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Electric field generation in martian dust devils

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ABSTRACT

Terrestrial dust devils are known to generate electric fields from the vertical separation of charged dust particles. The particles present within the dust devils on Mars may also be subject to similar charging processes and so likely contribute to electric field generation there as well. However, to date, no Mars in situ instrumentation has been deployed to measure electric field strength. In order to explore the electric environment of dust devils on Mars, the triboelectric dust charging physics from the Macroscopic Triboelectric Simulation (MTS) code has been coupled to the Mars Regional Atmospheric Modeling System (MRAMS). Using this model, we examine how macroscopic electric fields are generated within martian dust disturbances and attempt to quantify the time evolution of the electrodynamical system. Electric fields peak for several minutes within the dust devil simulations. The magnitude of the electric field is a strong function of the size of the particles present, the average charge on the particles and the number of particles lifted. Varying these parameters results in peak electric fields between tens of millivolts per meter and tens of kilovolts per meter.

1. Introduction

While martian dust devils have been monitored through decades of observations, no instrument package has been capable of studying their possible electrical effects. However, evidence for the existence of active electrodynamic processes on Mars is provided by laboratory studies of analog material and field campaigns of dust devils on Earth. Dust charging studies using Mars soil simulant (Krauss et al., 2003; Sternovsky et al., 2002) suggest that the charged dust observed within terrestrial dust disturbances (e.g., Farrell et al., 2004; Renno et al., 2004) is very possible on Mars.

Initial terrestrial field observations noted the electrical activity of dust devils seen off in the distance, e.g., Crozier (1964) measured a field of −60 V/m at a distance of about 450 m. Frier (1960) noted that two negative troughs with a positive peak between (−100 V/m, +200 V/m, −400 V/m; closest approach of 30 m) was indicative of a dipole structure to the dust devil and calculated a dipole moment of 1.7×10^9 esu cm. Internal electric field measurements in terrestrial dust devils registered up to instrument (field mill) saturation levels at −4.35 kV/m (Farrell et al., 2004) for a 7 m diameter dust devil and −20 kV/m (Farrell et al., 2003; Delory et al., 2006) for a 30 m diameter dust devil. Jackson and Farrell (2006) used an electrometer designed to measure larger electric fields and found the horizontal component to range 50–100 kV/m during passes through the dust devil. As the dipole field varies as $1/r^3$, at 10s of meters distance from the dust devil seen by Crozier (1964), one would expect to measure an electric field around −50 kV/m, consistent with the larger values measured by Jackson and Farrell.

These strong electric fields are the result of charged dust grains. The exact mechanism of charging is still highly debated, but it is likely a form of contact electrification where two grains exchange charge after coming into contact with one another. There can be different degrees of contact – simple touching, low-impact sliding, or high-impact rubbing – and relating these to a specific method of charge exchange (e.g., through electron, ion, chemical, or particulate exchange) is also not fully understood (e.g., see Harper, 1967, which still remains the most comprehensive treatment of the subject). Tribocharging, triboelectric charging, or triboelectrification (tribo from the Greek word for rubbing) is generally used when the interaction involves multiple, frictional contacts as the two surfaces slide, roll, or rub against one another – though often the terms contact charging and tribocharging are used interchangeably in the literature (e.g., see James et al., 2008). Triboelectric charging applies to charge exchange between both objects of identical composition and objects of differing composition. When triboelectrification occurs between colliding particles of like composition, it has been observed that the smaller particle tends to charge negatively; Melnik and Parrot (1998) model this as

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proportional to the particle radius at a rate of 1 fC/μm. When the colliding particles are of different composition, their placement on the triboelectric series is used to determine the degree (and sign) of charging – though particle size effects are still apparent as well.

Once charged, some of these grains are further entrained into the air where they are transported upward by atmospheric currents. Differential transport and gravitational sedimentation sorts the dust devil aerosols by size so that the smaller and predominantly negatively charged particles populate the higher portion of the disturbance while the larger, positively charged particles fall to the ground or remain in the lower portion of the vortex. This gravitationally induced charge separation in dust devils is analogous to that which occurs in terrestrial thunderstorms (e.g., Rafkin et al., 1994; Paluch and Sartor, 1973). In addition to the DC electric field associated with the macroscopic dipole, the organized swirling of the charged aerosols results in a current and concomitant magnetic field (Houser et al., 2003; Farrell et al., 2004).

While a landed electrostatic package has yet to fly to the surface of Mars, there exists ample laboratory evidence for electrical discharge in dust agitation experiments in low pressure CO_2 gas. This is likely some of the strongest evidence for dust devil electrification; Eden and Vonnegut (1973), Mills (1977), and Krauss et al. (2003, 2006) all reported glows and spark-like discharges for dust mixing at martian-like pressure and composition. The 'spark' discharges are not lightning-like but are a mildly ionized discharge that reaches the spark condition (see discussion in Delory et al. (2006) and references therein). We do not model the discharge effect here, but examine the *E*-field environment that might lead to such glows and sparks.

