends to be negatively charged, and the larger grain obtains an equal but opposite charge. On the basis of this tribocharging scenario, *Melnik and Parrot* [1998] developed a fully numerical model of dust electrification. With some realistic assumptions, their model predicts time evolution of the maximum electric field in a dust devil. Their results indicate that electric discharging occurs in all circumstances analyzed, even though the time to reach electric breakdown may vary by circumstances. Existing evidence on Earth, however, indicates that dust devil discharging is not common, and it is not clear that their model would support these terrestrial observations.

[5] *Desch and Cuzzi* [2000] proposed that when two particles with different contact potentials collide, electrons are transferred to the material with a larger contact potential and leave the material with a smaller contact potential positively charged. Upon collision, a significant amount of charge is placed on each particle. More recent studies show that the charge of dust grains after collision depend on humidity, temperature, and its velocity [*Poppe and Schrapler*, 2005]. On the basis of the two tribocharging scenarios and the vertical charge transport similar to the thunderstorm precipitation electrification mechanism [*Mathpal et al.*, 1980], *Farrell et al.* [2003] developed a fully analytical electrodynamic model of a dust devil with simplified assumptions of dust devil structures, time rate of charging, etc. The large vertical electric fields quickly exceed breakdown values, consistent with simulations by *Melnik and Parrot* [1998]. The tribocharging process therefore will trigger electrostatic discharge in Martian dust storms. The modeled terrestrial dust devil electric field reaches breakdown value (3 MV/m) in less than 5 min. This model predicts unlimited growth of dust devil electric fields that are not consistent with past observations of terrestrial dust devils, where only a maximum electric field of a few kV/m has been observed [*Crozier*, 1970; *Farrell et al.*, 2004]. Most recently, Jackson and Farrell (submitted manuscript, 2005) measured near 120 kV/m QE fields of dust devils with a carefully calibrated electrometer. A self-regulating mechanism as suggested by *Crozier* [1964], or a saturation mechanism such as the instantaneous charge dissipation and electric field relaxation due to atmosphere electric conductivity should be introduced properly into the analytical or numerical models [*Desch and Cuzzi*, 2000].

[6] The saturation of electric field growth depends on numerous factors, such as the atmosphere conductivity, dust grain charge capacity [*Desch and Cuzzi*, 2000], recombination of grain charges through subsequent collisions [*Melnik and Parrot*, 1998], possible neutralizing effect of free charge produced by ionizations of gas molecules [*Desch and Cuzzi*, 2000], and retardation of grain charging similar to the electrification produced by the collision of ice crystals with polarized hail pellets [*Mason*, 1988]. Therefore the local atmospheric conductivity controlling charge leakage rate is dynamically coupled with the tribo-charging rate. To include all the microphysics of dust devil tribocharging into a simplified model is beyond the scope of our present paper. The primary factor limiting the electric field growth, however, is conduction electric current [*Mason*, 1972] such that space charge in the region decays exponentially over the relaxation time [*Desch and Cuzzi*, 2000]. To this end, we assume a constant local atmospheric electric conductivity and focus in this paper on the effect of atmosphere conductivity and how it saturates the tribocharging process.

[7] The quasi-electrostatic (QE) nature of dust devil contact electrification and the charge and electric field relaxation are in fact similar to the evolution of thunderstorm space charge and electric field leading to conventional breakdown that produces sprites in the upper ionosphere [*Pasko et al.*, 1997]. The QE model formulation has been applied to the numerical study of Martian dust devils in the 2-D cartesian coordinate [*Melnik and Parrot*, 1998]. In this paper, we develop a 2-D cylindrically symmetric QE model using the finite element method to study space charge and electric field evolution of dust devils as a result of atmospheric conductivity. We present a modified analytical model that incorporates charge dissipation into the time rate of tribocharging process. Simulations presented below show that peak electric fields in dust devils saturate through a simultaneous relaxation of the triboelectric charge and electric field due to conductivity. We also discuss the 2-D cylindrical field structures surrounding a dust devil and how the conductivity gradient affects field growth, and spatial variation of the QE field in Martian dust devils of different size and time rate of charging.

2. Quasi-Electrostatic Model Formulation

[8] The contact electrification of a dust devil involves dust particle collision, tribo-charge separation, and dust grain mass saltation around the center of a warm-air dust column. The rapid growth of electric field in a dust devil and its surroundings is the result of the frictional electrification of dust particles with different sizes and compositions. Similar to thunderstorm inductive charging, and its associated field relaxation in the QE heating model for upward mesosphere discharges [*Pasko et al.*, 1997], we anticipate an exponentially growing QE field at the initial stage of devil formation and charge accumulation, and much slower rate of field increase later, and eventually a steady state field and charge distributions with a time constant depending on atmospheric electric conductivity. This steady state is achieved when, on individual dust particles, the rate of collisional charge separation balances charge relaxation through conduction electric currents. The necessary condition for continued charge and electric field growth is that the time rate of tribocharging among dust particles is faster than the local charge relaxation determined by atmospheric conductivity [*Desch and Cuzzi*, 2000].

