

Contact charging of lunar and Martian dust simulants

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[1] Dusty regolith particles accumulate charge through grain-grain contact and contact with various surfaces. These processes affect vertical and horizontal transport and may cause electrical discharges in dust storms. We report the results of a simple experimental setup used to investigate the contact charging properties of two planetary analog dust samples: lunar (JSC-1) and Martian (JSC-Mars-1) regolith simulants. In these experiments, dust particles are brought into contact with various surfaces of known work functions (metals: Co, Ni, Au, Pt, and silica glass), and the resulting contact charges on the dust particles are measured. The surfaces are in the form of a thin disc mounted horizontally in a vacuum chamber. Agitation causes the dust grains to drop through a small hole into a Faraday cup, where their charge is measured. The charge on a ~ 100 micron dust grain is typically more than 10^5 elementary charges and varies linearly with dust size. The measured contact charge of a dust particle increases with repeated agitation of the surface. The average contact charge also varies linearly with the work function of the contacting surface. The contact charging with oxidized metal surfaces is found to be independent of the metal's work function. The effective work functions of the planetary analogs are determined by extrapolation to be 5.8 eV and 5.6 eV for the lunar and Martian dust simulants, respectively. **INDEX TERMS:** 3914 Mineral Physics: Electrical properties; 3947 Mineral Physics: Surfaces and interfaces; 5470 Planetology: Solid Surface Planets: Surface materials and properties; 6225 Planetology: Solar System Objects: Mars; 6250 Planetology: Solar System Objects: Moon (1221); **KEYWORDS:** Dust, contact charging, lunar dust, Martian dust, work function

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1. Introduction

[2] Dust particles in space, often embedded in plasmas and exposed to UV radiation, can become electrostatically charged. The motion of charged particles is influenced or even dominated by the presence of electric and magnetic fields, resulting in complex dust dynamics and transport [Goertz, 1989; Mendis and Rosenberg, 1994; Horányi, 1996]. Similarly, particles on planetary surfaces can become charged due to exposure to plasma and UV radiation or just by contacts with other dust particles [Cross, 1987; Harper, 1967]. While there have been several experiments to support theories of dust charging in a plasma and/or UV radiation [e.g., Sickafoose et al., 2000, 2001; Walch et al., 1995], our theoretical or experimental understanding of the processes leading to electrification due to contacts is very limited.

[3] Electrification due to dust-dust collisions has been observed in terrestrial dust storms [Stow, 1969; Karma, 1972]. Contact electrification is thought to be responsible, in part, for large cohesive/adhesive forces between dust grains in the lunar soil, and possibly leading to electrical

discharges during dust storms on Mars [Melnik and Parrot, 1998]. The intermittent, radially expanding dust clouds in Saturn's rings, called 'spokes', suggest the sudden release of fine dust grains from much bigger boulders in the rings. The tendency of the small particles to settle on big boulders is best explained to be due to electrostatic interaction. This 'bond' can be broken due to micrometeoroid impact generated plasmas and the dust grains entrained in the magnetic field may lead to the formation of the spokes [Goertz and Morfill, 1983; Goertz, 1989]. In addition, the recent NEAR observations of the asteroid Eros revealed dust filled craters. In Eros's weak gravitational field, charged dust lifted off the surface by impacts or electrostatic levitation may be transported preferentially into some regions by electrostatic forces. This process was observed as a horizon glow due to levitated dust particles on the Moon [Veverka et al., 2001; Rennilson and Criswell, 1974].

[4] We have developed a simple experimental method to investigate dust charging on surfaces [Sternovsky et al., 2001]. The induced charging in an electric field and contact charging processes were studied for both metallic and insulating dust grains irregular in shape. The charge on the grains was measured as they fell from the surface into a Faraday cup. The contact charge on dust was found to be a

linear function of the work function of the metal surfaces. By contacting a given dust sample with metals of different work functions, the effective work function of the sample was estimated. A separate dust charging experiment [Sickafoose *et al.*, 2001] detected a large amount of triboelectric charge on planetary regolith analogs JSC-1 (lunar regolith simulant) and JSC-Mars-1 (Martian regolith simulant). In the present paper, we show results using the same experimental method as *Sternovsky et al.* [2001] to further analyze the properties of the planetary regolith analogs. Our results show that contact charging can take place in planetary regoliths, making any dust particles lifted off the surface candidates for electrostatic transport. Contact charging is not reduced on the dark side of planetary bodies as is UV charging and charging by the solar wind.

