A simple electrodynamic model of a dust devil

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[1] We present an electrodynamic model of a dust devil applying a similar methodology as performed previously for charging in terrestrial thunderstorms. While thunderstorm processes focus on inductive charging between large graupel and smaller ice and water droplets, we tailor the model to focus on the electric charge transfer between dust grains of different sizes and compositions. We specifically compare and contrast the triboelectric dust charging processes presented previously in *Melnik and Parrot* [1998] and *Desch and Cuzzi* [2000] in the development of macroscopic dust devil electric fields. We find that large vertical E-fields (~20 kV/m) can develop in the devil. *INDEX TERMS:* 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3346 Meteorology and Atmospheric Dynamics: Planetary meteorology (5445, 5739); 5409 Planetology: Solid Surface Planets: Atmospheres—structure and dynamics; 5445 Planetology: Solid Surface Planets: Meteorology (3346). **Citation:** Farrell, W. M., G. T. Delory, S. A. Cummer, and J. R. Marshall, A simple electrodynamic model of a dust devil, *Geophys. Res. Lett.*, *30*(20), 2050, doi:10.1029/2003GL017606, 2003.

1. Introduction

[2] Dust devils form via fluid micro-instability associated with the inversion of a surface-warmed air mass and cooler overlying layers [*Renno et al.*, 1998]. Pressure gradients develop in these systems, which force dust grains upward, and in the process act to form coherent convective miniature cyclones. Such dust formations are generated at the air-surface interfaces both on Earth and on Mars [*Thomas and Gierasch*, 1985; *Ryan and Lucich*, 1983].

[3] In dust devils, grains in contact with each other and the surface are known to generate and transfer electric charge via frictional or triboelectric processes [*Ette*, 1971; *Eden and Vonnegut*, 1973; *Mills*, 1977; *Jayaratne*, 1991; *Marshall*, 1994]. There is a tendency to charge-polarize grains based on mass and compositional differences [*Ette*, 1971; *Melnik and Parrot*, 1998; *Desch and Cuzzi*, 2000]. This mass-based charging preference combined with the mass stratification within the convective devil leads to a macroscopic, vertically-stratified charge distribution in the devil and consequently the development of a large inter-devil electrostatic potential. Large devil electric fields have been measured at kilovolt per meter strengths in the vicinity and within terrestrial dust devils [*Freier*, 1960; *Crozier*, 1964; *Delory et al.*, 2002] and the charge separation and potential development process has been simulated in *Melnik and Parrot* [1998]. Figure 1 shows DC E-field measurements from a field mill in the Arizona desert during a dust devil interception. Note that field strengths are in excess of 20 kV/m within the dust devil. The devil was ~30 m wide and passed directly over the sensor.

[4] In this work, we develop an analytical electrodynamic model of the tribocharging dust devil to explain the field strengths like those in Figure 1. These models draw heavily on previous thunderstorm research, but are customized to consider triboelectric charge transfer.

2. Electrostatic System

[5] Our approach is to solve the electrostatic field development of the dust devil based on vertical charge transport (i.e., currents) only. The methodology parallels the electrostatic models for the development of induction-produced electric fields in terrestrial thunderstorms [*Mathpal et al.*, 1980; *Kuettner et al.*, 1981; *Volland*, 1984]. Much like the terrestrial case, we assume two species of particles: large dust grains primarily influenced by gravity that are in saltation and small grains driven by wind flow that are entrained in the fluid. While particle distributions really are Gaussian type functions with large spreads, this division based on particle trajectory represents a clear delineation of particle type.

[6] A general description of the electric field, E, developing in a dust devil is derivable from the continuity equation:

$$dE/dt = -J/\varepsilon_o \tag{1}$$

with current density, J, as

$$J = n_L Q_L v_L + n_S Q_S v_S + \sigma E \tag{2}$$

where $n_{L,S}$ are the density of the large and small particles, respectively, $Q_{L,S}$ are the charge on the large and small

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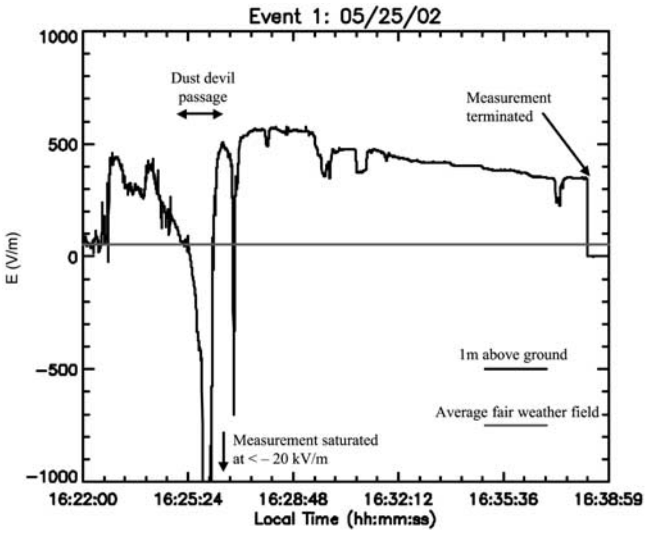