[9] The electrostatic field $\mathbf{E}$, derived from the electrostatic potential by $\mathbf{E} = -\nabla\phi$, the total charge density ρ, the source current density $\mathbf{J}_w$ induced by charged particle motion due to wind and gravity, and the conduction current density $\mathbf{J}_c = \sigma\mathbf{E}$ are governed by the system of Poisson's equation and the charge continuity equation,

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}, \tag{1}$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \mathbf{J}_w - \sigma(\nabla \cdot \mathbf{E}) - (\nabla\sigma) \cdot \mathbf{E}, \tag{2}$$

where the first term on the right-hand side of (2) is the result of tribocharge separation due to wind and gravity, the second term is the charge relaxation due to electric conductivity, and the third term is the charge accumulation due to conductivity gradient.

[10] Owing to atmospheric electric conductivity, the dissipation of space charge generated via grain contact and the dissipation of dust devil electric field are directly related and must be modeled properly in the numerical or theoretical analysis. Previous models use simplifying assumptions to explain individual grain charging, such as assuming a constant charge rate [*Farrell et al.*, 2003], or assuming grains in isolation [*Melnik and Parrot*, 1998]. In this work, we examine the more advanced case where grain charge relaxes in an atmosphere, creating local grain charge dissipation. We demonstrate that the inclusion of this microscopic effect at the grain level has significant effect on the derived macroscopic large-scale electric field.

3. Local Analytical Model

[11] On the basis of the coupled system of equations (1) and (2), we show that the exponential growth of the dust devil electric field and the space charge density, can be balanced by the electric conductivity. Substituting (1) into (2) to eliminate ρ while neglecting conductivity gradient and remove the divergence operator in (2), and substituting (2) into (1) to eliminate $\nabla \cdot \mathbf{E}$ in (1), we obtain

$$\frac{\partial \mathbf{E}}{\partial t} + \frac{\sigma}{\epsilon_0}\mathbf{E} = -\frac{\mathbf{J}_w}{\epsilon_0} + \nabla \times \mathbf{f}, \tag{3}$$

$$\frac{\partial \rho}{\partial t} + \frac{\sigma}{\epsilon_0}\rho = -\nabla \cdot \mathbf{J}_w, \tag{4}$$

where function $\nabla \times \mathbf{f}$ is introduced in (3) as a result of space integration to remove the divergence operator in (2). The only constraint of $\mathbf{f}$ is that the divergence of (3) vanishes.

[12] The purely local, zero-dimensional electrodynamic model by *Farrell et al.* [2003] is based on solving analytically the scalar form of (3). The scalar model solution is a reasonably simplified but physically meaningful approximation of the dust devil electrification in a large, finite volume. There are no external sources in such a scalar model in an infinite domain of computation and the vector function $\nabla \times \mathbf{f}$ in (3) vanishes. The scalar equation governing the dust devil electric field is [*Farrell et al.*, 2003]

$$\frac{\partial E}{\partial t} + \frac{\sigma}{\epsilon_0}E = -\frac{J_w}{\epsilon_0} = -\frac{n_L \Delta v Q_L}{\epsilon_0}, \tag{5}$$

where the source term $J_w = n_L Q_L \Delta v$ is the dust particle induced vertical current density due to charge separation, with n_L, Q_L and Δv the large grain density, the large grain charge and the relative drift velocity between large and small dust particles, respectively.

[13] Assuming that the time rate of charge increase on large grains is constant, a system of equations (5) and $\frac{\partial Q_L}{\partial t} = \nu \Delta q$ is solved by *Farrell et al.* [2003], where $\nu = \pi r_L^2 \Delta v n_s$ is the collision frequency with r_L and n_s the large grain radius and the small grain density, respectively. The charge exchange per collision is defined on the basis of either grain size [*Melnik and Parrot*, 1998] or both grain size and difference of triboelectric potentials [*Desch and Cuzzi*, 2000]. The solution is given below,

$$E = \frac{n_L \Delta v \nu \Delta q}{\sigma}\left\{t - \frac{\epsilon_0}{\sigma}\left(1 - e^{-\frac{\sigma}{\epsilon_0}t}\right)\right\}, \tag{6}$$

$$Q_L = \nu \Delta q t. \tag{7}$$

The first term of (6) indicates that the electric field grows linearly (unfortunately, also without limit). They demonstrated that a mass-preferential tribocharging process will create charge polarity difference between grains of various sizes, and that subsequent vertical winds will stratify these grain based upon mass (and hence charge).