2. Contact Charging

[5] When two materials are brought into contact, charge transfer can occur between them. After the contact is broken, a nonzero charge may remain on each species. This phenomenon is called the contact charging. Since a number of review articles on this topic exist in the literature [Lowell and Rose-Innes, 1980; Cross, 1987; Lee, 1994] only a short overview of the problem is presented here.

[6] Contact charging is usually treated on the basis of band theory and the establishment of a thermodynamic equilibrium between the contacting materials. Electrons from the material with a lower work function, ϕ_1 , are transferred to the one with a larger work function, ϕ_2 , until the corresponding energy levels are equalized. This model is satisfactory for metal-metal contacts only. For these, the amount of transferred charge is, $Q = CV_C$, i.e. the product of the contact potential $V_C = (\phi_1 - \phi_2)/e$ and the capacitance of the system C , where e is the elementary charge. During separation, however, electron tunneling removes most of the transferred charge. Thus C is assumed to be the capacitance of the species separated by a critical distance (on the order of nm) at which tunneling stops [Lowell and Rose-Innes, 1980]. This effective capacitance also depends on the size, shape, geometrical arrangement, and the surface properties of the contacting objects [Lowell, 1975].

[7] The residual contact charge after separation is considerably greater when at least one of the contacting materials is an insulator. This is because of the reduced backflow tunneling current. The observed surface charge densities for different insulators are usually in the $\sigma \sim 10^{-5} - 10^{-3} \text{ C/m}^2$ range [Lowell and Rose-Innes, 1980]. For the contact charging of insulators there is no unified theory. Many authors interpret insulator contact charging in the light of localized energy levels inside the forbidden energy gap of the insulator. These levels exist due to impurities, defects, or the presence of the surface and can be filled up to a certain energy level. This energy level is customarily assigned as the “effective” work function of the insulator. The insulator then charges positively when in contact with materials of larger work function and vice versa. Triboelectric series of insulators have been constructed according to their effective work functions [Lowell and Rose-Innes, 1980; Cross, 1987]. In metal-insulator contacts the residual charge is often a linear function of the metal work function [Lowell and Rose-Innes, 1980; Lee, 1994]. Also it is

Table 1. Polycrystalline Work Functions of Different Metals Used in the Experiments

Metal	Work Function ϕ [eV]
Zr ^a	4.05
V ^a	4.3
Stainless steel ^b	4.4
W ^a	4.55
Co ^{a,c}	5.0
Ni ^{a,c,d}	5.20
Au ^{a,c,d}	5.38
Pt ^{a,c}	5.64

^aLide [2001].

^bFeuerbacher and Fitton [1972].

^cMetal resistive to oxidation on air.

^dThe average of work functions for orientations (100), (110), and (111).

commonly observed that the contact charge accumulates as contacts are repeated. This phenomenon is poorly understood and can be caused by increased contact area [Lowell and Rose-Innes, 1980] as well as increased charge penetration into the insulator [Labadz and Lowell, 1991; Brennan *et al.*, 1992]. Single versus multiple contact charging is an important issue, because some attempts at calculating charge transfer assumes thermodynamic equilibrium, which is unlikely to be achieved in a single contact [Lowell and Rose-Innes, 1980; Lee, 1994].

[8] In the contact charging process the properties of the surfaces are important. The surfaces of several metals used in the present experiments rapidly oxidize in air (see Table 1). Harper [1967] describes a model for the changes in contact potential when a metal surface is oxidized. This model assumes the presence of an adsorbed layer of oxygen atoms on the outside of the oxide layer. Since the acceptor levels of oxygen atoms are close to 5.5 eV, which is below the work function of most of the metals, electrons from the metal occupy these acceptors. The transferred electrons bring the oxygen acceptor level into a thermodynamic equilibrium with the metal. Consequently, the oxidized metal behaves like a metal with a work function equal to the depth of the oxygen acceptor level (~ 5.5 eV) rather than with its own work function. Harper’s [1967] model was found adequate in our previous investigation of dust charging on surfaces [Sternovsky *et al.*, 2001]. Contact charging between dust samples and various metal and glass surfaces can lead to surprisingly large charges that can be easily observed in our experimental setup.

