



Particle lifting at the soil-air interface by atmospheric pressure excursions in dust devils

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[1] Dust devils, small-scale convective vortices found on Earth and on Mars, can transfer substantial quantities of dust from the ground into the atmosphere. It has been proposed that the low-pressure region found at the center of dust devil vortices provides a lift (the ‘ ΔP ’ effect) that ‘sucks up’ material from the surface. Two simple models are compared to investigate the physics behind the ΔP effect and the relevance of competing processes. The first considers an impermeable bed of particles where lifting is by vertical pressure gradients, the second considers a permeable bed where lifting is by drag forces on the particles as gas is sucked from the bed. Pressure gradient lifting appears to be far more efficient than drag force lifting. We describe conditions that favor lifting by the ΔP effect and make qualitative predictions that might be tested in the laboratory, the field, or through observations from Mars Landers. **Citation:** Balme, M., and A. Hagermann (2006), Particle lifting at the soil-air interface by atmospheric pressure excursions in dust devils, *Geophys. Res. Lett.*, 33, L19S01, doi:10.1029/2006GL026819.

1. Introduction

[2] Dust devils are small convective vortices that are visible due to the dust and sand they entrain. They are common on Earth [e.g., Sinclair, 1969; Metzger, 1999; Renno *et al.*, 2004] and on Mars [e.g., Thomas and Gierasch, 1985; Metzger *et al.*, 1999; Edgett and Malin, 2000]. Terrestrial examples are usually a few to a few tens of meters in diameter, and 100s of meters in height but on Mars they can be orders of magnitude larger (e.g., review by Balme and Greeley [2006]).

[3] On Earth, dust devils are not thought to be important in the global transport of dust, but this might not be so for Mars, where the atmosphere is persistently dusty, even between global dust storms [e.g., Pollack *et al.*, 1979]. This haze must be maintained through removal of dust from the surface by some means. Dust devils have long been suggested as such a mechanism [e.g., Neubauer, 1966; Greeley and Iversen, 1985] because the lifting ability of ambient boundary layer winds is low compared to Earth due to the low density and pressure of Mars’ atmosphere and the small particle size of the dust ($\leq 2\mu\text{m}$ [e.g., Pollack *et al.*, 1979]). As summarized by Greeley and Iversen [1985], there is an

optimal particle size ($\sim 100\mu\text{m}$) for lifting by boundary layer winds; particles smaller or larger than this require stronger winds to lift them. For particles smaller than $\sim 100\mu\text{m}$ cohesion forces dominate and they ‘stick’ together and resist lifting. Cohesion includes the capillary force in moist soils, chemical bonding forces, van der Waals forces, and electrostatic forces [Shao, 2000]. This is why progressively stronger boundary layer threshold wind speeds have been measured for smaller and smaller particles sizes.

[4] Greeley *et al.* [2003] used a laboratory vortex generator to compare the vortex threshold point (i.e., how fast the apparatus needed to be run to begin to lift particles) of different sized particles under different atmospheric pressures. They compared their results with results for horizontal boundary layer threshold, finding that under both Martian and terrestrial conditions, vortices are more efficient at lifting fine particles.

[5] Negative pressure excursions exist at the core of dust devils [e.g., Sinclair, 1964]. Greeley *et al.* [2003] suggest that this low-pressure region provides an additional lift (the ‘ ΔP ’ effect) which ‘sucks up’ material as the dust devil sweeps across the surface. However, they do not suggest how this ‘ ΔP ’ effect might work or how to quantify it.

[6] The effects of horizontal wind shear caused by dust devil circulation can be estimated in the field [Balme *et al.*, 2003] and the pressure structure determined from laboratory simulations [Greeley *et al.*, 2003] or field investigations [Metzger, 1999; Ringrose, 2003; Tratt *et al.*, 2003]. Although vertical pressure gradient forces have been studied in tornadoes [e.g., Snow, 1982; Fiedler and Rotunno, 1986] and these measurements might be appropriate to describe the behavior of particles *within* the vortex, no attempts have been made to identify, let alone quantify, the physical processes that are required to transfer a particle from the soil surface into the atmospheric vortex by the passage of a low pressure excursion across the surface. In this paper, we identify the physics behind the ‘ ΔP ’ effect, compare the potential relevance of competing processes and describe the optimal conditions for the ΔP effect to act.