[14] While the work shows dust devils may develop substantial electric fields, it was assumed that the grain charging rate is a constant. In fact, the timescales for grain charge relaxation may be on the same order of (or exceed) the currents generated from collisions. We incorporate microscopic grain charge relaxation into the model by allowing charge relaxation as

$$\frac{\partial Q_L}{\partial t} + \frac{\sigma}{\epsilon_0}Q_L = \nu \Delta q, \tag{8}$$

and the solution for the charging of individual dust particles is

$$Q_L = \nu \Delta q \frac{\epsilon_0}{\sigma}\left(1 - e^{-\frac{\sigma}{\epsilon_0}t}\right). \tag{9}$$

In contrast to (7), (9) is a saturable and more physically reasonable solution. The saturated value of grain charge is $Q_L = \frac{\epsilon_0}{\sigma}\nu \Delta q$. Unlike the original model formulation, this solution depends on atmospheric conductivity. Similarly, the electric field solution to (5) is

$$E = \frac{n_L \Delta v \nu \Delta q}{\sigma}\left\{t e^{-\frac{\sigma}{\epsilon_0}t} - \frac{\epsilon_0}{\sigma}\left(1 - e^{-\frac{\sigma}{\epsilon_0}t}\right)\right\}, \tag{10}$$

and the maximum electric field is $E = \frac{\epsilon_0}{\sigma^2}(n_L \Delta v \nu \Delta q)$.

[15] Figure 1 (right) compares the electric fields from the original and our modified models for charging scenario from *Melnik and Parrot* [1998]. Saturation of the tribocharging process in the modified model clearly indicates that there is a limit to the electric field growth in both terrestrial and Martian dust devils. The big difference between the two models on Mars is mainly due to the higher atmospheric conductivity near Martian surface, which is about 2 orders of magnitude higher than the atmospheric conductivity on Earth. Using the assumptions of *Farrell et al.* [2003] with Δv = 1 m/s, the maximum electric fields for this zero-dimensional model on Earth and Mars saturate at ~3 MV/m and ~2 kV/m, respectively, before reaching breakdown levels. However, as suggested by (10), the maximum electric field varies directly with Δv,

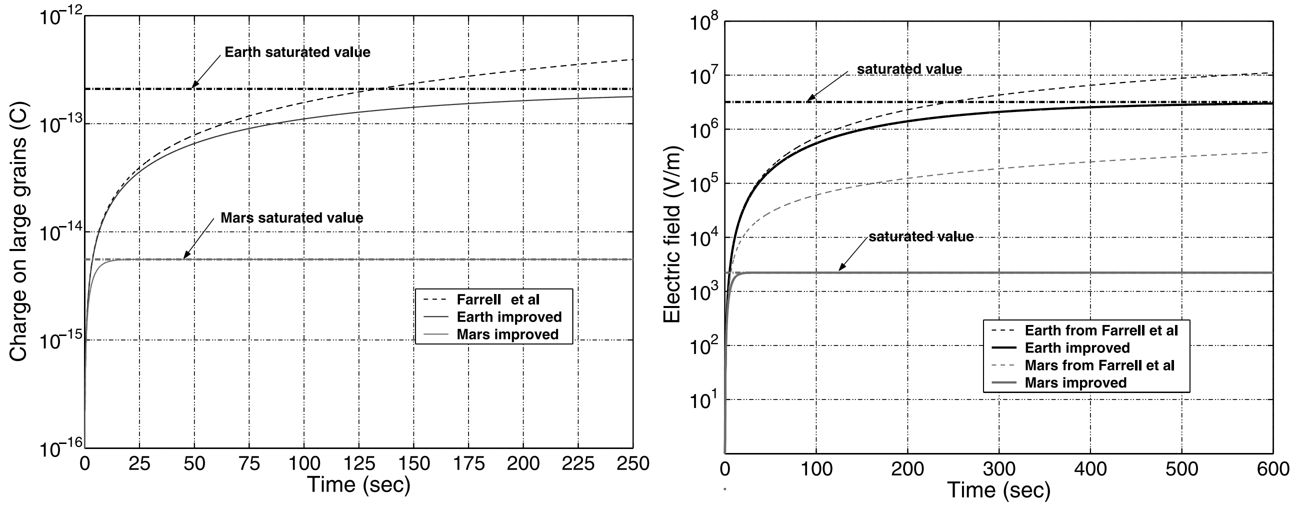

Figure 1. Comparison of triboelectric charge of large grains and the E-field without charge relaxation and that with charge relaxation. The saturated charge value on Mars is 5.56×10^{-15} C, which is much smaller than what is predicted by Farrell's model, 7.85×10^{-14} C at the time of 50 s. The saturated field values on Earth and Mars are 3.2 MV/m and 2.2 kV/m, respectively.

and an increase in vertical wind speeds will also increase Δv proportionally. The input parameters (i.e., atmospheric conductivity, charge transfer per grain collision, etc.) are not at all well bounded and thus these numbers are only reasonable guesses.

