Space Sci Rev (2008) 137: 419–434
DOI 10.1007/s11214-008-9377-5

Electrical Activity and Dust Lifting on Earth, Mars, and Beyond

Nilton O. Renno · Jasper F. Kok

Received: 14 December 2007 / Accepted: 12 May 2008 / Published online: 20 June 2008

Abstract We review electrical activity in blowing sand and dusty phenomena on Earth, Mars, the Moon, and asteroids. On Earth and Mars, blowing sand and dusty phenomena such as dust devils and dust storms are important geological processes and the primary sources of atmospheric dust. Large electric fields have been measured in terrestrial dusty phenomena and are predicted to occur on Mars. We review the charging mechanisms that produce these electric fields and discuss the implications of electrical activity to dust lifting and atmospheric chemistry. In addition, we review theoretical ideas about electric discharges on Mars. Finally, we discuss the evidence that electrostatics is responsible for dust transport on the Moon and asteroids.

Keywords Saltation · Dust lifting · Dust electrification · Electrostatics · Electric discharges

1 Introduction

Mineral dust aerosols affect climate by absorbing and scattering radiation (Myhre and Stordal 2001; Fenton et al. 2007). On Earth, dust aerosols also play an important role in cloud formation by serving as cloud condensation and ice nuclei (DeMott et al. 2003). Indeed, the 'climate forcing' produced by the interactions of radiation with dust and clouds are among the most uncertain processes in climate change predictions (IPCC 2007). Part of this uncertainty arises from the limited ability of current models to accurately simulate the quantity and size distribution of dust lifted from the surface (Cakmur et al. 2006).

Atmospheric dust aerosols generally have diameters smaller than a few microns (DeMott et al. 2003) and therefore are subject to large interparticle forces that prevent them from being directly lifted by wind (Greeley and Iversen 1985; Shao and Lu 2000; Merrison et al.

N.O. Renno (✉) · J.F. Kok
Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, MI, USA
e-mail: renno@alum.mit.edu

N.O. Renno · J.F. Kok
Applied Physics Program, University of Michigan, Ann Arbor, MI 48109, USA

2007). On Earth, dust aerosols are predominantly lifted into the air by saltation, a process by which larger sand particles are moved by wind and bounce on the surface, ejecting the smaller, harder to lift, dust particles (aerosols) into the air (Bagnold 1941). Saltation lifts dust in blowing sand, dusty plumes, dust devils, and dust storms. Moreover, both on Earth and Mars saltation is an important geological process that leads to the formation of sand dunes and the erosion of geological features.

The lifting of dust aerosols on Mars is still poorly understood, but as on Earth it is possibly caused mainly by saltation (Greeley et al. 2002). Other dust lifting mechanisms include the breakup of low-density aggregates of dust particles (Merrison et al. 2007), and lifting aided by moving low-pressure centers of dust devils (Greeley et al. 2003).

The understanding of saltation and dusty phenomena is thus important to a wide range of atmospheric and geological processes on Earth, Mars and beyond. Recent studies have shown that on Earth, saltation and dusty phenomena can be highly electrified, with electric fields (E-fields) exceeding 100 kV/m (Stow 1969; Schmidt et al. 1998; Renno et al. 2004; Jackson and Farrell 2006; Kok and Renno, 2006, 2008). Theory and laboratory experiments suggest that these E-fields reduce the wind stress necessary to initiate saltation, thereby increasing the concentration of saltating particles at a given wind speed (Kok and Renno, 2006, 2008). Moreover, electric forces arising from sand electrification can be strong enough to significantly affect the motion of saltating particles (Schmidt et al. 1998; Zheng et al. 2003). Indeed, their inclusion in numerical models of saltation can resolve observed discrepancies between measurements and theory (Kok and Renno 2008; Zheng et al. 2006).

On Mars, electric forces might also play a role in dust lifting by reducing the threshold wind stress necessary to initiate saltation (Kok and Renno 2006). Moreover, several studies suggest that E-fields generated in Martian dust storms can cause electric discharges (Eden and Vonnegut 1973; Melnik and Parrot 1998; Krauss et al. 2006; Farrell et al., 2003, 2006a; Zhai et al. 2006; Kok and Renno 2008). The possible occurrence of large E-fields and the associated electric discharges has potentially important implications for Martian atmospheric chemistry, human exploration, habitability (Atreya et al. 2006; Delory et al. 2006), and even the possible development of life (Miller 1953). In particular, E-fields exceeding $\sim$10 kV/m might produce large quantities of hydrogen peroxide, a strong oxidant that could make the martian surface inhospitable to life as we know it (Atreya et al. 2006).

This article reviews electrical activity in dusty phenomena on Earth, Mars, the Moon, and asteroids. In the next section, we review measurements of electrification in saltation and dusty phenomena, discuss the charge transfer between colliding sand/dust particles, and describe the effects of the resulting E-fields on dust lifting, possible electric discharges, and atmospheric chemistry on both Earth and Mars. Finally, in Sect. 3, we discuss possible electrostatic dust lifting on celestial bodies without atmospheres, such as the Moon and asteroids.