2. Two Simple Models of the ΔP Effect

[7] To model the ΔP particle lifting ability of dust devils we consider only the effects of a negative pressure excursion (representing the passage of the dust devil), we do not in any of the following consider the horizontal surface shear stress generated by the swirling winds within the dust devil. This negative pressure excursion is applied to the surface of a bed of homogenous spherical particles representing the soil. We begin by examining two possible ways the ΔP effect might work: by pressure differential forces in which trapped air below the surface lifts the particles due to

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Table 1. Typical Terrestrial and Martian Dust Devil Parameters Used in This Paper

Parameter	Earth	Mars
Typical ΔP range, % ambient	0.1 to 1 ^a	0.075 to 0.75 ^b
Typical ΔP range, Pa	100 to 1000 ^a	0.5 to 5 ^b
Typical dust devil diameter, m	1 to 50 ^c	10 to 2000 ^d
Typical translational velocity, m s ⁻¹	<10 ^c	<20 ^c
Gravity, m s ⁻¹	9.81	3.68
Particle density, kg m ⁻³	2500	2500

^aTypical range from *Sinclair* [1964, 1973], *Metzger* [1999], *Ringrose* [2003], *Tratt et al.* [2003].

^bFrom Mars Pathfinder (MPF) lander data [*Murphy and Nelli*, 2002].

^cVarious authors; see review of *Balme and Greeley* [2006].

^dObservations from MPF [*Metzger et al.*, 1999], Viking Orbiter [*Thomas and Gierasch*, 1985], and Mars Global Surveyor [*Fisher et al.*, 2005; *Cantor et al.*, 2006].

^eFrom Mars Exploration Rover Spirit images [*Greeley et al.*, 2006].

vertical pressure gradients, or by drag in which air sucked out of the surface lifts the particles. In reality, the pressure deficit is not applied instantaneously and instead decreases from ambient to maximum ΔP at a rate dependent upon the pressure structure and rate of travel of the dust devil. These models do not consider the dynamic system, and instead are extreme cases illustrating the physical processes occurring if the ΔP effect *does* lift particles. Cohesion forces are not considered for two reasons: 1) There are few data describing the magnitude of cohesion forces in terrestrial settings, let alone on Mars. *Shao* [2000], describing modeling of the effects of moisture content and chemical bonding on soil erosion, notes that the moisture correction function does not match experimental data and that the best model for chemical bonding uses subjective observations of surface crusting. Neither of these examples constitutes a reliable model input. *Shao* [2000] also notes that “uncertainties in estimating the cohesive forces are at least several orders of magnitude”. 2) Our aim is to understand how the ΔP effect works to help explain the results of *Greeley et al.* [2003] who compared boundary layer and vortex threshold. Thus, unless cohesion resists particle lifting differently for vortices than boundary layer winds (which seems unlikely) then discounting cohesion forces does not affect the study.

[8] In model 1, the soil is impermeable such that there is no exchange between trapped sub-surface gas and the atmosphere. The pressure excursion is applied instantaneously – the lifting force is a result of the pressure difference acting over the top layer of particles which is assumed to be perfectly flat. The air trapped in the bed does not move. In model 2, the soil is permeable and gas is drawn out of the surface at a rate that is a function of the permeability of the soil and the applied pressure difference. The lifting force is the drag on the particles caused by the exiting gas. The lifting effects of pressure gradients across the upper soil layers are not considered.

2.1. Model 1: Impermeable Surface

[9] For a particle of diameter D_p , the lifting force per particle in the uppermost layer is simply given by

$$F_p = \frac{\Delta P \pi D_p^2}{4}, \quad (1)$$

where ΔP is the negative pressure excursion in the center of the dust devil. The pressure within the particle bed is assumed to be the same as the ambient pressure away from the dust devil. On the other hand, the force due to gravity on each particle is simply

$$F_g = \frac{\pi D_p^3 \rho_p g}{6}, \quad (2)$$

where ρ_p is the particle density and g the gravity. The ratio of the pressure lifting force to the gravity force is thus

$$\frac{F_p}{F_g} = \frac{3\Delta P}{2D_p \rho_p g}. \quad (3)$$

[10] Particles are lifted if this ratio is >1 . Table 1 gives values used in the model. Figure 1a shows that, except for