Figure 1. The electric field variation associated with a dust devil passage. Note that the average fair weather field is about 50 V/m, there is a positive field in the near-vicinity, but the interior dust devil gives rise to a large negative field excursion that saturated the instrument at −20 kV/m.

particles, $v_{L,S}$ are the vertical velocities of the particles, σ is the local atmospheric conductivity and ε_o is the free space permittivity. The σE term represents the current dissipation into the atmosphere. While we anticipate the development of charge centers within the devil, we also expect that the overall charge in the devil to have a net value of zero, making $n_L Q_L = -n_S Q_S$ and

$$J = n_L Q_L \Delta v + \sigma E \tag{3}$$

where $\Delta v = v_L - v_S < 0$. Placing Equation (3) into Equation (1) and time-differentiating yields

$$E'' + \sigma E'/\varepsilon_o = -n_L \Delta v Q_L'/\varepsilon_o \tag{4}$$

where the prime indicates the time-differentiation operation, d/dt. At this point, the expression is similar to Equation (A10) of *Mathpal et al.* [1980] that describes the induction electrification process between graupel and water/ice in terrestrial thunderstorms. We now deviate from that work in two key ways: First, a different driving function Q_L' will be implemented based on triboelectric processes [*Melnik and Parrot*, 1998; *Desch and Cuzzi*, 2000] instead of induction process, and the atmospheric conductivity, σ, will be considered for both Earth and Mars.

[7] In considering tribocharging, there have been two approaches modeled. Laboratory studies reveal the tendency for smaller grains to become preferentially-charged negative upon collision with larger grains [*Ette*, 1971]. To simulate this effect, *Melnik and Parrot* [1998] assumed that, upon collision of two grains, the lighter grain obtained a fC of negative charge for each micrometer of its radius, and the heavier grain carried away an equal but opposite charge. Since the charge capacity of a spherical grain varies directly with r, this relationship makes intuitive sense. Consequently, the time-rate of charging on the larger grains is approximately

$$Q_L' = \nu \Delta q \tag{5}$$

with ν equal to the large/small grain collision frequency and the charge exchange per collision is defined by

$$\Delta q = (1\mathrm{fC/um}) r_S, \tag{6}$$

with r_S as the radius of the small grain.

[8] While the *Melnik and Parrot* [1998] approach focuses on grain size (and charge capacity), *Desch and Cuzzi* [2000] indicate that both size and grain composition controls the charging process. Specifically, their Equation (11) indicates that the charge transfer to the large grain goes as

$$\Delta q = f_1 \Delta\Phi - (1 - f_2) q_{tot}, \tag{7}$$

where $\Delta\Phi$ is the difference between surface triboelectric potentials of the grains (Φ defined in Table II of *Desch and Cuzzi* [2000]), q_{tot} is the sum of charge on both grains, $f_1 = (c_{12}c_{21} - c_{11}c_{12})/(c_{11} + c_{12} + c_{21} + c_{22})$, $f_2 = (c_{11} + c_{12})/(c_{11} + c_{12} + c_{21} + c_{22})$, and c_{11}, c_{12}, c_{21}, and c_{22} the mutual capacitance of the two particles, defined by Equation (7–10) in *Desch and Cuzzi* [2000]. The triboelectric potential is related to the surface work function and the ability of a material to give up electrons. Insulators like quartz tend to have small potentials while metals tend to have large potentials. For particles of identical composition, $\Delta\Phi = 0$, charge is still exchange based on the particle's mutual capacitance (i.e., their geometry). In the case of $\Delta\Phi \neq 0$ and $r_L \gg r_S$, f_2 approaches very close to unity thereby making the second term small in comparison to the first term, particularly when insulators and metals are mixed [*Desch and Cuzzi*, 2000]. Consequently, Equation (7) can be rewritten as [*Desch and Cuzzi*, 2000]

$$\Delta q \sim 2668(\Delta\Phi/2V)(r_f/0.5\mathrm{um})e \tag{8}$$

where r_f is the reduced radius, $r_f = (r_L^{-1} + r_S^{-1})^{-1} \sim r_S$ and e is elementary charge.

[9] In Equation (2) we emphasize the vertical velocities, $v_{L,S}$, since the force of gravity determines which particles become suspended and which return to the ground in saltation. The velocity of the small grains may also develop horizontal (vortex-like) trajectories but these are ignored in this model. The simulation of *Melnik and Parrot* [1998] considered 3-D motion and found that the vertical E-fields develop in association with gravity-filter mass separation.