2 Dust/Sand Electrification and Its Effects on Dust Lifting and Atmospheric Chemistry

The electrification of blowing sand and dusty phenomena is caused by charge transfer during collisions among saltating sand particles, between saltating sand particles and the ground, and between sand particles and dust particles (Harper 1967; Renno et al. 2004; Kok and Renno 2008). The physical mechanism that governs this charge transfer is not

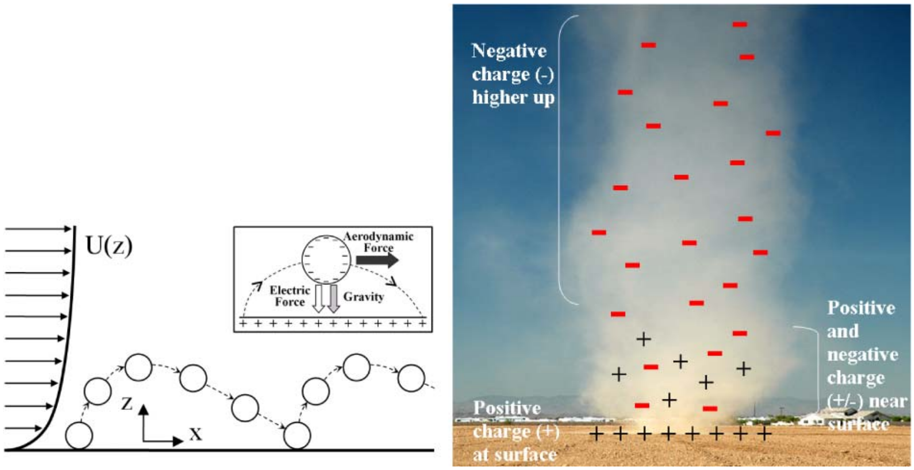

Fig. 1 (**a**) Schematic of saltation, showing the logarithmic wind profile $U(z)$ to the left of a sand particle propelled by the wind and bouncing along the surface. Saltating particles absorb horizontal momentum from the wind, which is partially converted into vertical momentum upon collision with the soil bed. The *inset* illustrates the charge distribution in saltation in the absence of suspended dust, and shows the force diagram of a negatively charged sand grain saltating over the positively charged soil surface. After Kok and Renno (2008). (**b**) Hypothesized charge distribution in dusty phenomena (i.e., a dust storm or dust devil). Collisions with saltating particles are expected to charge the soil surface positively, and dust particles negatively (see main text). The net charge held by saltating particles thus depends on the relative frequency of collisions with the surface and suspended dust, and can probably be both negative and positive. The small dust particles are transported upwards through convection or turbulent diffusion, while the larger and heavier saltating particles stay closer to the surface. This charge separation can produce large electric fields

clear (see Sect. 2.2), but measurements indicate that, on average, the larger particle becomes positively charged with respect to the smaller particle (Freier 1960; Schmidt et al. 1998; Inculet et al. 2006; Duff and Lacks 2008). Since the ground can be interpreted as the surface of an infinitely large particle, it is expected to charge positively with respect to saltating particles (Kok and Renno 2008). This is consistent with measurements of upward-pointing near-surface E-fields in saltation (Schmidt et al. 1998; Zheng et al. 2003; Qu et al. 2004), dust devils (Freier 1960; Renno et al. 2004), dust storms (Stow 1969), and saltating snow (Schmidt et al. 1999). While the ground is thus expected to charge positively in dusty phenomena, the net charge of saltating particles depends on the relative frequencies of collisions with the surface (which charges them negatively) and suspended dust particles (which charges them positively). In the absence of suspended dust particles, saltating particles are therefore expected to charge negatively (Zheng et al. 2003; Kok and Renno 2008).

After undergoing collisions, the smaller (negatively charged) dust particles can be lifted by turbulent eddies and updrafts, while the larger particles (whose charge can be either positive or negative) stay close to the positively charged surface. Figure 1 shows the hypothesized charge distribution in saltation and dusty phenomena and is based on the measurements reviewed in the next section.

2.1 Measurements of Electrification in Saltation and Dusty Phenomena

Electrification in blowing sand (saltation), dust devils, and dust storms has been studied in laboratory and field experiments. These studies have been performed under Earth ambient conditions, but they also serve as analog studies of the electrification of saltation and dusty phenomena on other planetary bodies, especially Mars (Farrell et al. 2004; Jackson and Farrell 2006).

Field measurements by Schmidt et al. (1998) found E-fields of up to 160 kV/m in saltation. These E-fields were found to be upward-pointing, indicating negatively charged saltating particles over a positively charged surface (Fig. 1a). Surprisingly, Schmidt et al.'s simultaneous measurement of particle charge found saltating particles at 5 cm above the surface to be positively charged, in disagreement with their finding of upward-pointing E-fields uniformly increasing towards the surface. However, wind-tunnel studies by other investigators found negatively charged saltating particles, and upward-pointing E-fields in saltation (Zheng et al. 2003; Qu et al. 2004).

A significant number of measurements of E-fields have also been made in dust devils. Freier (1960) made the first reliable measurement of the E-fields in dust devils. He used a grounded electric field mill to measure the E-field produced by a dust devil tens of meters away and found a significant deviation from the fair-weather value. This result is consistent with the idea that dust devils have a negative dipole moment (i.e., negative over positive charges). Freier's measurements were confirmed by Crozier (1964, 1970). Field measurements by Farrell et al. (2004) and Renno et al. (2004) also found negative charges aloft, with measured E-fields exceeding the instrument range of 4 and 20 kV/m respectively, well before the dust devil passed over their sensors. More recently, Jackson and Farrell (2006) measured the horizontal E-field in dust devils and found values of up to 120 kV/m.

Though detailed measurements of E-fields in dust devils are numerous, fewer measurements have been made in dust storms. There is anecdotal evidence of significant electrification of dust storms observed during the 'dust bowl' on the American Great Plains in the 1930s (Keith 1944). Later measurements in the Sahara found both downward (Demon et al. 1953) and upward-pointing (Stow 1969) E-fields, with values of 1–15 kV/m at about 1 m above the ground, increasing to 50–200 kV/m at the ground (Stow 1969). Kamra (1972) made a series of measurements in dust storms in the southwestern deserts of the United States and found both upward and downward-pointing E-fields with magnitudes similar to those measured by Demon et al. (1953) and Stow (1969). He also reported measurements of both positive and negative space charges at a height of 1.25 m. More recently, Williams et al. (2008) reported measurements during dust storms ('haboobs') in the Sahel and also found E-fields pointing both up and downwards, although most measurements indicated upward-pointing fields.