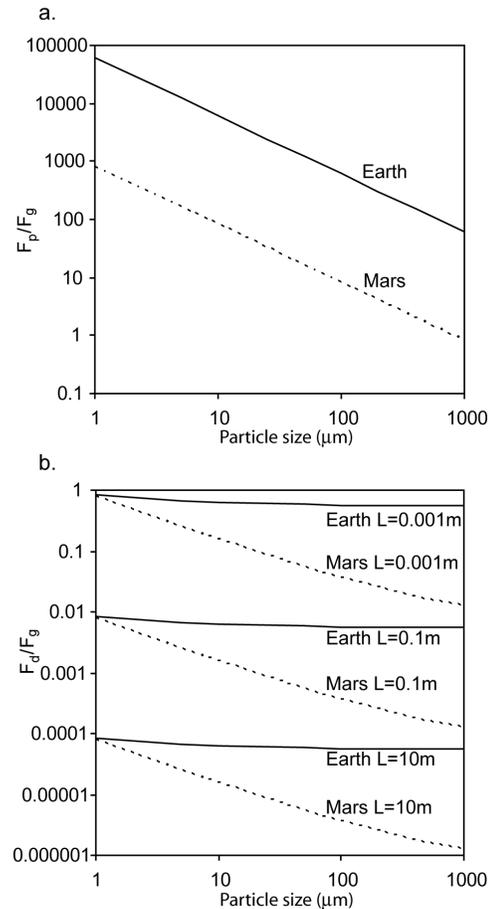


Figure 1. (a) Ratio of pressure gradient lifting force to weight of top layer of particles as a function of particle size for model 1 – impermeable bed. Pressure gradient lifting force dominates for all but the largest particles. (b) Ratio of airflow-drag lifting force to weight for model 2, the permeable bed. L refers to the depth over which the pressure gradient acts in the Darcy equation. $L = 10m$ is from scaling to a typical diameter for a dust devils. In general the pressure gradient lifting force is many orders of magnitude higher than the drag force even when $L = 0.001m$ and the flow from the bed is maximized.

sand-grade particles on Mars, the lift force dominates the gravity force. Thus if the top layer of a soil bed were perfectly sealed, or if a pressure change were applied instantaneously without giving the soil time to equilibrate, particles would be removed due to the pressure gradient. The lifting effect is greater for smaller particles.

2.2. Model 2: The Permeable Bed

[11] By ‘permeable’ in this extreme case we mean a soil bed whose air flow is allowed to equilibrate with the pressure change at the surface. Air is sucked up from an infinite reservoir, be it in the ground below, or in the higher pressure region outside the dust devil. We must, therefore, first calculate the permeability of the ‘soil’. Assuming a bed of randomly packed homogeneous spheres, the Carman-Kozeny relation gives the permeability K of the bed as

$$K = \frac{D_p^2 \Phi^3}{72\tau(1 - \Phi)^2}, \quad (4)$$

where τ is the tortuosity (a measure of how convoluted the connectivity of the pores is) and Φ the porosity [Panda and Lake, 1994]. The porosity is the fraction of a porous medium occupied by ‘space’ rather than solid material. Porosity of beds of homogeneous spheres ranges from 0.26 (close-packed face-centered cubic structure [Hales, 2002]) to 0.48 (cubic packing [Smith et al., 1929]). A suitable packing for soil science is a random close packing called the Finney Pack [Finney, 1970] which has a porosity of 0.36. The tortuosity is estimated to be 25/12 [Scheidegger, 1960]. Equation (4) is a simplification that holds for ideally viscous fluids traveling through the pores and assumes no slip of the flowing fluid at the grain surfaces. Gases, however, especially at low pressures, experience slippage at these surfaces. The resulting increase in permeability with decreasing gas pressure is called the ‘Klinkenberg Effect’ [Klinkenberg, 1941] and is particularly important for the low pressure regime of Mars. It has been quantified as

$$k_g = k + \frac{6.9}{p} \times k^{0.64}, \quad (5)$$

where p is pressure (in psi) and the permeabilities for gas and liquid k_g , k are given in mdarcies [Ahmed, 2001]. For conversion from the commonly used engineering units to SI note that $k = c \times K$ and $k_g = c \times K_g$, with $c = 0.986923 \times 10^{-3} \mu\text{m}^2$.

