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Electrical discharges and broadband radio emission by Martian dust devils and dust storms

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[1] Triboelectric charging of saltating and colliding sand and dust particles produces strong electric fields in terrestrial dust devils and dust storms. Acceleration of the charged particles, as well as microdischarges between them, generates wideband electromagnetic radiation. Similar phenomena are expected to be ubiquitous on Mars, because Martian dust devils and dust storms are larger, stronger and more frequent than their terrestrial analogues, and electrical discharges occur at a much lower potential gradient in the thin Martian atmosphere. We present theoretical arguments and observational evidence that Martian dust events produce nonthermal wideband electromagnetic radiation detectable from Earth. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0654 Electromagnetics: Plasmas; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3314 Meteorology and Atmospheric Dynamics: Convective processes; 5445 Planetology: Solid Surface Planets: Meteorology (3346). **Citation:** Renno, N. O., A.-S. Wong, S. K. Atreya, I. de Pater, and M. Roos-Serote, Electrical discharges and broadband radio emission by Martian dust devils and dust storms, *Geophys. Res. Lett.*, *30*(22), 2140, doi:10.1029/2003GL017879, 2003.

1. Introduction

[2] Aeolian processes have been actively modifying the surface of Mars. The evidence for these processes in the form of wind erosion features, dust devils, and dust storms [*Leovy et al.*, 1972; *Thomas and Gierasch*, 1985; *Schofield et al.*, 1997; *Malin et al.*, 1998; *Metzger et al.*, 1999; *Renno et al.*, 2000; *Cantor et al.*, 2001; *Cantor et al.*, 2002] is abundant. On Mars, dust devils are much bigger and stronger than on Earth. Terrestrial dust devils have typical diameters of less than 10 m and are seldom higher than a few 100 m [*Sinclair*, 1973]. In contrast, dust devils with diameters between 100 m and 1 km, and heights of up to 7 km are frequently observed on Mars [*Thomas and Gierasch*, 1985; *Malin et al.*, 1998]. Martian dust devils have ~700 times the dust particle concentration of the local background atmosphere [*Metzger et al.*, 1999].

[3] Regional dust storms occur frequently on Mars [*Cantor et al.*, 2001]. Sometimes they grow and become global in extent. Observations indicate that dust devils and dust storms have a higher probability of occurrence and are potentially more intense in regions of sloping terrain and large horizontal temperature gradients [*Cantor et al.*, 2001, 2002]. Dust storms frequently form near the edge of the south Martian polar cap during the warm season [*Kieffer et al.*, 1992; *James et al.*, 1999; *Cantor et al.*, 2001, 2002]. These polar storms are convective heat engines driven by the rising (expansion) of the warmer air and the sinking (compression) of the colder air, similar to convective vortices such as dust devils, waterspouts, and hurricanes [*Renno et al.*, 2000].

[4] Triboelectric charging of saltating and colliding sand and dust particles produces strong electric fields in terrestrial dust events, sometimes in excess of 100 kV/m [see *Schmidt et al.*, 1998; *Farrell et al.*, 2002; *Krauss et al.*, 2002; *Towner et al.*, 2002]. Acceleration of charged particles and microdischarges between colliding sand and dust grains generate electromagnetic radiation. *Farrell et al.* [2002] measured radio emission by terrestrial dust devils in the ULF/ELF range, *Farrell et al.* [1999] predicted higher frequency radio emission by glow discharges from single dust grains, and our calculations indicate microwave emissions. This phenomenon can be compared with well-established theory, laboratory experiments, and observations of microdischarges between hydrometeors, and aerosol particles [*Atkinson and Paluch*, 1966; *Barreto*, 1969; *Keeney*, 1970; *Keith and Saunders*, 1988; *Chauzy and Kably*, 1989; *Coquillat et al.*, 1995], which show that microdischarges between colliding particles produce microwave emission.

[5] Triboelectric charging of dust is expected to be important also on Mars. Evidence for this is the charging of the MPF Sojourner Rover wheel while it operated in a Martian environmental chamber [*Ferguson et al.*, 1999]. Because of the low atmospheric density, electrical discharge occur at electric field gradient between ~5 and 20 kV/m on Mars, much lower than the ~3,000kV/m on Earth. Thus, microdischarges and storm-scale electrical discharges might occur in Martian dust devils and dust storms, and generate wideband electromagnetic emission.