In summary, most measurements in saltation, dust devils and dust storms show upward pointing E-fields. These measurements support the hypothesis that saltating particles charge negatively upon collision with the ground, and that dust particles become negatively charged after collisions with larger saltating particles (Fig. 1). However, the situation appears to be more complex in dust storms, with E-fields pointing both up and downwards (Kamra 1972; Williams et al. 2008). This apparent discrepancy between measurements in saltation and dust devils on the one hand, and measurements in dust storms on the other, stresses the need for a better understanding of the charging processes involved in dust/sand electrification. The current state of knowledge of this charging process is reviewed in the next section.

2.2 Charge Transfer in Colliding Dust/Sand Particles

While the electrification of blowing sand and dusty phenomena is well documented (see Sect. 2.1), the physical process responsible for it is still a puzzle. It is well established that two objects get charged when rubbed against each other, and that the charge transfer depends on the difference in contact potential between their materials (Harper 1967;

Desch and Cuzzi 2000). Thus, little or no charge transfer is expected when particles of identical material such as sand and/or dust collide with each other. Since measurements show that significant charging does occur, a mechanism different than the 'traditional' contact electrification (Harper 1967) must play an important role in dust/sand electrification.

Lowell and Truscott (1986) proposed a heuristic model for charge transfer during collisions of particles of similar dielectric materials. According to their model, electrons confined in the high-energy states of one particle tunnel to more abundant empty low-energy levels on the other particle when they rub against each other. Thus, the particle that rubs a larger surface area with the other loses more electrons and therefore charges positively. Thus, 'asymmetric rubbing' during collisions of smaller with larger particles leads to a net transfer of electrons from the larger to the smaller particles (Kok and Renno 2008). This prediction is consistent with measurements in blowing sand and dusty phenomena.

An alternative, but related model was proposed by Duff and Lacks (2008). They used particle dynamics simulations to show that the mere presence of confined high-energy states in insulators can lead to the transfer of electrons from larger to smaller particles, even without explicit 'asymmetric rubbing.' The physical reason for the charge transfer is that, after multiple collisions in which high-energy electrons from one particle are transferred to empty, low-energy, states on the other particle, the smaller particles lose a larger fraction of its electrons than the larger. The ability of smaller particles to give up electrons is therefore reduced, such that the smaller particles become negatively charged after multiple collisions.

Though the hypotheses put forth by both Lowell and Truscott (1986) and Duff and Lacks (2008) are promising, they have not been rigorously tested yet. In the absence of a clear physical understanding of the mechanism driving 'collisional charge transfer' between particles, various simple parameterizations have been proposed to describe the charging of colliding sand and/or dust particles. Melnik and Parrot (1998) proposed that when sand/dust particles collide with each other, the amount of negative charge that the smaller particle acquires depends on its radius, while the larger particle acquired an equal and opposite amount of positive charge. Though appealing in its simplicity, this idea is problematic because it does not take into account pre-existing charges on the colliding particles and therefore poses no limit to the amount of charge transferred after many collisions. Moreover, the amount of charge transferred per collision is likely too large to be realistic (Zhai et al. 2006). Desch and Cuzzi (2000) developed a more sophisticated parameterization in which the charge transferred during each collision depends on the pre-existing charge, the particle radii, and the difference in contact potential between them. Based on previous research summarized by Harper (1967), they proposed that

$$q_S = C_1(q_S + q_L) - C_2\Delta\Phi; \tag{1a}$$

$$q_L = (1 - C_1)(q_S + q_L) + C_2\Delta\Phi, \tag{1b}$$

where q_S and q_L are the charges of the smaller and larger particles before a collision, q'_S and q'_L are the charges after a collision, $\Delta\Phi$ is the difference in particle contact potential, and C_1 and C_2 are functions of the mutual capacitances of the two particles, as defined by (5)–(10) of Desch and Cuzzi (2000). As noted above, the second term in (1a) and (1b) is zero for particles of similar composition such as typical sand/dust particles because $\Delta\Phi = 0$. Therefore, this model is not technically applicable to sand/dust electrification, as it predicts that no charge is transferred during collisions of uncharged particles of identical material. This led Farrell et al. (2003) to postulate a contact potential difference between sand and dust. Kok and Renno (2008) expanded upon this idea and proposed an *effective* potential difference $\Delta\Phi_{\mathrm{eff}}$ between particle pairs of similar composition but different sizes,

$$\Delta\Phi_{\mathrm{eff}} = S(r_{\mathrm{L}} - r_{\mathrm{S}})/(r_{\mathrm{L}} + r_{\mathrm{S}}), \quad (2)$$

where S (in volts) is a physical parameter that scales the collisional charge transfer, and r_{S} and r_{L} are the radii of the smaller and larger particles. Using a detailed numerical model of saltation, Kok and Renno (2008) calibrated the parameter S with E-field measurements in saltation, finding $S = 6 \pm 4$ volts. Since typical dust/sand particles are of identical material, this *effective* potential difference is thus likely not due to an actual difference between the contact potentials of the colliding particles. Rather, the physical mechanism that drives the transfer of charge (such as the 'asymmetric rubbing' described above) can be expressed as an *effective* potential difference, and therefore the Desch and Cuzzi model can be used to describe the charge transfer.

The simple model described by (1) and (2) has a functional form consistent with observations—smaller particles acquire net negative charge during collisions with larger particles, and the charge transfer increases with the relative difference in particle size. However, this model does not account explicitly for other variables that likely affect the charge transfer such as temperature, humidity (Guardiola et al. 1996) and particle speed (Poppe and Schrapler 2005). Moreover, it assumes that particles get fully charged after a single collision. That is, multiple collisions between two particles yield the same final charges as only one collision, which is probably not realistic (Kwetkus et al. 1992). Detailed measurements of the collisional charging of similar materials are thus required to facilitate the formulation of realistic charging parameterizations.