[12] Darcy’s Law [e.g., Ahmed, 2001] states that the discharge q of a gas (in terms of volume per time) through a bed of surface area A and length L with a pressure gradient dP/dL can be expressed as

$$q = -\frac{K_g A}{\eta} \frac{dP}{dL}, \quad (6)$$

where η is the dynamic viscosity of the gas. We apply Darcy’s law to our problem as follows. First, we assume the soil bed to be a homogeneous half-space. The simplified dust devil can be represented as a circular low pressure region of radius R , with pressure decreasing from R to the center by a total amount ΔP . This results in a pressure

gradient and thus an outflow of air into the de-pressurized region. The characteristic length of the bed, L , is hard to quantify, but we can assume R and L to be of similar length scales for the following reasons: If we assume that the pressure decreases approximately linearly from R to the center of the vortex, we can comfortably assume that $L = R$ since this approximates the pressure gradient in the air (and thereby the maximal pressure gradient at any point in the soil). We can therefore set $dP/dL = \Delta P/L$ and (6) becomes

$$v = -\frac{K_g}{\eta} \frac{\Delta P}{L}, \quad (7)$$

where $v = q/A$ is the mean flow speed through the surface of the bed. In reality, L could be somewhat smaller because of the non-stationary nature of dust devils. We must also consider smaller values of L because, for example, a thin layer of dust or sand could be deposited over a porous bedrock. In this case we assume that the pore volume and permeability of the base layer are much higher than the bed of particles and so the gas pressure below remains constant over the short durations the ΔP is applied. Using Stokes’ law and the velocity of the escaping gas, we now estimate the maximum drag force F_d on a spherical particle at the surface of the bed:

$$F_d = -3\pi\eta v D_p. \quad (8)$$

[13] For simplicity we ignore the effects of turbulence and do not apply any correction to Stokes’ law for flow in the transitional, Knudsen or slip-flow regimes. Thus, particularly for small particle size or low atmospheric pressure (8) actually gives an overestimate of drag on the particle. The ratio of drag force to gravity is therefore

$$\frac{F_d}{F_g} = \frac{18\eta v}{D_p^2 \rho_p g}. \quad (9)$$

Despite the simplification of the drag equation Figure 1b shows that the drag force is in no case sufficient to combat the effects of gravity. Even if we reduce L to only a depth of 1mm, the drag force is still not enough to counteract gravity. Therefore we suggest that drag of the gas escaping the soil plays no role in the lifting of particles.

3. Discussion

[14] We have shown that if the ΔP effect is strong enough to lift material then the situation is more similar to model 1 than model 2 and thus the pressure gradient force dominates the drag force. In reality, model 1 is only a crude approximation because in nature the ΔP is not applied instantaneously but instead acts at a rate dependent on the magnitude of the ΔP and the radius and speed of translation of the dust devil across the surface. Although model 2 suggests that drag is not the dominant lifting mechanism, the model is still useful because it describes whether the soil will degas quickly, disallowing a significant pressure gradient to build up over the top layer, or whether exchange of gas from the subsurface to the atmosphere will be so slow that substantial vertical pressure gradients will occur within

the upper layers of the bed (generating conditions similar to model 1). Thus, while model 1 suggests that the magnitude of the negative pressure excursion is important for determining if the ΔP effect lifts material, model 2 suggests that the rate of change of pressure is also important to the mechanisms of particle lifting. Both models essentially illustrate extreme cases of permeability and pressure equilibration.

[15] We can estimate the approximate rate of change of pressure applied to the surface by a dust devil by simply assuming a linear decrease in pressure beginning at the edge of the dust devil column radius and reaching a minimum at the center. Pressure profiles within natural dust devils approximate Rankine vortices, having an inverted bell-shape [Greeley *et al.*, 2003; Schofield *et al.*, 1997]. However, the assumption of a linear decrease in pressure gives similar rates of change to the peak values of the Rankine-vortex approximation. Using this assumption and data for real dust devils from Table 1, we note that the greatest rates of change in pressure will be for the smallest observed dust devils, with the largest observed negative pressure excursions, traveling at greatest speed. For Earth this will be $\sim 2 \times 10^4 \text{ Pa s}^{-1}$ for a 1 m diameter dust devil traveling at 10 m s^{-1} with a central pressure deficit of 1% of ambient, and for Mars $\sim 20 \text{ Pa s}^{-1}$ for a 10 m diameter dust devil traveling at 20 m s^{-1} , again with a central pressure deficit of 1% of ambient. It is clear that the rate of change of pressure applied can be three orders of magnitude larger on Earth than on Mars.