[16] The electric breakdown values for terrestrial and Martian atmospheres on the ground are about 3 MV/m and 20 kV/m, respectively. More realistic modeling is presented below, but these numbers suggest that reaching breakdown in terrestrial dust devils may be difficult, which is supported by the lack of discharging in observed terrestrial dust devils. It may be even more difficult to achieve breakdown on Mars because of the higher atmospheric conductivity. In real situations the average fair weather electric field on Mars may vary from a few hundred volts per meter in storm season to less than a volt per meter during the nonstorm season [*Farrell and Desch*, 2001]. In such cases, our simplified model analysis is still physically meaningful and it can be viewed as the change in the field strength due to dust devil electrification as compared to the fair weather electric field.

[17] Although Martian atmosphere is generally known to be highly conductive compared to terrestrial atmosphere, Martian atmospheric conductivity is far from well quantified. We assume that the Martian surface conductivity is $\sigma = 2.8 \times 10^{-12}$ S m^{-1} [*Farrell et al.*, 2003], and exponentially increases with altitude only owing to ion pair production by cosmic rays, on the basis of an electron-neutral collision frequency profile and electron density profile described by *Cummer and Farrell* [1999].

4. Quasi-Electrostatic Dust Devil Simulations

[18] The zero-dimensional analytical model presented above gives valuable insight into the problem but is not realistic enough to simulate realistic, finite-sized dust devils and dust storms. In this section we compute fields for realistic geometries using a 2-D quasi-static finite element model.

[19] The two-step quasi-static simulation is performed by an electrostatic finite element solver to obtain the dust devil induced electric field first, and a time-stepping solver to obtain the total charge relaxation at each time step next. The source term to the electrostatic finite element solver of (1) is the time rate of charge separation due to wind and gravity obtained from the charge continuity equation,

$$\Delta\rho_s = -(\nabla \cdot \mathbf{J}_w)\Delta t.$$

This $\Delta\rho_s$ is used to update the total charge density (which includes background charge in the conducting atmosphere) $\rho = \rho + \Delta\, \rho_s$ in (1), for the computation of the electric field **E**. The total charge evolution (with relaxation) governed by the charge continuity equation

$$\frac{\partial\rho}{\partial t} + (\nabla\sigma) \cdot \mathbf{E} + \frac{\sigma}{\epsilon_0}\rho = 0 \qquad (11)$$

is solved by a finite difference time stepping algorithm. Equations (1) and (11) are then solved alternatively with the finite element method in space and the finite difference method in time for the QE fields generated by dust particle electrification. The source term is imposed on a region that is finite in altitude and width to realistically reflect the finite size of the dust devil. Unlike the finite difference simulation [*Melnik and Parrot*, 1998], where the differential form of (1) (the strong form) is directly discretized with uniform grid and a purely local solution is obtained by marching in space and time step by step, the Galerkin finite element formulation employs a weak form of the Maxwell's equations before a discretization is performed and a globally averaged solution of the triangular mesh is obtained. A nonuniform finite element triangular mesh can capture more effectively the expected space charge concentration and the electric field distribution within and surrounding a dust devil. The flexibility of a finite element discretization in space allows us to use a fine spatial scale within the dust

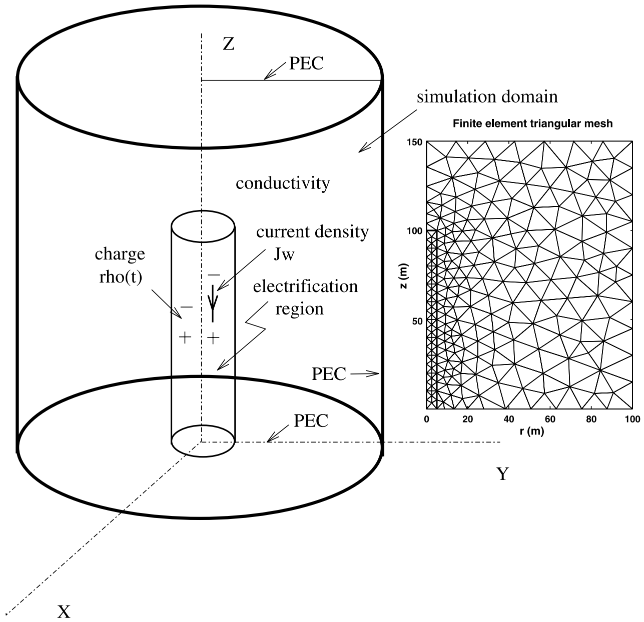

Figure 2. FE model simulation domain of a dust devil.