2. Electrical Discharges in Martian Dust Events

2.1. Microdischarge Theory

[6] Laboratory experiments show that colliding grains generate charges in excess of 10^{-10} C per grain [*Bernhard et*

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al., 1992], become highly electrified, and produce electrical discharges visible to the naked eye in a Mars environmental chamber [*Eden and Vonnegut*, 1973]. We propose a mechanism for the emission of electromagnetic radiation by colliding sand and dust particles. Frequently, during particle collisions, enough charge is transferred to create electric fields sufficient not only to produce electrical discharges [*Harper*, 1967], but also field emission [*Bernhard et al.*, 1992]. We surmise that the discharges are electric arcs that occur when the charged particles are breaking away from their last point of contact. The initial charge transfer and amount of energy emitted by discharges depends on many variables such as the energy of the collision, the contact area, and particles size, composition, and surface conductivity. However, in spite of the uncertainties, a simple calculation can be performed to estimate the energy and spectral distribution of the discharges.

[7] First we estimate the minimum charge that a particle must carry in order for bulk electrical breakdown to occur on Mars. We assume that a pair of colliding particles is locally a flat plate capacitor in the region where discharge occurs. It follows from Gauss law that $q = AE\epsilon$, where q is the charge in the contact region, A is the contact area, $E \sim 10$ kV m^{-1} is the breakdown electric field near Mars surface, and $\epsilon = 8.85 \times 10^{-12}$ C^2 N^{-1} m^{-2} is the permittivity of Martian air. Assuming that the contact area is 10% of the surface area of the smaller particle, for a typical particle of radius r ranging from 10^{-5} to 10^{-4} m (10–100 μm), we find that the minimum charge necessary to produce electrical breakdown is $q_{\min} \sim 10^{-18}$–10^{-16} C. To the first approximation, $q_{\min}$ is the residual charge left on the particles after arc discharges, and is the charge that produces the bulk electric field observed in the dust events. Using the bulk electric fields produced by terrestrial dust devils, we estimate that ~10% (factor α) of the dust particles are charged to this limit. On the other hand, the electric field necessary to produce field emission is $\sim 10^6$ kV m^{-1} [*Harper*, 1967]. Therefore, the maximum charge a typical dust particle can hold is $q_{\max} \sim 10^{-13}$–10^{-11} C before field emission occurs. Indeed, dust grains with charges of up to 10^{-12} C have been observed in terrestrial dust devils [*Farrell et al.*, 2003].

[8] The number of discharges in a single Martian dust devil can be estimated as follows. Martian dust devils have dust concentrations of $>10^{10}$ particles m^{-3} [*Metzger*, 1999]. Most of the energetic collisions between sand and dust particles occur in the saltation layer [*Bagnold*, 1941], and measurements in terrestrial dust events suggest that most of the charge transfer occur near the ground [*Schmidt et al.*, 1998; *Towner et al.*, 2002]. It follows from dimensional analysis that the number of particle-to-particle collisions in the saltation layer of a dust event is approximately $N_{pp} \sim n_1 n_2 v_1 \pi r_1^2$, where n_1 is the number density of the larger (sand) particles, n_2 is the number density of the smaller (dust) particles, v_1 is the velocity of the larger particles with respect to the smaller ones, and r_1 is the radius of the larger particles. Taking $n_2 \sim 10^{10}$ particles m^{-3}, and assuming that the particle size distribution in the saltation layer of a Martian dust devil is similar to that over terrestrial deserts [*Bagnold*, 1941; *D'Almeida*, 1987], we have $n_1 \sim 0.01 n_2$, $r_1 \sim 1$ mm, and $N_{pp} \sim 10^{13}$ collisions m^{-3} s^{-1} with a typical value of $v_1 \sim 10$ m s^{-1}. Since the saltation layer is ~1 m deep [*Bagnold*, 1941], the rate of collisions in the saltation layer of a Martian dust devil is $N_c \sim 10^{13}$ collisions m^{-2} s^{-1}.