[16] Equations (4) and (7) show that the rate of degassing of the bed will depend strongly on the permeability; degassing is less significant for beds of smaller particles. Taken together, the two models show that the ΔP effect is most significant for beds composed primarily of fine particles over which the ΔP is applied faster than the rate at which the subsurface can degas. Thus optimal conditions for ΔP lifting are encountered in small dust devils with large magnitude low pressure cores, traveling quickly over beds of fine particles. We can also conclude that for a given particle sizes, in a highly consolidated soil, or one with an impermeable crust, pressure can build up more effectively, increasing the likelihood of ΔP lifting. In a loose, highly porous soil with high permeability, however, the ΔP effect will be less.

[17] The competing factors that determine if the ΔP effect can lift particles by build-up of pressure gradients are shown in Figure 2. Our work suggests that terrestrial dust devils have more efficient ΔP effects for lifting material than Martian ones, even taking into account Mars' weaker gravity. However, this does not mean that the ΔP effect is sufficient to lift particles because, in nature, the bed might degas fast enough to preclude build-up of large pressure gradients on both Earth and Mars. Thus we need to look for corroborating evidence from field and laboratory studies.

[18] Some confirmation of this result comes from laboratory experiments [Neakrase *et al.*, 2006] that show that the dust removal flux is larger for smaller vortices. Also, Mars Exploration Rover observations [Neakrase *et al.*, 2006; Greeley *et al.*, 2006] suggest that smaller radius dust devils remove dust from the surface more quickly than larger ones. The observation that vortex threshold is more efficient for smaller particles than ambient wind threshold

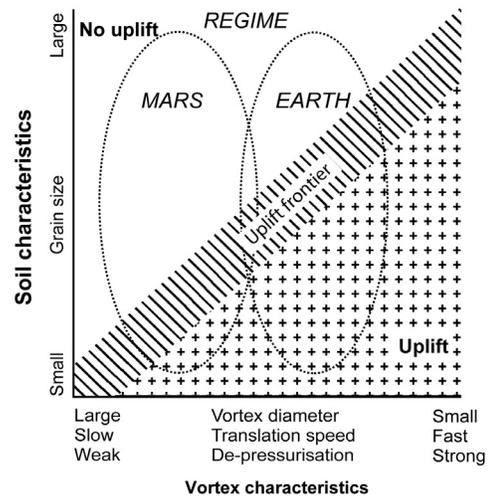


Figure 2. Illustration of the factors affecting the ability of the ΔP effect in dust devils to lift particles. Small, fast moving vortices with large magnitude negative pressure excursions are the optimum vortex characteristics for lifting material by the ΔP effect. Soils with small particle sizes (or with low permeability due to other factors such as surface crusting) are more likely to be lifted by the ΔP effect. Conditions appear to be more favorable for ΔP lifting on Earth than on Mars.

[Greeley *et al.*, 2003] is consistent with a rate of degassing of the bed slow enough to allow the ΔP to be effective at lifting particles.

[19] It would seem that our results, which show that terrestrial dust devils have ΔP effects orders of magnitude more effective at lifting dust than Martian ones, could be easily tested on Earth through simple fieldwork. However, Balme *et al.* [2003] show that horizontal surface wind stresses caused by the circulation of terrestrial dust devils are sufficient to lift even fine dust and this might prevent the ΔP effect from being easily observed. Thus perhaps most loose particles are lifted by horizontal wind shear associated with the circulation of the dust devil (which has a maximum value at about the radius of the dust column) well before the point at which the maximum pressure gradient occurs and where the ΔP effect might lift them. On Mars though, despite the slow rates that the pressure gradient is applied and its small magnitude, the weak horizontal surface wind shear associated with the dust devil circulation might allow the ΔP effect to dominate. If this is the case then it is likely that only beds of the smallest particles will be lifted in this way; larger particle size beds will instead tend to degas. Future in-situ measurements of particle size and ΔP within Martian dust devils are required to test this theory.