devil and a coarse spatial scale outside and surrounding the dust devil where the fields vary slowly in space.

[20] A cylindrical coordinate system (r, ϕ, z) is used in our finite element model with the z-axis representing altitude, as shown in Figure 2. The ground, top, and radial boundaries of the computational domain are assumed to be perfectly conducting and the entire system is taken to be cylindrically symmetric about the z-axis. The symmetric boundary along the z-axis is set to be Neumann type. Figure 3 shows a simulated electric field and charge density distribution of a terrestrial dust devil to illustrate a sample solution.

[21] With the finite element model, we impose a region of vertical wind-driven current J_w that self-consistently results in a dipole charge structure with charge centers in the top half and bottom half of this generator region. The height and diameter of this generator region can be specified arbitrarily and we assume that the generator region fills the entire dust devil. Although more complicated charge structures can be included in this model, the dipole model of a dust devil is thought to be reasonable and has been used to estimate space charge densities [*Crozier*, 1964; *Farrell et al.*, 2004]. The dipole charge model has a uniform distribution of negative space charge density at the dust devil top and a uniform distribution of positive space charge density at the dust devil bottom in a modeled cylindrical dust cloud.

[22] The input to the QE solver is the incremental volume charge density $\Delta\rho_s(\mathbf{x}, t)$, either from particle simulations or analytic electrodynamic models, or in situ measurements, where $\mathbf{x}$ is the spatial coordinate and t is the time. The solver then computes the electric potential ϕ, the electric field $\mathbf{E}$, the total charge density ρ, and the conduction current densities $\mathbf{J_c} = \sigma\mathbf{E}$. At each time step, the QE solver computes first the electric potential from the Poisson's equation (1), and the electric field $\mathbf{E} = -\nabla\phi$ due to the charge separation and dissipation within the dust devil. The dissipation of the incremental source charge due to atmospheric conductivity σ is obtained by solving the charge continuity equation (11) with a time-stepping algorithm. The QE solver computes field components in a two-dimensional rz plane assuming invariance in the azimuthal direction.

[23] We perform QE simulations of a terrestrial dust devil of 10 m in diameter and 100 m high to demonstrate saturability of the space charge and electric potential gradient growth in our FE model. We use an incremental source charge density per time step of $\Delta\rho_s(z, t) = 1.57 \times 10^{-10}$ C/m^3, similar to *Melnik and Parrot* [1998] and *Farrell et al.* [2003], as the input of the dipole charge configuration. The time step change between each density frame is 0.05 s. All elements in the bottom half of the dust devil are incremented with this positive source charge density at each time step, while all elements in the upper half of the dust devil are incremented with the same negative charge density. This results in a distributed dipole charge structure in the dust devil.

[24] Figure 4 shows the charge density and the electric field from the simulated dust devil. The maximum electric field within this 10 m by 100 m dust devil is 150 kV/m after 10 min. The time evolution of space charge density is very similar to the initial accumulation of the thunderstorm space charge in the QE heating model before a conventional breakdown is reached [*Pasko et al.*, 1997]. This maximum electric field for a typical terrestrial dust devil is difficult to compare with experimental measurements, all of which have strongly saturated at a few kV/m [*Freier*, 1960; *Crozier*, 1964, 1970; *Farrell et al.*, 2004], but the predicted value of 150 kV/m is not inconsistent with these measurements. Very recently, Jackson and Farrell (submitted man-