3. Solutions

[10] We will now solve

$$E'' + \sigma E'/\varepsilon_o = -n_L \Delta v \nu \Delta q/\varepsilon_o \tag{9}$$

for Δq defined by *Melnik and Parrot* [1998] (i.e., Equation (6)) and by *Desch and Cuzzi* (i.e., Equation (8)), for E = 0 and dE/dt = 0 at t = 0.

3.1. Case 1: $\Delta q = (1\mathrm{fC/um})\, r_S$

[11] Figure 2 shows a terrestrial and Martian case for constant collision frequency and charge transfer as defined

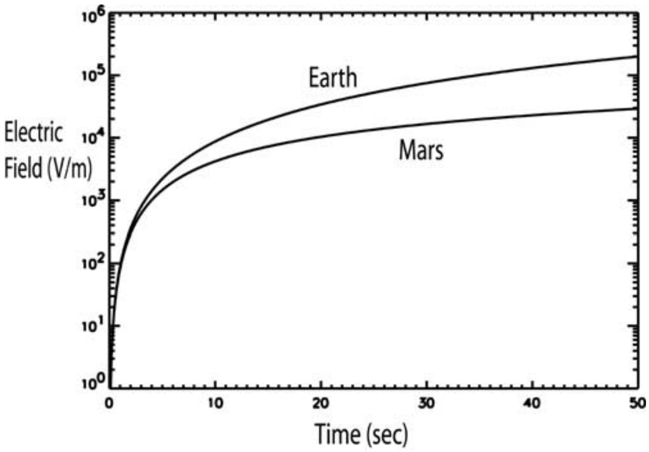

Figure 2. The dust devils electric field using the *Melnik and Parrot* [1998] charging scenario. Equation (9) is solved with n_L = 1/cc, n_s = 50/cc r_L = 100 um, r_S = 1 um, and $\Delta v = -1$ m/s. The collision frequency [*Volland*, 1984] is defined as $\nu = \pi\, r_L^2\, \Delta v\, n_S$.

by *Melnik and Parrot* [1998]. All variables are identical in the two cases, except for the ambient atmospheric ground-level conductivity (terrestrial conductivity $\sim 6.6 \times 10^{-14}$ S/m and Martian conductivity $\sim 2.5 \times 10^{-12}$ S/m [*Farrell and Desch*, 2001]). Note that the electric fields in the devils build up very quickly, reaching 20kV/m in $\sim$10–20 seconds. An exponential growth in field strength over the first 10 seconds is common to both the analytical model (presented here) and simulated [*Melnik and Parrot*, 1998] result (see their Figure 3). As describe in their work, the particle-in-cell simulation started with a random spatial distribution of tribocharged particles but allowed the heavier particles to filter out via gravitational forces. The E-fields were monitored as these charged particles separated. As described, PIC codes are inherently noisy and do not give quite starts, limiting their sensitivity particularly for field build-up at early times below 1 kV/m. Our analytical approach obtains a truly "quiet start," allowing a model of the low-level fields.

[12] Figure 2 is a juxtaposition of the same dust devil in a terrestrial and Martian atmosphere. As evident, the Martian devil does not obtain the same E-field values as the terrestrial case, primary because the conductivity relaxation current back into the atmosphere is greater in the Martian case (σE term larger). This dissipation current essentially increases the charge carriers in the ambient atmosphere and effectively removes charge from the mass stratification grain-related current flow that is responsible for the macroscopic E-field.

[13] Martian atmospheric breakdown occurs near 20 kV/m [*Melnik and Parrot*, 1998] and we note that the fields in the Martian devil very quickly rise to this breakdown point. Our analysis is no longer valid above 20 kV/m, since another current is required in Equation (2) that appropriately represents this breakdown process. In contrast, the breakdown of the terrestrial atmosphere is near 3 MV/m, and while the terrestrial devil fields are significant, they still do not approach breakdown in the time span shown in Figure 2.

3.2. Case 2: $\Delta q = 2668(\Delta\Phi/2V)(r_f/0.5um)e$

[14] Figure 3 again shows the solution to Equation (9), now run with the *Desch and Cuzzi* [2000] charge exchange process described by Equation (8). The calculations are made for three different situations, the first with $\Delta\Phi$ = 2V consistent with a metal/insulator (iron/silica) mix, the second with $\Delta\Phi$ = 0.02V consistent with material of slightly differing triboelectric potentials, and the third with $\Delta\Phi$ = 0.0002V consistent with nearly identical material in the mixture.