4. Conclusions and Future Work

[20] Using simple models we have investigated competing mechanisms in the ΔP effect and found that particles are lifted by a kind of explosive release of subsurface air rather than dragged upwards by air 'sucked' from the ground. Our models suggest that this effect will be stronger on Earth than Mars but, due to the relative weakness of horizontal surface wind shear stress caused by dust devil circulation, on Mars it

could be the dominant dust lifting process in dust devils. At this point though, we still cannot quantitatively determine if the ΔP effect is significant or if beds of soil will degas fast enough to preclude pressure gradients building up. Our results show that the most significant ΔP effects will be associated with smaller, faster-moving vortices. This observation appears to agree with flux experiments and Mars Exploration Rover observations. Our results agree with the vortex threshold test data of Greeley *et al.* [2003], that show fine particles being lifted more easily by vortices than by ambient boundary layer winds. The ΔP effect seems only to be important for low permeability surfaces, such as beds of fine dust. This result matches the observations of the small particle size in Mars' atmosphere.

[21] It could be argued that our models are somewhat simplistic. Nevertheless, they have enabled us to identify *why* the ΔP in dust devils can lift surface material and are therefore an important first step towards a quantitative solution of the problem. Based on these results, we have started work on a quantitative, dynamic solution which does not require application of arbitrary length or time scales. This will allow us to quantitatively investigate whether the rate of degassing of the soil will support the build up of pressure gradients large enough to lift particles.