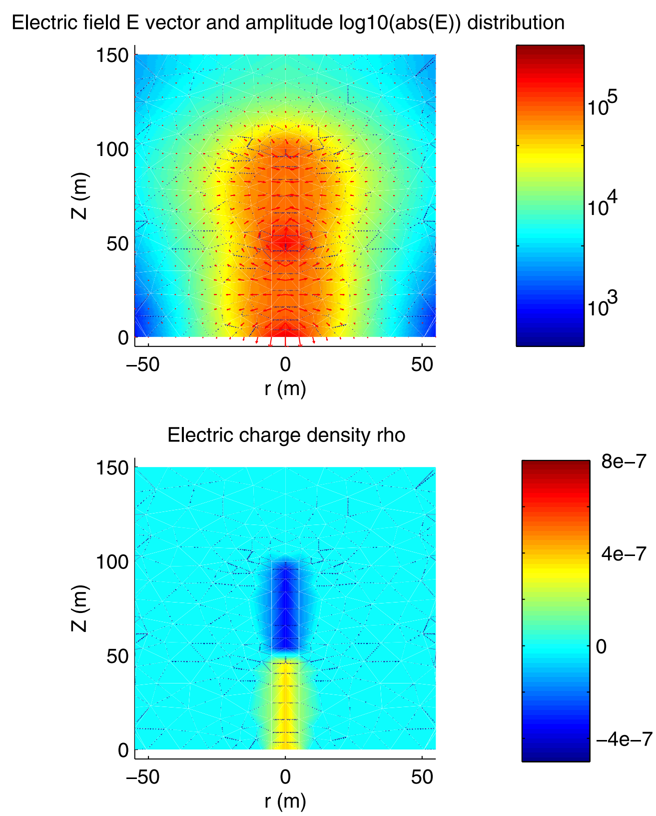

Figure 3. Electric field and charge density of a typical terrestrial dust devil.

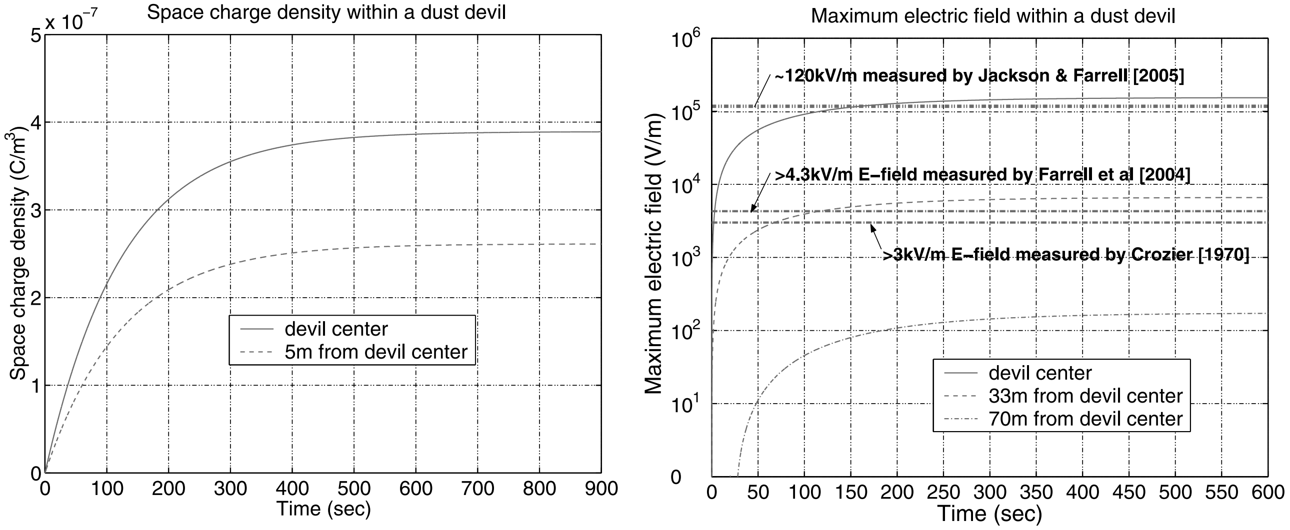

Figure 4. Space charge density and maximum electric field in a 10-m-wide and 100-m-high terrestrial dust devil. The saturated space charge values are 3.9×10^{-7} and 2.6×10^{-7} C/m^3, comparable to our model prediction: 2.1×10^{-7} C/m^3. The saturated E-field values are 150 (comparable to measurement by Jackson and Farrell, submitted manuscript, 2005), 6.6 and 0.17 kV/m.

uscript, 2005) found that the maximum electric field of typical terrestrial dust devils is near 120 kV/m, which is consistent with our simulation.

[25] Unlike the analytical model of *Farrell et al.* [2003] and the numerical model of *Melnik and Parrot* [1998], the dissipation of dust grain charge due to atmospheric conductivity is fully considered in our FE simulation. As shown in (11), the atmospheric conductivity gradient along altitude z is also included in our FE model. A large background conductivity gradient may cause significant charge redistribution. Here we impose Martian atmospheric conductivity $\sigma_m = 2.8 \times 10^{-12}$ S m^{-1} [*Cummer and Farrell*, 1999; *Farrell et al.*, 2003] at the ground and a small conductivity gradient such that the relaxation time at the top of the devil is 1.5 s, roughly half of what is on the ground. Although we do not see a significant difference of the maximum electric field between simulations of a 100 m by 10 km Martian dust storm with conductivity gradient and that without conductivity gradient, there is a smoothing effect of the conductivity gradient to the space charge distribution in the electrification region along the interface of the positive and negative charge regions. A small conductivity gradient in large Martian dust storms will smooth out sharp boundaries of positive and negative charge regions.