3. Experimental Technique

[9] The experimental apparatus (Figure 1) used in this work was identical to that used in the previous investigations and its detailed description is given by *Sternovsky et al.* [2001]. Briefly, the apparatus consisted of a simple dust dropper and a Faraday cup for measuring charge. The dropper was a grounded thin metal or glass disc mounted horizontally inside a vacuum chamber. The disc was mechanically agitated by magnetic pulses acting on a pair of small permanent magnets attached to the disc. The magnetic pulses were generated by a discharge of a capacitor through a tiny magnetic coil.

[10] The dust sample was loaded onto the horizontal disc and spread uniformly over the surface. Only a small amount of dust was used in order to keep the inter-grain

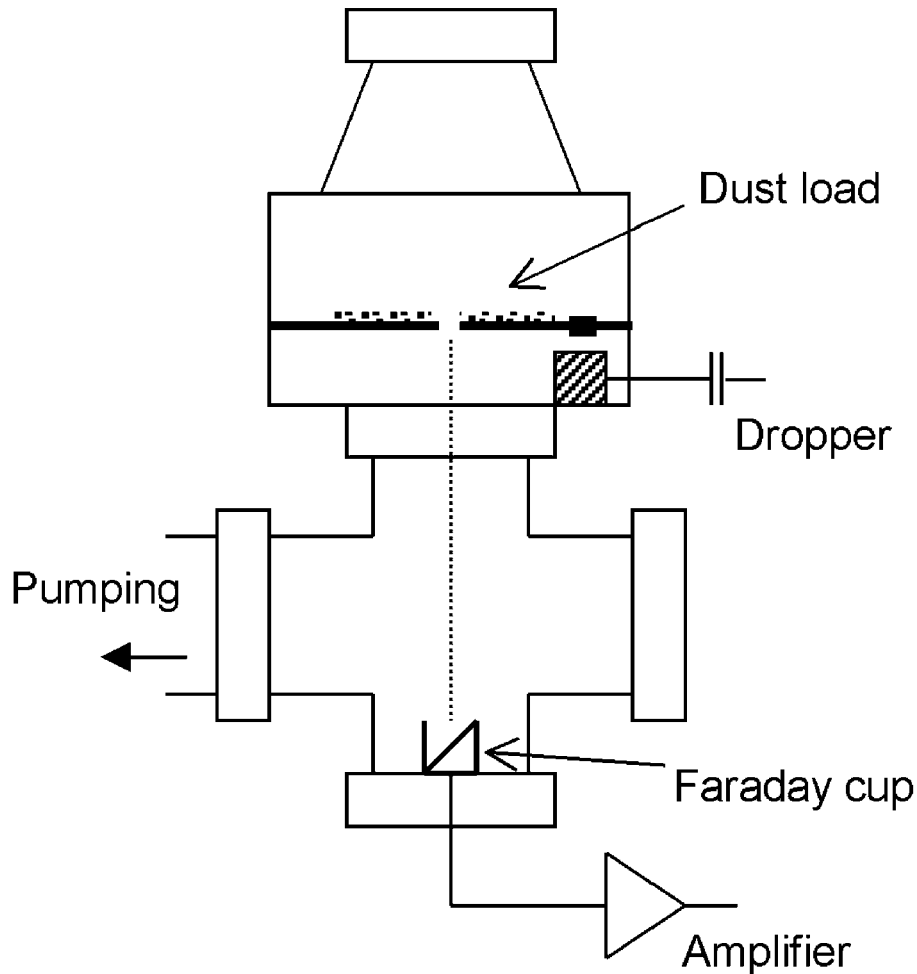


Figure 1. The schematic diagram of the experiment.

distances larger than the grain size. Thus the grains charged through contact with the dropper disc rather than through contact with one another. Due to the repeated mechanical agitation, the dust particles migrated on the surface and dropped through a central hole (with diameter ~ 1 mm) in the disc. The rate of dust migration and dropping increased with the amplitude of the agitation, which was set by the initial charge on the capacitor. The capacitor voltage was set to drop dust particles less frequently than one on every pulse. This resulted in drops primarily of single dust grains.