[9] Next we estimate the total energy flux due to microdischarges from dust events over the Martian disk. The electrostatic energy dissipated in a single discharge is $W = \frac{1}{2}CV^2 = \frac{1}{2}qEd \sim 10^{-10}$–$10^{-8}$ J, where $d \sim 15$ μm is the distance between the "capacitor plates" when discharges occur [*Bernhard et al.*, 1992] under Martian conditions. The dust-settling rate observed at the MPF landing site is of the order of 10^8 particles m^{-2} sol^{-1} (a sol is a Martian day, ~24 hours) during a period in which no major dust storms were present on the planet [*Landis*, 1996; *Smith and Lemmon*, 1999]. Assuming that the observed dust particles are pumped into the atmosphere by dust devils forming during the afternoon (6 hours), the total afternoon flux of dust particles into the atmosphere is $\phi_d \sim 10^4$ particles m^{-2} s^{-1}. Martian dust events have fluxes of $>10^{11}$ particles m^{-2} s^{-1} [*Metzger et al.*, 1999], and therefore the fraction of the planet surface covered by dust devils is $\beta \sim 10^{-7}$. For the entire planet, the maximum broadband emission due to particle-to-particle collisions within the saltation layer of dust devils is $\delta F \sim \beta N_c (\alpha\gamma W) \sim 10^{-5}$ W m^{-2}, where $\alpha \sim 0.1$ is the fraction of dust particles charged to breakdown potential (see above), and γ is the fraction of the total energy that goes into nonthermal emission, which is at least 1% [*Uman*, 1987]. Assuming that each dust particle also become charged when propelled into the atmosphere by a saltating sand grain, a broadband emission of $\delta F \sim \phi_d (\alpha\gamma W) \sim 10^{-6}$ W m^{-2} is produced, a much smaller contribution to the total emission. We conclude that, dust devils produce broadband emission over the Martian disk $\delta F \sim 10^{-5}$ W m^{-2}. The energy flux is greater by many orders of magnitude during dust storms, perhaps making their disk-averaged signature detectable (see below).

[10] In order to estimate the effect of microdischarges on the planet's brightness temperature, we consider a black body radiating at the disk temperature. It follows from the Stefan-Boltzmann law that perturbations in the energy flux produce changes in the planet's brightness temperature of $\delta T \sim \delta F/(4\sigma_R T^3)$, where $\sigma_R = 5.67 \times 10^{-8}$ W m^{-2} K^{-1} is the Stefan-Boltzmann constant, and $T \sim 200$ K is the average Martian disk temperature. Thus, microdischarges due to dust devils produce perturbations in the planet's brightness temperature of $\sim 10^{-5}$ K, a negligible effect. Dust storms can produce perturbations larger than ~10 K in disk-average brightness temperature if $\beta \sim 0.1$, a measurable effect, even if their dust concentration is not larger than that of dust devils.

[11] To estimate the spectral distribution of the emission from microdischarges, we consider the time constant for discharging the "capacitor" formed by two colliding particles. The time constant for electrical breakdown is $\tau \sim RC$, where $C = q/V$ is the capacitance, $V = Ed \sim (10^9$ V m$^{-1})$ $(15 \times 10^{-6}$ m) is the potential across the capacitor, and R is the capacitor's resistance across the electric arc, calculated using Ayrton's formula [*Ayrton*, 1902; *Loeb*, 1939] to be $\sim 10^7$ Ω. For dust particles of 10–100 μm size, $\tau \sim 10^{-12}$–10^{-10} s. Assuming that a microdischarge is a decaying exponential pulse, the amplitude of its Fourier transform is proportional to $1/(1/\tau^2 + \omega^2)^{1/2}$, where ω is the emission frequency. Thus most of the emission is at frequencies

$\omega < 10^{12}$ Hz, corresponding to microwaves. The spectral distribution distinguishes the microdischarge emission from the background thermal emission. Therefore, observations at various wavelengths can be used to "fingerprint" the nonthermal emissions by dust events.

2.2. Evidence of Microwave Emissions

[12] Ground-based radio observations of Mars show a strong correlation between Martian dust storm activity and anomalously high microwave radio emission. We suggest that the anomalous radio emissions are caused by electrical activity in dust events, rather than thermal emission by the dusty and warmer atmosphere. Suspended dust directly absorbs and scatters solar radiation, and therefore affects the atmospheric heating rate [*Gierasch and Goody*, 1972; *Zurek*, 1978] and modifies the surface radiative balance [*Davies*, 1979]. This causes increases in the atmospheric temperature near the top of the dust layer, and decreases in the temperature at low levels and the surface. Thus, the thermal emission by the planet decreases, as illustrated in Figure 1. Since a dusty atmosphere is optically thin at microwave wavelengths [*Paltridge and Platt*, 1976], nonthermal emissions from the lower atmosphere are more likely to be detected at these wavelengths.