2.3 The Effects of Electric Forces on Saltation and Dust Lifting

The electrification of blowing sand and dusty phenomena affects saltation and dust lifting. First, electric forces affect the trajectories of saltating particles, as first suggested by Schmidt et al. (1998) and Zheng et al. (2003). Indeed, the presence of electric forces might explain the puzzling discovery that the height to which saltating particles bounce does not increase with wind speed (Greeley et al. 1996; Namikas 2003). This is in direct contradiction with saltation theory (Bagnold 1941; Owen 1964), which predicts that the height of the saltation layer increases markedly with wind speed. A possible explanation for this discrepancy between theory and measurements is the presence of downward-pointing electric forces on the saltating particles as illustrated in Fig. 1a (Kok and Renno 2008). As the wind speed increases, so does the concentration of saltating particles and therefore the E-field. Thus, the downward-pointing electric forces increase with wind speed and counteract the increased momentum that saltating particles obtain from the wind. Kok and Renno (2008) show that the inclusion of electric forces in saltation models can resolve the discrepancy between theory and measurements (Fig. 2). Detailed numerical simulations of saltation by Zheng et al. (2006) also showed better agreement with wind-tunnel measurements by Shao and Raupach (1992) and Rasmussen and Mikkelsen (1998), when electrostatic forces were included in the model.

A second effect of electrification on saltation and dust lifting is that electric forces facilitate the lifting of particles from the surface by wind, leading to an increase in the concentration of saltating particles. This occurs because the negatively charged cloud of saltating particles attracts the positively charged particles on the surface, facilitating their lifting by wind and ejection into the air by saltating particles. Kok and Renno (2006) derived an expression

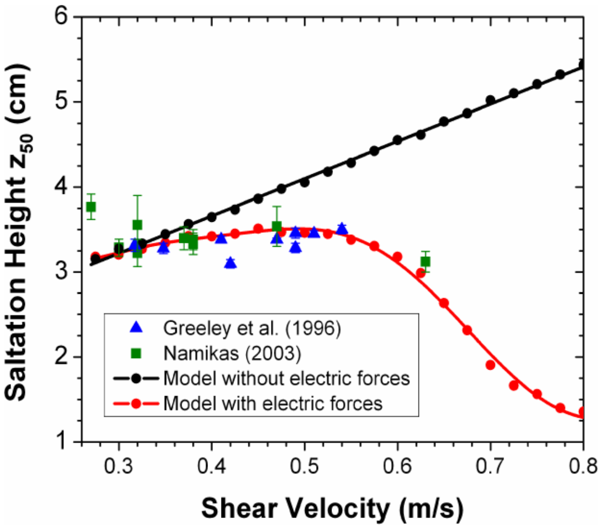

Fig. 2 Numerical study by Kok and Renno (2008) of the dependence of the saltation height z_{50} on the wind shear velocity. z_{50} is defined as the height below which 50% of the mass transport in saltation occurs, and the wind shear velocity is the square root of the wind shear stress divided by the air density. Classical saltation theory predicts that z_{50} increases strongly with shear velocity (Bagnold 1941; Owen 1964), which the numerical model also predicts when electric forces are not included (*black circles*). However, field measurements [*squares* Namikas (2003) and *triangles* Greeley et al. (1996)] show that z_{50} remains approximately constant with shear velocity. The inclusion of sand electrification in the numerical model (*red circles*) apparently resolves the discrepancy between theory and measurements

for the threshold shear velocity required to lift particles from the surface that includes the effect of electric forces,

$$u^*_{\text{thr}} = \sqrt{\frac{A_{\text{n}}}{\rho_{\text{air}}}\left(\rho_{\text{part}} g d + \frac{6\beta G}{\pi d} - \frac{8.22\varepsilon_0 E_{\text{surf}}}{c_{\text{s}}}\right)}, \tag{3}$$

where $A_{\text{n}} \approx 0.0123$ is a dimensionless parameter that scales the aerodynamic forces (Shao and Lu 2000), ρ_{air} and ρ_{part} are the densities of air and of soil particles, g denotes the gravitational acceleration, d is the average size of the surface grains, c_{s} is a dimensionless correction factor for the non-sphericity of soil particles, β scales the soil cohesive forces and lies in the range of 10^{-5} to 10^{-3} kg/s^2, G is a geometric parameter that depends on the bed stacking and is of order 1 (Shao and Lu 2000), ε_0 is the electric permittivity, E_{surf} is the surface E-field, and the shear velocity $u^* = \sqrt{\tau/\rho_{\text{air}}}$ is a measure of the wind shear stress τ. Kok and Renno (2008) use (3) to parameterize the effect of electric forces on particle lifting in their model of saltation and find that electric forces can substantially increase the concentration of saltating particles (see their Fig. 4). They also find that the lower near-surface wind speed (due to the reduction of the surface shear stress through (3) leads to a decrease in the velocity of the saltating particles. Thus the simulations of Kok and Renno predict that electrification leads to an increase in saltating particles impacting the soil, but that the saltating particles have smaller speeds than in the absence of electric forces. The effect of the combination of these two processes on the ejection of dust aerosols is unclear and needs to be investigated further.

In addition to aiding aerodynamic lifting, electric forces can also directly lift particles from the surface. Kok and Renno (2006) derived an expression for the threshold E-field necessary to lift sand particles by the action of electric forces alone,

$$E_{\text{thr}}(d) = \sqrt{c_s \left(\frac{\beta}{1.37\pi \varepsilon_0 d} + \frac{\rho_{\text{part}} d g}{8.22 \varepsilon_0} \right)}. \quad (4)$$

Kok and Renno (2006) found the E_{thr} for sand particles to be around 175–250 kV/m, which is at the upper range of the ground-level E-fields measured in saltation and dusty phenomena (see Sect. 2.1).