[11] The dust particles fallen from the surface were collected into a Faraday cup. The Faraday cup was connected to a sensitive electrometer that generated output voltage pulses upon charged dust particle impacts [Walch *et al.*, 1994]. Multiple dust drops were recognized according to their more complicated pulse shapes and were not considered further. The dust charge was calculated from the pulse height and the calibration constant of the electrometer. The output noise level of the electrometer was equivalent to about $10^4 e$ and dust charges larger than $2 \times 10^4 e$ could be clearly recognized. The experiment was automated by a computer data card: the pulse to the dust

dropper triggered the data acquisition and a simple routine found the peak maximum in the recorded data set afterward.

[12] Experiments were performed with two regolith dust samples: JSC-1 and JSC-Mars-1 regolith simulants. These samples imitate the chemical composition, mineralogy, density, and other properties of the lunar mare soil and the oxidized soil of Mars, respectively. The lunar regolith simulant is a basaltic ash with the composition of many terrestrial types of basalt. It is composed primarily of SiO_2 (47.7%), Al_2O_3 (15.0%), and CaO (10.4%) [McKay *et al.*, 1994]. The primary constituents of JSC-Mars-1 are SiO_2 (43.5%), Al_2O_3 (23.3%), and Fe_2O_3 (15.8%). Calcium feldspar and minor magnetite dominate the x-ray diffraction spectra of bulk JSC-Mars-1 [Allen *et al.*, 1998]. By using standard sieves the dust samples were sorted into intervals of size in diameter from $d_{min} - d_{max}$: 38–45, 45–53, 53–63, 63–75, 75–90, 90–106, 106–125, and 125–150 microns. Photomicrographs of the dust samples are shown in Figure 2. The particles are irregular in shape and have rough surfaces. The discs on which the particles rest were made of Zr, V, W, Co, Ni, Pt, and stainless steel, in the form of high purity thin foils with thickness in the range 0.02 to 0.2 mm. Additionally, two gold-plated discs and a glass disc were used. The