[26] Past in situ measurements of terrestrial dust devils indicate that the maximum electric field depends on various parameters such as dust devil size, atmospheric conductivity, time rate of tribocharging directly related to wind velocity, etc. [*Crozier*, 1964, 1970; *Farrell et al.*, 2004]. To study the evolution of field and charge in a dust devil and how the tribocharging process is saturated by atmospheric conductivity that controls the exponentially growth of the maximum in-devil electric field, we perform following simulations of quasi-static electrification with our finite element model for Martian and terrestrial dust devils of different size, conductivity, and time rate of charging. The reference input to the FE model for the QE simulations is the same constant rate of tribocharging used by *Melnik and Parrot* [1998] and *Farrell et al.* [2003]. The simulation domain is 50 m in radius and 150 m in height for the reference dust devil with a dimension of 1 m × 100 m. The reference time rate of charging is similar to that of *Melnik and Parrot* [1998], which is 3.14×10^{-9} C/m^3/s for wind speed of 40 m/s and particle density of 5×10^6/m^3. Figures 5–7 show the evolution of the maximum electric fields in the dust devil. As expected, the results indicate electric breakdown in Martian dust devils is mostly likely to occur in the largest events (a few tens of meters wide and a

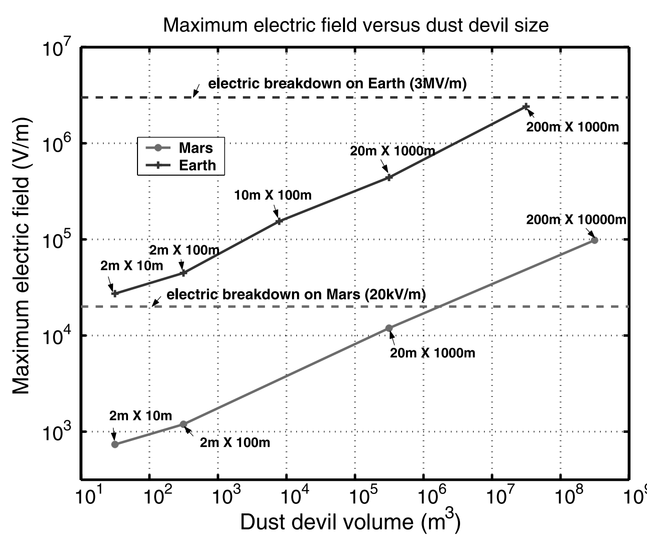

Figure 5. Comparison of maximum in-devil electric fields of Martian and terrestrial dust devils of different size in terms of cylindrical dust devil volume. The $\sigma_{Mars} = 2.8 \times 10^{-12}$ S m^{-1}, $\sigma_{Earth} = 7.4 \times 10^{-14}$ S m^{-1}, charging rate is 3.14×10^{-9} C/m^3/s.

kilometer high) if the atmospheric conductivity is 2.8 × 10^{-12} S m^{-1}. If the conductivity is lower, then breakdown can occur in smaller dust devils. These results also depend on the charging parameters assumed, which are not well constrained experimentally. On the basis of the FE simulations, if we known the dust devil volume *V*, Martian atmospheric conductivity σ and time rate of charging *D*, an empirical maximum electric field will be useful for estimating Martian dust devil electrification,

$$E_{\max} \propto V^{\frac{1}{3}}\left(\frac{D}{\sigma}\right). \qquad (12)$$

[27] These results are somewhat different from those reported by *Melnik and Parrot* [1998] from their numerical model of Martian dust storm electrification based on a particle-in-cell and QE-field integrated solver. *Melnik and Parrot* [1998] are the first to show that dust devil mass stratification and a mass-preferential charging process can generate large electric fields. Their 2-D solver in rectangular coordinates combined the dust particle motion, charge generation, and time evolution of the electric field. Their simulations of small-sized dust storms showed the exponentially growth of the electric field in a Martian atmosphere. The fields quickly reach Martian breakdown in less than 10 s. Extrapolating from their simulation, if we replace the Martian atmospheric conductivity with Earth's atmospheric conductivity, the maximum electric field will reach the terrestrial breakdown value (~3 MV/m) in less than a minute. However, electric discharging has not been observed in terrestrial dust devils. It is not clear whether their model accounts for the relaxation of charge on individual dust grains, but on the basis of this extrapolation it is possible that their model may overestimate the charging that occurs in Martian dust devils. By incorporating the relaxation of individual grains, we have connected microscopic "discharges" to the overall development of the macroscopic electric field.