As summarized above, significant progress has been made in assessing and quantifying the effects of electrification on saltation and dust lifting on Earth. However, the importance of electric forces to saltation and dust lifting on Mars remains unclear, especially because E-fields on Mars are probably limited by the relatively low breakdown E-field of ∼25 kV/m (Melnik and Parrot 1998). Thus, electrification is probably not as important to Martian saltation as it is for terrestrial analogs, but the possible occurrence of electric discharges in Martian dusty phenomena could be highly significant. The unique thermodynamic conditions created by electric discharges could have significant effects on atmospheric chemistry (Miller 1953; Schumann and Huntrieser 2007). Experiments (Eden and Vonnegut 1973; Krauss et al. 2006) have clearly demonstrated the potential of electrified dust and sand to produce discharges in the thin Martian atmosphere. Simple numerical studies generally confirm these experimental results. Melnik and Parrot (1998) were the first to numerically investigate the generation of E-fields in Martian dust storms and predicted that electric discharges are readily produced, although their charge transfer model was probably not realistic (see above). More recently, Renno et al. (2004), Farrell et al. (2003, 2006a), and Zhai et al. (2006) developed simple models of the E-fields in terrestrial and Martian dust devils. These models also suggest the occurrence of electric discharges in Martian dusty phenomena.

In addition to electric discharges, increases in the atmospheric conductivity can also limit the bulk E-fields on Mars. A recent study by Delory et al. (2006) found that E-fields exceeding 5 kV/m accelerate free electrons to energies sufficiently large to ionize CO_2 and H_2O molecules. These additional ions lead to large increases in the air conductivity that can reduce the charge in sand and dust particles, thus also limiting the E-fields in Martian dusty phenomena. Moreover, the production of energetic electrons by E-fields (Delory et al. 2006) has potentially important effects on Martian atmospheric chemistry, as these energetic electrons can catalyze chemical reactions that would not otherwise occur.

2.4 An Example of the Effects of Electric Fields on Atmospheric Chemistry

The planetary science community was surprised that no trace of organics was found at the surface of Mars by the Viking Gas Chromatograph Mass Spectrometer (GCMS) experiments. This was a surprise because meteorites and space dust bring complex organics to the surface of Mars. Indeed, meteorites alone deliver approximately 300 $\text{g}\,\text{s}^{-1}$ of micrometeoritic dust to Mars (Flynn 1996), of which about 3% is organic material. More recently, the Mars Express Planetary Fourier Spectrometer (Formisano et al. 2004), and ground-based measurements (Krasnopolsky et al. 2004; Mumma et al. 2004) found trace amounts of methane in the martian atmosphere. These recent findings suggest the possibility of extant or extinct life on Mars. However, chemolithotrophic microbial colonies are only one of several possible sources of methane or more complex organic molecules (Atreya et al. 2007). Indeed, serpentinization at *low* temperatures and involving the hydration of ultramafic silicates could be just as effective in producing methane (Atreya et al. 2007).

An understanding of potential sinks of methane and other organics on Mars is important for constraining their sources. Oxidizers such as hydrogen peroxide can destroy organics at the surface (Oyama et al. 1977). Hydrogen peroxide (H_2O_2) is produced by photochemical processes (Atreya and Gu 1994; Nair et al. 1994), and it was recently detected on Mars (Encrenaz et al. 2003, 2004; Clancy et al. 2004). The abundance of H_2O_2 was observed to vary between 20 ppbv and 40 ppbv around the planet (Encrenaz et al. 2004), in agreement with predictions of photochemical models at the season of the observations. At the surface, the concentration of hydrogen peroxide is estimated to vary between 1 ppm (Zent and McKay 1994) and 250 ppm (Mancinelli 1989), on the basis of the reactivity of the surface measured by the Viking Gas Exchange experiment. A problem with these estimates is that this H_2O_2 abundance is too small to efficiently remove organics from the martian surface. Interestingly, laboratory studies also show that, even with 100–1000 times larger concentrations of H_2O_2 the surface would not be sterilizing (Mancinelli 1989). Therefore, a substantially larger concentration of hydrogen peroxide or others oxidants are necessary to explain the lack of detection of organics in the martian soil. Atreya et al. (2006) showed that electric fields in excess of 20 kV/m in dust storms can produce more than 100 times the amount of hydrogen peroxide produced by photochemical processes. Farrell et al. (2006b) show that the electric fields predicted in Martian dust storms can directly dissociate methane.

3 Other Dust Electrification Processes and Their Effect on Dust Lifting

3.1 Dust Lifting on the Moon

The Surveyor-6 and 7 Landers photographed bright glows along the western lunar horizon after sunset (Rennilson 1968; Criswell 1973). This horizon glow (HG) follows the contour of surface features such as rocks (Fig. 3). The HG usually persists for ~90 min after sunset (Gault et al. 1968a, 1968b). It is not polarized (Shoemaker et al. 1968) and extends vertically 3 to 30 cm above the surface, ruling out the idea that it is caused by secondary ejecta from the impact of micrometeorites (Criswell 1973). Moreover, the HG is not due to solar corona because it is much brighter and is parallel to the horizon, not elliptical like the corona. Since the Surveyor cameras are sensitive to light at wavelengths between 0.4 and 0.6 µm, scattering at these wavelengths must cause the HG.