[13] Observations of Mars at 2.8 cm were made in December 1975 [*Andrew et al.*, 1977, 1978] and January 1978 [*Doherty et al.*, 1979]. These observations show that the brightness temperature and its temporal variability are strongest in the regions of known enhanced dust activity as summarized in Figure 2. Indeed, during January–May 1978, regional dust storms were observed in the region of anomalously high radio emission [*Kieffer et al.*, 1992]. The brightness temperature observed in 1978 was so much higher than in 1975 (nine times the standard deviation of the measurements) that even after corrections for all possible calibration errors were done, the 1978 observations showed significantly larger values.

[14] Although *Andrew et al.* [1977, 1978] recognized that calibration of the Mars data using Jupiter is difficult, in hindsight they may have overcorrected their data. First, although they included beam broadening due to changes in the angular size of Jupiter's disk, they did not correct the data for beam broadening of the nonthermal radiation. The received emission needs a correction factor of ~1.5 [*de Pater et al.*, 2003], being 3–4% larger in January than February. Also, they adopted a thermal flux density of 20 Jy for Jupiter, leaving ~9 Jy for nonthermal radiation after correction for beam broadening, which is impossible. The thermal emission for a 190 K Jupiter at 10.5 GHz on ~20 January 1979 is 25.0 Jy, leaving 1.5 Jy for the nonthermal component after correction for beam broadening, consistent with previous measurements [e.g., *de Pater and Dunn*, 2003]. Since *Andrew et al.* [1977, 1978] used 6 Jy for Jupiter's nonthermal emission, and corrected the Mars data based upon Jupiter's beaming curve, which gives ~10% peak-to-peak fluctuations over 5 hours, the errors in their Mars data may be as large as ~5 K. It is difficult to correct the data with the information in their paper. If part of the variability is true, we note that it is in the CML range of 240°–360°, corresponding to regions of large dust activity such as the Hellas, Argyre, and Arcadia-Amazonis Plantia [see *Cantor et al.*, 2001, 2002].

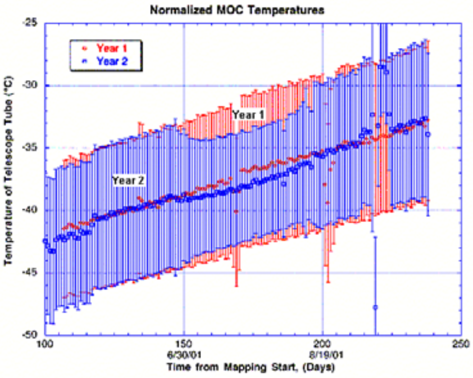

Figure 1. Temperature of the Mars Orbiter Camera telescope tube during a year of weak dust storm activity (Year 1, 2000) and during a year of intense dust storm activity (Year 2, 2001). Courtesy of NASA/JPL/Malin Space Science Systems.

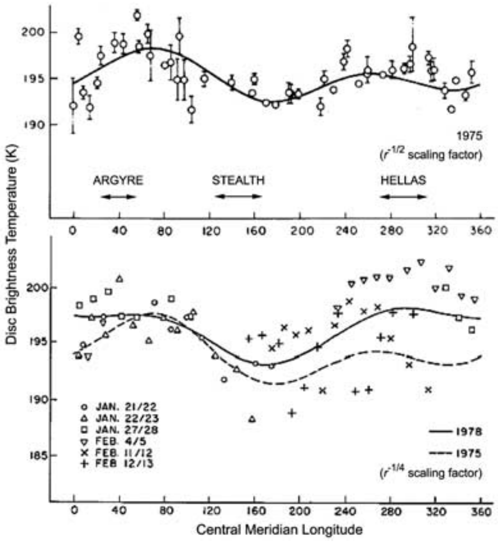

Figure 2. Measured Martian disk radio brightness temperatures as a function of the central meridian longitude for 1975 (top) and 1978 (bottom) campaigns. The re-normalized brightness temperature for 1975 is also shown in the bottom plot [after *Doherty et al.*, 1979]. Some of the most active dust devil/storm incubator regions are marked in plot at the top.

[15] In 1995 during the Martian northern spring ($L_s = 60$), the Tharsis and Amazonis regions (the Stealth region) were observed with the VLA at 1.35 cm (22 GHz) [*Ivanov et al.*, 1998]. The low radar signature of the Stealth region has been attributed to the existence of loose and unconsolidated sediments such as a thick mantle of fine sand or volcanic ash [*Muhleman et al.*, 1991]. The observations of variations in regional surface brightness temperature during a period of 12 hours were compared with predictions made with a Martian surface/atmosphere model. The discrepancy in microwave emission between model and observations was found to be highest between the local Noon and 4 PM, the

period in which dust devils are most frequent and strongest [*Renno et al.*, 2000].