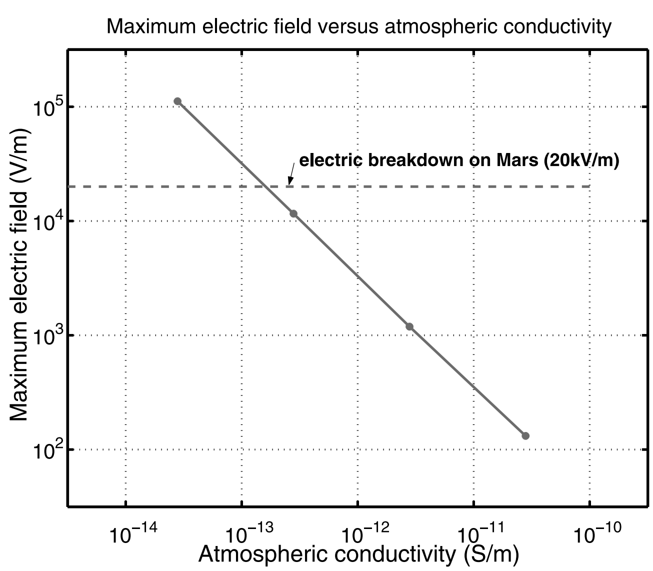

Figure 6. Comparison of maximum in-devil electric fields of Martian dust devils of different atmospheric conductivities. The dust devil size is 2 m × 100 m and charging rate is 3.14 × 10^{-9} C/m^3/s.

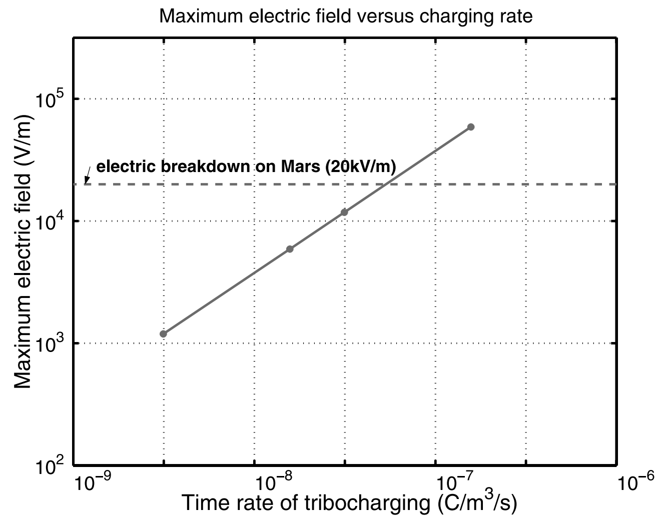

Figure 7. Comparison of maximum in-devil electric fields of Martian dust devils of different charging rate. Conductivity is σ = 2.8 × 10^{-12} S m^{-1}. The dust devil size is 2 m × 100 m.

5. Conclusions

[28] Contact electrification of a dust devil due to its particle movement, grain tribocharge transfer and mass separation can generate large electric field in and surrounding the dust devil. The exponentially growing electric field, however, is limited by a steady state value, called the saturation value. The saturation value depends on parameters like dust devil size, wind velocity and atmospheric conductivity. With a Martian conductivity of σ = 2.8 × 10^{-12} S m^{-1}, our model predicted saturation value exceeds Martian electric breakdown value for dust storms with a dimension larger than 10 m wide and 1 km high, and a time rate of charging greater than 31.4 × 10^{-9} C/m^3/s. We derive a maximum electric field $E = \frac{\epsilon_0}{\sigma^2}(n_L \Delta\nu\nu\Delta q)$ for a local, zero-dimensional electrodynamic model, which gives valuable insight into the basic physics of dust devil electrification. An empirical maximum electric field $E_{\max} \propto V^{\frac{1}{3}}(\frac{D}{\sigma})$ is also introduced on the basis of the more realistic numerical model simulation. We demonstrate in the numerical model and the modified analytical model that although large electric fields can be generated in a dust devil, the tribocharging process will reach a steady state. By adding grain charge relaxation, which is found to be a very important saturation process, our model connects the microscopic grain charge dissipation to its effect on the macroscopic field. Our model can easily take any particle-in-cell simulated charge density profile and incorporate the associated magnetic field generated in a dust devil.

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