The Lunar Ejecta And Meteorite (LEAM) Experiment was designed to measure the impact of micrometeorites and their hypervelocity ejecta (Berg et al. 1976). However, most

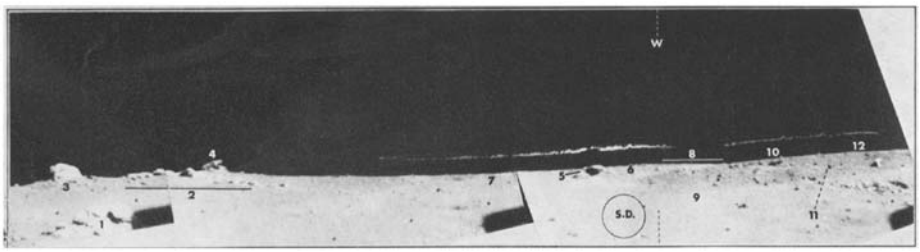

Fig. 3 Composite of morning and evening (about 1 hour after sunset) images of the western lunar horizon taken by the Surveyor-7 Lander. The horizon glow (HG) is probably the result of forward scattering by soil regolith particles of ~10 µm at concentrations of ~50 particles/cm^3 levitating between ~3 and 30 cm above the surface (Criswell 1973). After Rennilson and Criswell (1974)

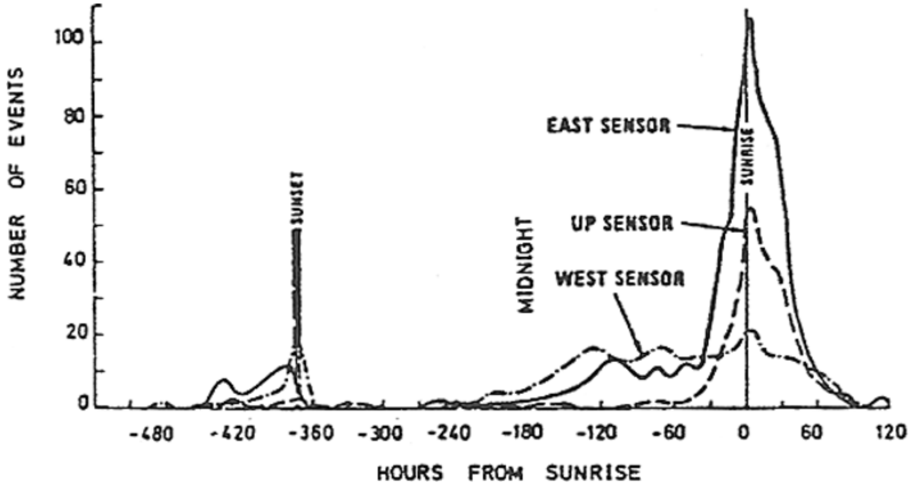

Fig. 4 Number of particle impacts (events) on the LEAM instrument sensors. Hypervelocity impacts from micrometeorites were rare, but impacts of particles with velocities of up to 1 km/s were detected. After Berg et al. (1976)

impacts detected were not from hypervelocity particles, and they occurred at the terminator as illustrated in Fig. 4. Stubbs et al. (2006) suggests that most of the impacts detected by the LEAM sensors were from particles lifted from the surface of the Moon by electrostatic forces. They hypothesized that electric fields eject highly charged particles from the surface. Then, the particles follow ballistic trajectories and return to the surface (Vondrak et al. 2005; Stubbs et al. 2006). The Lunohod-2 astro-photometer showed that the "twilight" lunar sky is 20 times brighter at visible wavelengths than expected from starlight alone (Severny et al. 1975). This suggests that dust particles levitating above the Moon's surface scatter solar light and make the sky brighter. The observation of crepuscular rays at the terminator by Apollo astronauts provides further evidence of dust lifting on the Moon (McCoy 1976). These lunar crepuscular rays are probably caused by the scattering of sunlight by small dust particles with diameters of $\sim$0.2 μm at altitudes ranging from 1 to 100 km (Berg et al. 1976).

Rennilson and Criswell (1974) estimates that the HG can be explained by forward scattering from particles with diameters of $\sim$10 μm levitating a few cm above the surface. Moreover, they estimate that the concentration of levitating particles necessary to explain the HG is 7 orders of magnitude larger than what is ejected by the impact of micrometeorites. Indeed, they suggest that electrostatic forces eject these particles from the surface and keep them levitating a few cm above the surface.

Both intense solar radiation and the solar wind turn the lunar surface into a complex plasma environment (Manka 1973; Stubbs et al. 2006; Farrell et al. 2007). Surface particles are charged by photoelectric emission, impingement of electrons and ions, and secondary ejection of electrons from the lunar regolith by the impact of energetic particles. Photoemission dominates the current budget on the dayside and charges the surface positively, leading to positive surface potentials of a few volts (Manka 1973; Freeman and Ibrahim 1975; Stubbs et al. 2006; Farrell et al. 2007). On the nightside, electron currents from the wake of the solar wind are much larger than ion currents and the surface charges negatively. Moreover, the plasma Debye length, a characteristic length-scale of the E-field, is much larger on the night side because of the increased electron temperature (Halekas et al. 2005;

Farrell et al. 2007). The resulting E-fields on the night side are of the order of a few V/m, similar to what is expected on the day side (Farrell et al. 2007).

At the terminator, where most lunar dust is lifted, the processes producing E-fields are more complex. Manka (1973) and Farrell et al. (2007) use a plasma model to study the surface potential at this region. They find that the lunar surface potential at the terminator is enhanced relative to the dayside, and is on the order of −50 volts. Measurements of the suprathermal ion detector experiment (SIDE) on the Apollo landers (Freeman and Ibrahim 1975) are consistent with these predictions. The plasma Debye length at the lunar terminator is also enhanced to ∼10 m (Manka 1973; Freeman and Ibrahim 1975; Stubbs et al. 2006; Farrell et al. 2007), such that the large-scale E-field at the terminator does not exceed about 10 V/m. It is unclear whether such small E-fields could actually lift dust particles from the surface. Sickafoose et al. (2002) and Farrell et al. (2007) show that the force on a spherical surface particle in a plasma environment is