3. Conclusions

[16] Radio observations of Mars show evidence of anomalous strong microwave emissions in regions of enhanced dust activity. The strongest emission anomalies, as well as their temporal variability, take place during times of intense dust activity. We show that the observed anomalies might be caused by microdischarges during dust events. Thus, observation of microwave radio emissions may be an important remote sensing probe for disturbed weather on Mars, in the same way that global lightning observations are a proven measure of disturbed weather conditions on Earth. An understanding of electrical activity associated with dust events has important implications for the safe operation of Mars landers and rovers (J. Kolecki, personal comm.), and possibly for local chemistry at the surface and the boundary layer.

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References

Andrew, B. H., G. A. Harvey, and F. H. Briggs, Rotational variations in the radio brightness of Mars, *Astrophys. J.*, *213*, L131–134, 1977. (Correction, *Astrophys. J., 220*, L61, 1978.)

Atkinson, W. R., and I. Paluch, Electromagnetic emission from pairs of water drops exchanging charge, *J. Geophys. Res.*, *71*(16), 3811–3816, 1966.

Ayrton, H., *The Electric Arc*, The Electrician Publishing and Printing Co., 1902.

Bagnold, R. A., *The physics of blown sand and desert dunes*, Methuen, New York, 1941.

Barreto, E., Electrical discharges from and between clouds of charged aerosols, *J. Geophys. Res.*, *74*(28), 6911–6925, 1969.

Bernhard, A. K., K. Sattler, and H. C. Siegmann, Gas breakdown in contact electrification, *J. Phys. D.*, *25*, 139–146, 1992.

Cantor, B. A., P. B. James, M. Caplinger, and M. J. Wolff, Martian Dust storms: 1999 Mars Orbiter Camera Observations, *J. Geophys. Res.*, *106*(E10), 23,653–23,687, 2001.

Cantor, B., M. Malin, and K. S. Edgett, Multiyear Mars Orbiter Camera (MOC) observation of repeated Martian weather phenomena during the northern summer season, *J. Geophys. Res.*, *107*(E3), 5014, doi:10.1029/2001JE001588, 2002.

Chauzy, S., and K. Kably, Electric discharges between hydrometeors, *J. Geophys. Res.*, *94*(D11), 13,107–13,114, 1989.

Coquillat, S., S. Chauzy, and J.-C. Medale, Microdischarges between ice particles, *J. Geophys. Res.*, *100*(D7), 14,327–14,334, 1995.

D'Almeida, G., On the variability of desert aerosol radiative characteristics, *J. Geophys. Res.*, *92*(D3), 3017–3026, 1987.

Davies, D. W., Effects of dust on the heating of Mars' surface and atmosphere, *J. Geophys. Res.*, *84*(B14), 8289–8293, 1979.

de Pater, I., et al., Jupiter's radio spectrum from 74 MHz up to 8 GHz, *Icarus*, *163*, 434–448, 2003.

de Pater, I., and D. E. Dunn, VLA observations of Jupiter's synchrotron radiation at 15 and 22 GHz, *Icarus*, *163*, 449–455, 2003.

Doherty, L. H., B. H. Andrew, and F. H. Briggs, Confirmation of the longitudinal dependence of the radio brightness of Mars, *Astrophys. J.*, *233*, L165–L168, 1979.

Eden, H. F., and B. Vonnegut, Electrical breakdown caused by dust motion in low pressure atmospheres: Considerations for Mars, *Nature*, *280*, 962–963, 1973.

Farrell, W. M., M. L. Kaiser, M. D. Desch, J. G. Houser, S. A. Cummer, D. M. Wilt, and G. A. Landis, Detecting electrical activity from Martian dust storms, *J. Geophys. Res.*, *104*(E2), 3795–3802, 1999.

Farrell, W., M. Desch, G. Delory, G. Hillard, and J. Marshall, Quantification of charge in a dust devil based on its ULF magnetic signature, *Eos Trans. AGU*, *83*(47), Fall Meet. Suppl., Abstract P51A-0036, 2002.

Farrell, W. M., et al., Electric and magnetic signatures of dust devils from the 2000–2001 MATADOR desert tests, submitted to *J. Geophys. Res.*, 2003.

Ferguson, D. C., J. C. Kolecki, M. W. Siebert, D. M. Kilt, and J. R. Matijevic, Evidence for Martian electrostatic charging and abrasive wheel wear from the Wheel Abrasion Experiment on the Pathfinder Sojourner rover, *J. Geophys. Res.*, *104*(E4), 8747–8760, 1999.