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References

- Ahmed, T. (2001), *Reservoir Engineering Handbook*, 2nd ed., Elsevier, New York.
- Balme, M. R., and R. Greeley (2006), Dust devils on Earth and Mars, *Rev. Geophys.*, *44*, RG3003, doi:10.1029/2005RG000188.
- Balme, M. R., S. Metzger, M. C. Towner, T. J. Ringrose, R. Greeley, and J. Iversen (2003), Friction wind speeds in dust devils: A field study, *Geophys. Res. Lett.*, *30*(16), 1830, doi:10.1029/2003GL017493.
- Cantor, B. A., K. M. Kanak, and K. S. Edgett (2006), MOC observations of Martian dust devils and their tracks (September 1997 – January 2006) and evaluation of theoretical vortex models, *J. Geophys. Res.*, doi:10.1029/2006JE002700, in press.
- Edgett, K. S., and M. C. Malin (2000), Martian dust raising and surface albedo controls: thin, dark (and sometimes bright) streaks and dust devils in MGS high-resolution images, *Lunar Planet. Sci. [CDROM]*, *XXXI*, abstract 1073.
- Fiedler, B. H., and R. Rotunno (1986), A theory for the maximum wind-speeds in tornado-like vortices, *J. Atmos. Sci.*, *43*(21), 2328–2340.
- Finney, J. L. (1970), Random packings and the structure of simple liquids: I. The geometry of random close packing, *Proc. R. Soc., Ser. A*, *319*, 479–493.
- Fisher, J. A., M. I. Richardson, C. E. Newman, M. A. Szwarc, C. Graf, S. Basu, S. P. Ewald, A. D. Toigo, and R. J. Wilson (2005), A survey of Martian dust devil activity using Mars Global Surveyor Mars Orbiter Camera images, *J. Geophys. Res.*, *110*, E03004, doi:10.1029/2003JE002165.
- Greeley, R., and J. Iversen (1985), *Wind as a Geologic Process on Earth, Mars, Venus and Titan*, Cambridge Univ. Press, New York.
- Greeley, R., M. R. Balme, J. Iversen, S. Metzger, B. Mickelson, J. Phoreman, and B. White (2003), Martian dust devils: Laboratory simulations of particle threshold, *J. Geophys. Res.*, *108*(E5), 5041, doi:10.1029/2002JE001987.
- Greeley, R., P. L. Whelley, R. E. Arvidson, N. A. Cabrol, D. J. Foley, B. J. Franklin, P. G. Geissler, M. P. Golombek, R. O. Kuzmin, G. A. Landis, M. T. Lemmon, L. D. V. Neakrase, S. W. Squyres, and S. D. Thompson (2006), Active dust devils in Gusev Crater, Mars: observation from the Mars Exploration Rover, Spirit, *J. Geophys. Res.*, doi:10.1029/2006JE002743, in press.
- Hales, T. C. (2002), A computer verification of the Kepler conjecture, paper presented at 26th International Conference, Int. Conf. of Math., Beijing.
- Klinkenberg, L. J. (1941), The permeability of porous media to liquids and gases, API drilling and production practice, in *Drilling and Production Practice*, pp. 200–213, Am. Petrol. Inst., Washington, D. C.
- Metzger, S. M. (1999), Dust devils as aeolian transport mechanisms in southern Nevada and in the Mars Pathfinder landing site, Ph.D. thesis, Univ. of Nev., Reno.
- Metzger, S. M., J. R. Carr, J. R. Johnson, T. J. Parker, and M. T. Lemmon (1999), Dust devil vortices seen by the Mars Pathfinder camera, *Geophys. Res. Lett.*, *26*(18), 2781–2784.
- Murphy, J., and S. Nelli (2002), Mars Pathfinder convective vortices: Frequency of occurrence, *Geophys. Res. Lett.*, *29*(23), 2103, doi:10.1029/2002GL015214.
- Neakrase, L. D. V., R. Greeley, J. Iversen, M. R. Balme, and E. E. Eddlemon (2006), Dust flux within dust devils: Preliminary laboratory simulations, *Geophys. Res. Lett.*, *33*, L19S09, doi:10.1029/2006GL026810.
- Neubauer, F. M. (1966), Thermal convection in the Martian atmosphere, *J. Geophys. Res.*, *71*, 2419–2426.
- Panda, M. N., and L. W. Lake (1994), Estimation of single-phase permeability from the parameters of a particle-size distribution, *AAPG Bull.*, *78*(7), 1028–1039.
- Pollack, J. B., D. S. Colburn, F. M. Flasar, R. Kahn, C. E. Carlston, and D. Pidek (1979), Properties and effects of dust particles suspended in the Martian atmosphere, *J. Geophys. Res.*, *84*, 2929–2945.
- Renno, N. O., et al. (2004), MATADOR 2002: A pilot field experiment on convective plumes and dust devils, *J. Geophys. Res.*, *109*, E07001, doi:10.1029/2003JE002219.
- Ringrose, T. J. (2003), An investigation of Martian and terrestrial dust devils, Ph.D. thesis, Open Univ., Milton Keynes, U. K.
- Scheidegger, A. (1960), *The Physics of Flow Through Porous Media*, MacMillan, New York.
- Schofield, J. T., J. R. Barnes, D. Crisp, R. M. Haberle, S. Larsen, J. A. Magalhaes, J. R. Murphy, A. Seiff, and G. Wilson (1997), The Mars Pathfinder atmospheric structure investigation meteorology (ASI/MET) experiment, *Science*, *278*(5344), 1752–1758.
- Shao, Y. (2000), *Physics and Modelling of Wind Erosion*, Springer, New York.
- Sinclair, P. C. (1964), Some preliminary dust devil measurements, *Mon. Weather. Rev.*, *22*(8), 363–367.
- Sinclair, P. C. (1969), General characteristics of dust devils, *J. Appl. Meteorol.*, *8*, 32–45.
- Sinclair, P. C. (1973), The lower structure of dust devils, *J. Atmos. Sci.*, *30*(8), 1599–1619.
- Smith, W. O., P. D. Foote, and P. F. Busang (1929), Packing of homogeneous spheres, *Phys. Rev.*, *34*, 1271–1274.
- Snow, J. T. (1982), A review of recent advances in tornado vortex dynamics, *Rev. Geophys.*, *20*, 953–964.
- Thomas, P. C., and P. J. Gierasch (1985), Dust devils on Mars, *Science*, *230*(4722), 175–177.
- Tratt, D. M., M. H. Hecht, D. C. Catling, E. C. Samulon, and P. H. Smith (2003), In situ measurements of dust devil dynamics: Toward a strategy for Mars, *J. Geophys. Res.*, *108*(E11), 5116, doi:10.1029/2003JE002161.

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