$$F_{\mathrm{E}} = \frac{2\pi\varepsilon_0 d\phi^2}{\lambda}, \tag{5}$$

where ϕ is the surface potential, and λ is the Debye length. A simple balance of the electric force with the vertical gravitational, $F_{\mathrm{g}} = (\pi/6)\rho_{\mathrm{part}} g_{\mathrm{m}} d^3$, and cohesive force, $F_{\mathrm{c}} = \beta d$ (see Shao and Lu 2000) suggests that the electric potential necessary to lift dust particles from the lunar surface is

$$\phi_{\mathrm{lift}} = \sqrt{\lambda\left(\frac{\rho_{\mathrm{part}} d^2 g_{\mathrm{m}}}{12\varepsilon_0} + \frac{\beta}{2\pi\varepsilon_0}\right)}, \tag{6}$$

where g_{m} is the lunar gravitational acceleration. For terrestrial soil particles, $\beta \sim 10^{-4}$–10^{-3} kg/s^2 (Shao and Lu 2000; Kok and Renno 2006), while on the Moon β is probably much smaller because of the absence of moisture and therefore capillary forces (Merrison et al. 2007). Indeed, on the Moon β is expected to be smaller than on Mars, where it is in the range 10^{-5}–10^{-4} kg/s^2 (Merrison et al. 2007). If we conservatively assume that $\beta > 10^{-7}$ kg/s^2 on the lunar regolith, the second term in the square root of (6) dominates the balance of forces for the particles of diameter < 10 µm that are observed to levitate above the surface (Rennilson and Criswell 1974). Therefore,

$$\phi_{\mathrm{lift}} \approx \sqrt{\frac{\lambda\beta}{2\pi\varepsilon_0}}. \tag{7}$$

Thus, the threshold electric potential necessary to lift particles <10 µm from the surface depends primarily on the cohesion of the lunar regolith and the Debye length-scale of the lunar plasma. Notably, ϕ_{lift} for small particles does not depend on the gravitational acceleration, and therefore this approximation is general for celestial bodies surrounded by plasmas.

Although Stubbs et al. (2006) suggest that dust can be lifted by E-fields due to the large-scale lunar surface potential predicted by theoretical models (Manka 1973; Stubbs et al. 2006; Farrell et al. 2007) and the Apollo SIDE measurements (Freeman and Ibrahim 1975), they neglected the cohesive force, which is probably the dominant force on particles < 10 µm. Figure 5 shows the threshold electric potential necessary to lift particles from the surface of the Moon as a function of the parameter β that scales the cohesive forces. This threshold electric potential is significantly larger than the large-scale potential at the lunar terminator, even for very small values of β.

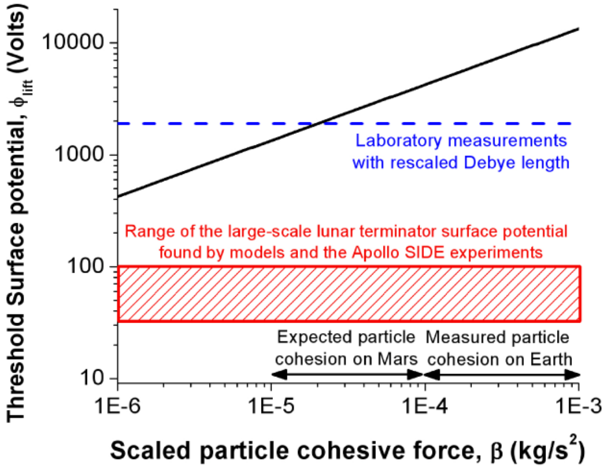

Fig. 5 Threshold electric surface potential required to lift micron and submicron dust from the lunar surface (*solid black line*) as a function of particle cohesive forces, using (7) with $\lambda = 10$ m (Manka 1973; Stubbs et al. 2006; Farrell et al. 2007). Included for comparison is the large-scale surface potential at the lunar terminator (*red rectangle*) found by models (Manka 1973; Stubbs et al. 2006; Farrell et al. 2007) and the Apollo SIDE experiment (Freeman and Ibrahim 1975). Laboratory experiments by Sickafoose et al. (2002) found that particles can be electrically lifted at negative potentials in excess of 30 volts, with a Debye length of ∼0.25 cm. The *blue dashed line* represents their measured value, rescaled for $\lambda = 10$ m using (7). Measured values of β for soils on Earth are in the range of 10^{-4}–10^{-3} kg/s^2 (Shao and Lu 2000; Kok and Renno 2006), while β is expected to lie in the range of 10^{-5}–10^{-4} kg/s^2 on Mars (Merrison et al. 2007)

An explanation for the observation of lunar dust lifting, despite both measurements and theory showing that the large-scale surface E-field is not strong enough to lift dust particles, is that surface heterogeneities on much smaller scales could enhance the local E-field to above the threshold required for dust lifting (Criswell 1973; Borisov and Mall 2006). A simple upper limit on the local enhancement of the lunar surface E-field was proposed by Criswell (1973). He assumed that the photoelectric effect removes electrons and increases the potential of the illuminated surface until the stopping voltage V_{stop} with respect to nearby surfaces is reached and the photoelectric current (I_p) vanishes. The stopping voltage is

$$V_{stop} = \frac{U_e}{e}, \tag{8}$$

where U_e is the kinetic energy and e the charge of the electron. When the energy of incoming light is large enough (UV or more energetic light such as soft X-rays) a few eV is spent to overcome the material work function and remove electrons from its surface. The remaining photon energy is used to increase the electrons' kinetic energy E_e. This kinetic energy, in turn, forces the free electrons to move against local potentials until the stopping potential value is reached. Since the work function (<10 eV) of materials is small compared to the energy of X-ray photons, we have that

$$V_{stop} \approx \frac{(500 - 1500)\ \text{eV}}{e} = (500 - 1500)\ \text{V}. \tag{9}$$

Therefore, neglecting leaking currents due to surrounding conducting plasmas, soft X-rays could generate small-scale potentials of up to 50–150 kV/m between shadows and illuminated areas of cm-scale surface protuberances. This is an upper bound to the E-fields that would occur in the absence of the conducting plasma generally found at the lunar surface.