Gierasch, P. J., and R. M. Goody, The effect of dust on the temperature of the Martian atmosphere, *J. Atmos. Sci.*, *29*, 400–402, 1972.

Harper, W. R., *Contact and Frictional Electrification*, Laplacian Press, Morgan Hill, Calif., 1967.

Ivanov, A. B., D. O. Muhleman, and A. R. Vasavada, Microwave thermal mapping of the Stealth region on Mars, *Icarus*, *133*, 163–173, 1998.

James, P. B., J. L. Hollingsworth, M. J. Wolff, and S. W. Lee, North polar dust storms in early spring on Mars, *Icarus*, *138*, 64–73, 1999.

Keeney, J., Observations on the microwave emission from colliding charged water drops, *J. Geophys. Res.*, *75*(6), 1123–1126, 1970.

Keith, W. D., and C. P. R. Saunders, Light emission from colliding ice particles, *Nature*, *336*, 362–364, 1988.

Kieffer, H. H., B. M. Jakosky, C. W. Snyder, and M. S. Matthews, *Mars*, Univ. Arizona Press, Tucson, 1992.

Krauss, C. E., M. Horányi, and S. Robertson, Laboratory experiments on electrostatic discharging in Martian dust devils and dust storms, *Eos Trans. AGU*, *83*(47), Fall Meet. Suppl., Abstract P51A-0338, 2002.

Landis, G., Dust Obscuration of Solar Arrays, *Acta Astronautica*, *38*, 891–895, 1996.

Leovy, C. B., J. B. Pollack, B. A. Smith, E. N. Shipley, R. L. Wildey, A. T. Young, and G. A. Briggs, Martian atmosphere - Mariner 9 television experiment progress report, *Icarus*, *17*, 373, 1972.

Loeb, L. B., *Fundamental Processes of Electrical Discharges in Gases*, John Wiley & Sons Inc., New York, 1939.

Malin, M. C., et al., Early views of the Martian surface from the mars orbiter camera of Mars global surveyor, *Science*, *279*, 1681–1685, 1998.

Metzger, S. M., J. R. Carr, J. R. Johnson, T. J. Parker, and M. T. Lemmon, Dust devil vortices seem by the Mars Pathfinder camera, *Geophys. Res. Lett.*, *26*(18), 2781–2784, 1999.

Muhleman, D. O., B. J. Butler, A. W. Grossman, and M. A. Slade, Radar Images of Mars, *Science*, *253*, 1508–1513, 1991.

Paltridge, G. W., and C. M. R. Platt, *Radiative Processes in Meteorology and Climatology*, Elsevier, 318 pp., 1976.

Renno, N. O., A. A. Nash, J. Lunine, and J. Murphy, Martian and terrestrial dust devils: Test of a scaling theory using Pathfinder data, *J. Geophys. Res.*, *105*, 1859–1865, 2000.

Schmidt, D. S., R. A. Schmidt, and J. D. Dent, Electrostatic Force on Saltating Sand, *J. Geophys. Res.*, *103*(D8), 8997–9001, 1998.

Schofield, J. T., J. R. Barnes, D. Crisp, R. M. Haberle, S. Larsen, J. A. Magalhaes, J. R. Murphy, A. Seiff, and G. Wilson, The Mars Pathfinder atmospheric structure investigation/meteorology (ASI/MET) experiment, *Science*, *287*, 1752–1758, 1997.

Sinclair, P. C., The lower structure of dust devils, *J. Atmos. Sci.*, *30*, 1599–1619, 1973.

Smith, P. H., and M. Lemmon, Opacity of the Martian Atmosphere measured by the imager for Mars Pathfinder, *J. Geophys. Res.*, *104*(E4), 8975–8986, 1999.

Thomas, P., and P. J. Gierasch, Dust devils on Mars, *Science*, *230*, 175–177, 1985.

Towner, M. C., S. M. Metzger, T. J. Ringrose, M. Balme, R. Greeley, and J. C. Zarnecki, Measurements of dust devil lower structure and properties, El Dorado Valley, Nevada, June 2002, *Eos Trans. AGU*, *83*(47), Fall Meet. Suppl., Abstract P51A-0342, 2002.

Uman, M. A., *The Lightning Discharge*, Academic, San Diego, Calif., 1987.

Zurek, R. W., Solar heating of the Martian dusty atmosphere, *Icarus*, *35*, 196–208, 1978.

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