Triboelectric charging has also been studied in interstellar dust clouds (e.g., Desch and Cuzzi, 2000) and in other natural phenomena on Earth (e.g., volcanic plumes, Aplin et al., 2014; sand storms, Schmidt et al., 1998). However, because the surface atmospheric pressure on Mars is low, the environment is somewhere between that of the near vacuum of the space environment and the dense terrestrial atmosphere. Ironically, gases maintained at a few torr (like the martian CO_2 atmosphere, ~700 Pa) can easily breakdown in relatively low *E*-fields, and the understanding and manipulation of this plasma physics was pursued in the early 1900s in the development of vacuum tube technology that predates solid state technology. Both the lower atmosphere of Earth and interstellar dust clouds are highly insulating compared to the near-surface environment of Mars (for the former because of the dense air and high ionization potential, and for the latter due to the existence of a collisional plasma). On Mars, electric fields are limited by large increases in atmospheric conductivity when they reach sufficient magnitude to ionize CO_2 (Delory et al., 2006) and by electric discharges thought to occur at ~20–25 kV/m (Melnik and Parrot, 1998). The Paschen law relates the breakdown voltage to the atmospheric pressure (e.g., see Manning et al., 2010 for experimentally measured Paschen curves representative of the martian atmosphere). Kok and Renno (2009) modeled dust charging within the saltation layer. Given a characteristic distance ~30 cm, the breakdown field is ~43 kV/m, so they concluded that discharges are unlikely to occur in this region. However, the vertical velocities within martian dust devils can lift the charged dust particles, the smallest particles, hundreds of meters or more above the surface in a coherent column creating a charge separation that may be large enough to produce significant electric fields. Also, large-scale discharges in these dust disturbances could occur at a lower electric field threshold than predicted by the Paschen law through electron runaway breakdown (Gurevich et al., 1992).

While the majority of terrestrial dust devils observed are found to be less than 1 km in height and 100 m in width, their martian counterparts are often seen to be a few kilometers high and 100s of meters in diameter (e.g., Balme and Greeley, 2006). Dust devil activity on Mars has been imaged from orbit; Viking orbiter (Thomas and Gierasch, 1985), Mars Global Surveyor (Edgett and Malin, 2000), Mars Express (Stanzel et al., 2006), and the Mars Reconnaissance Orbiter (McEwen et al., 2010); and observed directly from landed instruments on Mars Pathfinder (Smith and Lemmon, 1999), Mars Exploration Rover (MER) Spirit (Greeley et al., 2006), and Phoenix (Ellehoj et al., 2010). Dust devils are small-scale low pressure vortices formed through the heating of near-surface air in unstable atmospheric conditions. In contrast to boundary layer winds, dust devils are efficient in lifting small particles (Greeley et al., 2006). They have been suggested to play an important role in replenishing the background dust opacity on Mars (Ferri et al., 2003; Fisher et al., 2005), providing estimates of up to half the global dust suspension.

Toigo et al. (2003) and Michaels and Rafkin (2004) investigated the dynamics of dust devils on Mars. In a follow-up study, Michaels (2006) explored the production of dust devil tracks. However, none of these studies explored the electrical environment of the dust disturbance. Dust charging simulations generally assume that an atmospheric dust disturbance is present with some specified dust distribution, but the dynamical processes producing those disturbances are mostly ignored or parameterized (Farrell et al., 2003), and it is not clear that the assumed dust distributions are consistent with the dynamics. Electrochemical studies assume that dust charging is sufficient to produce an electric field, but the chemistry is conducted using one-dimensional models (e.g., Atreya et al., 2006; Delory et al., 2006) with a specified or simply parameterized electric field.

The study of Farrell et al. (2006) takes a first-order look at coupling triboelectric charging with an approximate analytic representation of a dust devil. Dust devil winds were prescribed assuming cyclostrophic balance with a central pressure well following Greeley et al. (2003). Vertical winds were prescribed following Renno and Ingersoll (1996) and Renno et al. (1998). Trajectories of individual grains within the prescribed vortex were calculated by integrating a force balance equation. Collisions between grains resulted in charge separation following Desch and Cuzzi (2000). The model was run for 0.5 s over a domain of 2 m × 2 m × 1 m. Thus, the simulation only covers the incipient formation of a small (terrestrial) dust devil. Halting the simulation at 0.5 s avoided boundary effects as the larger grains began to approach the walls of the box; nonetheless, results showed that electric fields, currents, and therefore magnetic fields, did develop and evolve within this time. However, it is difficult to extend these results to a fully mature terrestrial dust devil, and even more difficult to extend the results to martian dust devils that can be an order of magnitude or larger in size. In addition, the flow and particle transport within a dust devil is complex. For example, simulated dust devils are known to have relatively weakly descending or ascending central cores (Rafkin et al., 2001; Toigo et al., 2003; Michaels and Rafkin, 2004), and mass continuity requires that horizontal winds be at least slightly out of cyclostrophic balance to support vertical motion. Notwithstanding the domain size, short integration times and simplified dust devil dynamics, the work of Farrell et al. (2006) is significant as it represents the most advanced electrodynamic modeling to date.

We have integrated the dust devil dynamics studies of Michaels and Rafkin (2004) with the particle charging of Farrell et al. (2006) to create a model which can explore the charge environment throughout the lifecycle of a dust devil. Specifically, we have modified the Mars Regional Atmospheric Modeling System (MRAMS) to include charge distribution as a function of dust particle size and composition. An analytic representation of the charge distribution is derived based on the individual particle charge values provided by the Macroscopic Triboelectric Simulation (MTS) code. In this