More recently, Borisov and Mall (2006) showed that small-scale protuberances such as small craters can enhance the local potential at the lunar terminator. The slope associated with such craters makes it easier for solar wind electrons to penetrate the crater's wake than for solar wind protons, leading to a substantial increase in the negative surface potential.

The hypotheses of locally enhanced E-fields to explain the mystery of lunar dust levitation can be tested with measurements of E-fields near the surface of the Moon with a sensor that is both small enough to probe the small scale E-fields, and can distinguish the effects of charged particles impacting on it from that of the local space field (Renno et al. 2008).

3.2 Dust Lifting on Asteroids and Comets

The formation of regolith on asteroids is different from that on the Moon because of the large difference in gravity accelerations (Chapman et al. 2002). On asteroids, impact ejecta are usually spread uniformly over the entire surface, while on the Moon they are sorted by sizes and larger ejecta get confined to the areas around impact craters. In addition, asteroid regoliths appear to be deficient in dust and agglutinates when compared to the lunar regolith. Lee (1996) suggests that this happens because the smallest particles are preferentially lost when surface particles are levitated electrostatically. Moreover, Lee argues that levitated fine dust with diameters ranging from 0.01 to 1 μm may escape from asteroids, while larger particles with diameters of up to 100 μm migrate and get trapped in shadowed areas on craters and groves.

Low altitude images (up to 1 m per pixel) of asteroid Eros by the NEAR-Shoemaker spacecraft show that craters and groves are filled with fines (Veverka et al. 2001). High-resolution images (up to 6 mm per pixel) of the surface of asteroid Itokawa by the Hayabusa spacecraft show that it is covered with mm-size and larger particles (Fig. 6). Moreover, it shows that none of the smallest particles stay on top of boulders without being supported by other particles (Miyamoto et al. 2007). The high-resolution images also show craters with flat floors filled with fines. These findings suggest that the smallest particles migrate

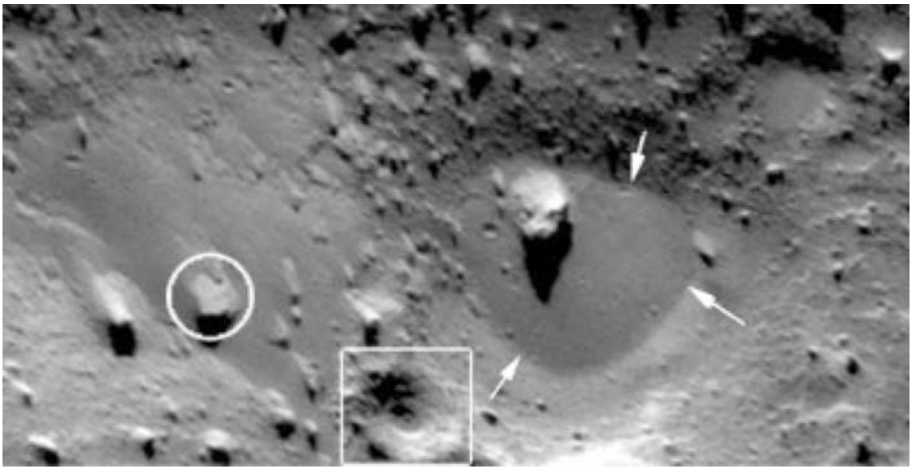

Fig. 6 Image of the surface of asteroid Eros showing evidence of dust particles moving downhill, filling craters and accumulating upslope of rocks

to gravitationally stable areas. Miyamoto et al. (2007) suggests that vibrations forced by impacts, tides and thermal fluctuations are responsible for these global migrations. However, electrostatic lifting of surface particles, similar to what is observed on the moon, could also explain the migration of dust to low terrains (Fig. 6).

4 Summary and Conclusions

We review theoretical and observational studies of electric fields in dusty phenomena, and their role in saltation and dust lifting on Earth, Mars, the Moon, and asteroids. Near-surface electric fields larger than 100 kV/m can occur in terrestrial dusty phenomena, and might play an important role in saltation and dust lifting. Electric forces reduce the threshold wind speed required to lift surface particles (Kok and Renno 2006), significantly affect saltation trajectories (Schmidt et al. 1998; Zheng et al. 2003) and their inclusion in numerical models improves agreement with measurements (Zheng et al. 2006; Kok and Renno 2008). On Mars, there is evidence that electric fields in dusty phenomena dissociate water vapor, catalyze the production of hydrogen peroxide, and dissociate methane (Delory et al. 2006; Atreya et al. 2006; Farrell et al. 2007). Moreover, electric fields in saltation and dusty phenomena on Mars might produce electric discharges (Melnik and Parrot 1998).

Finally, there is evidence dust particles of diameters $< 10\ \mu$m are lifted from the surface of the Moon by electrostatic forces, and perhaps also from the surface of asteroids. However, large-scale surface potentials predicted by plasma models (Manka 1973; Farrell et al. 2007) and confirmed by measurements (Freeman and Ibrahim 1975) are not large enough to lift dust particles from the lunar surface, but locally enhanced surface potentials might become large enough to lift dust particles (Criswell 1973; Borisov and Mall 2006). This hypothesis can be tested with measurements of small-scale electric fields at the lunar surface or from low orbit with "picosatellite sensors."

Acknowledgements We thank the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) for partially funding this research under award numbers NASA/06-PIDDP06-0111 and NSF/ATM 0622539. In addition we thank the organizers of the workshop on "Planetary Atmospheric Electricity" and our hosts at the International Space Science Institute in Bern Switzerland for the wonderful experience. Finally, we thank Earle Williams and two anonymous reviewers for helpful comments that improved the original manuscript.

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