[15] Note that vastly different charging occurs in the three cases, with the tribocharging of a devil being strongly dependent on grain composition. We note that the *Desch and Cuzzi* [2000] case with $\Delta\Phi$ = 2V produces fields at Earth and Mars comparable to the *Melnik and Parrot* [1998] case (see Figure 2). In both cases, Equation (6) and Equation (8) for the modeled particle size and composition gives charge exchange at similar values of nearly a fC. However, unlike the Melnik and Parrot process that is independent of composition, as $\Delta\Phi$ decreases there is substantially less charge exchange at each collision. For example, the $\Delta\Phi$ = 0.2mV case involves charge transfer of about a single elementary particle per collision in contrast to $\sim$50e per collision at $\Delta\Phi$ = 0.02V and $\sim$5300e per collision at $\Delta\Phi$ = 2V. The charge exchange situation for $\Delta\Phi$ = 0.2mV is so weak that we suspect other processes would give rise to grain charging, including photoelectron currents (on Mars, UV sources may lead to significant charging [*Grard*, 1995]), thermal conductivity, etc. Also, in the weakest field case, devil vertical fields are below 20 V/m, and even less than the fair weather electric field at Earth.

[16] We conclude that the *Melnik and Parrot* [1998] assumption for grain charging applies best when there is a distinct compositional mix in the grains, in which case both Equation (6) and Equation (8) yield comparable results. For like-grain interactions, the assumptions no longer yield similar results, with the more sophisticated treatment by *Desch and Cuzzi* [2000] predicting little charge exchange.

4. Conclusions

[17] This analytical work is simple, but complements and expands the previous simulation of *Melnik and Parrot* [1998]. The model here yields the following new results:

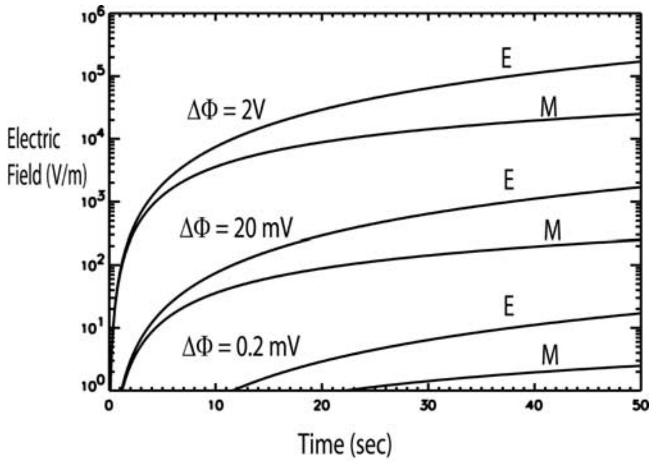

Figure 3. The dust devils electric field using the *Desch and Cuzzi* [2000] charging scenario. Again, Equation (9) is solved with n_L = 1/cc, n_s = 50/cc r_L = 100 um, r_S = 1 um, and $\Delta v = -1$ m/s. The collision frequency [*Volland*, 1984] is defined as $\nu = \pi r_L^2\, \Delta v\, n_S$.

[18] (1) Exponentially-growing electric fields develop in dust devils due to the tribocharging and subsequent mass (and thus charge) separation in the convective cloud. Electric fields in excess of 20 kV/m are obtainable consistent with observations. (2) When comparing the same dust devil on Earth and Mars, the electrostatic field levels are consistently lower in the Martian case due to the greater dissipation leakage current that removes charge from the stratified grains. (3) A comparison of the *Melnik and Parrot* [1998] and *Desch and Cuzzi* [2000] tribocharging microphysical models indicates similarities in cases where there is a substantial compositional difference. The models yield differing results in cases where compositions are nearly identical.

[19] Like the thunderstorm applications [*Mathpal et al.*, 1980], we have assumed a substantial size differential between large and small grains. The reality is that the grain sizes form an extended distribution. However, in mild winds, there should be a separation between those grains that are suspended and those that remain in saltation. For example, in a 1 m/s wind, the force of gravity on a 100 um particle exceeds the fluid wind force by a factor of 100, but the wind force dominates over gravity for the 1 um grain by a factor of 2. Thus, we use the 100 um grain as representative of those grains that congregate at the devil bottom, and 1 um as those that get lofted.

[20] Recently, an NRC committee indicated that triboelectric hazards needs to be considered in any design of a human system (''Safe on Mars: Precursor measurements necessary to support human operations on the Martian surface,'' National Academy Press, 2002). They surmised that tribocharging occurs but that the negative and positive grains remain in proximity rendering the dust devil quasi-neutral. We agree with the committee that electrical effects are a concern, and expand upon their results demonstrating here that lofting of the lighter preferentially-charged grains leads to the development of separated inter-devil charge centers, a large vertical cross-devil potential difference, and substantial E-fields.

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