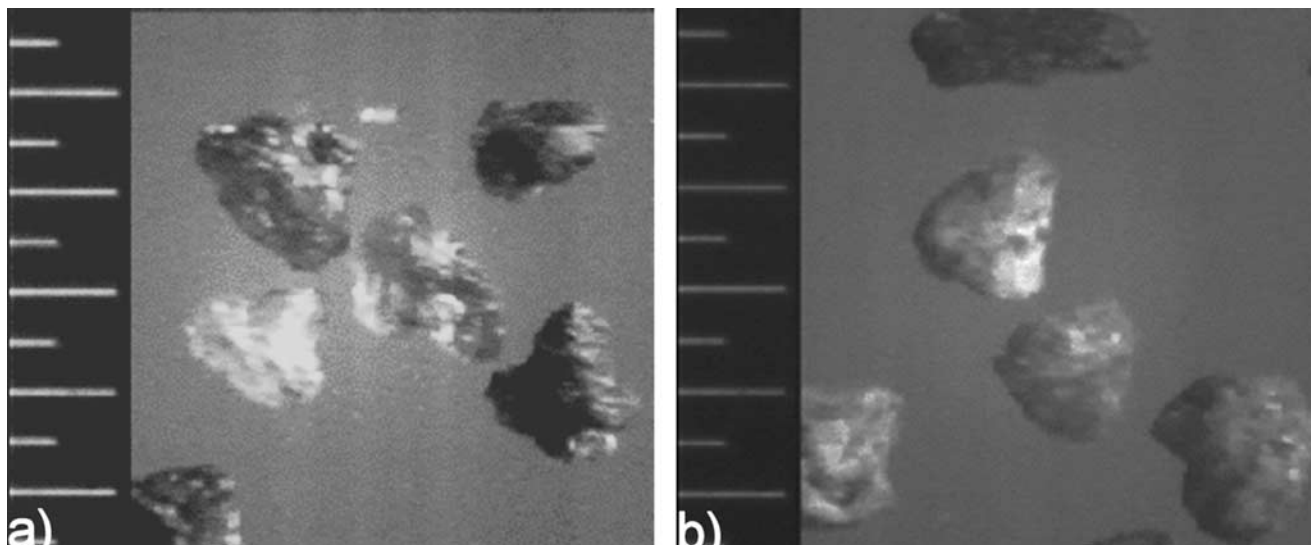


Figure 2. Microphotographs of 90–106 μm dust samples: (a) JSC-1 lunar dust simulant, and (b) JSC-Mars-1 Martian dust simulant. The displayed scale is 100 μm per large division

gold was deposited on stainless steel by the electrolytic method and with magnetron sputtering, respectively. Table 1 shows the known work functions of the metals. The surfaces of the metal discs are smooth relative to the dust. Before installation into vacuum, the discs were cleaned in organic solvents, diluted phosphoric acid, and distilled water in succession.

[13] The experiments were made in high vacuum conditions, at pressures below 1×10^{-6} Torr, in order to eliminate the unwanted effects of the ambient atmosphere. A 150 l/s turbomolecular and a rotary vane pump maintained the vacuum. This vacuum is not sufficient for atomic purity of the surfaces that were most likely covered by a monolayer of adsorbates from the residual atmosphere. The measurements, however, didn't seem to be affected by the adsorbates most likely due to the tunneling character of the contact charging process.

[14] In order to keep the measurements consistent and comparable to each other, the experiments were performed as follows. Approximately the same amount of dust was loaded onto the metal surface and distributed over the same surface area around the central hole in the disc. The strength of the dust dropper was carefully adjusted to have one dust graindrop on average for every 4–5 agitations. The goal was to achieve successive 120–150 dust drops out of 600 agitations with even distribution over the course of the measurement.

4. Experimental Results and Discussion

[15] An example of experimental data following the procedure described above is shown in Figure 3. It shows the charge measured on particles of the lunar dust simulant (JSC-1) from the 125–150 μm size range charged from a Ni surface. From this plot it is apparent that the contact charge on the dust increased during the course of the experiment, i.e. a dust particle dropped later in the queue had, on average, larger charge than one dropped earlier. This behavior was typical for all the dust samples used and was similar

to earlier observations made for nonconductor silica and alumina dust particles [Sternovsky *et al.*, 2001]. The charge increase is due to the repeated contact of the dust particles with the surface upon migration. The saturation of dust charging was not observed with the small amount of dust used in the experiments. As the displayed example in Figure 3 shows, there were dust particles charged up to 10^6 e. This is a considerable charge for a dust particle within the 125–150 μm size range. Assuming spherical shape, isolated dust, and homogeneous surface charge distribution this charge is equivalent to about -20 V of surface potential [e.g., Horányi, 1996]. Similarly, Sickafoose *et al.* [2001] also observed strong charging of the regolith analogs by triboelectrification. Most probably, however, the charge on the dust is localized to the spot of the contact and thus the local potential differences can be considerably larger. The local surface charge density, σ , determines the electric field intensity above the charged spot, $E = \sigma/\epsilon_0(\epsilon_r + 1)$, where ϵ_0 , ϵ_r are the permittivity of free space and the relative dielectric constant of the material, respectively [Harper, 1967]. The intensity E is on the order of 10^5 – 10^6 V/m depending on the size of the charged spot. Due to the irregular shape of the dust, separated charged areas on the dust surface may exist.

[16] The charging of the two dust samples (JSC-1, JSC-Mars-1), both within the 125–150 μm diameter size range, has been investigated on different metal plates. Measurements similar to that in Figure 3 were made for these dusts and the average dust charge calculated over the whole queue of data. The arithmetic mean charge and its standard deviation out of six individual measurements were calculated on each metal surface with renewed dust loads. Figure 4 shows the obtained results from contacts with different metals. Both dust samples behaved similarly. The dust charge after contact with oxidizing surfaces (Zr, V, W, and stainless steel) showed little variation with the work function of these metals. The JSC-1 charged negatively on all of the oxidized metals. The JSC-Mars-1 charged negatively on Zr, W, and stainless steel, but positively on V. These observations

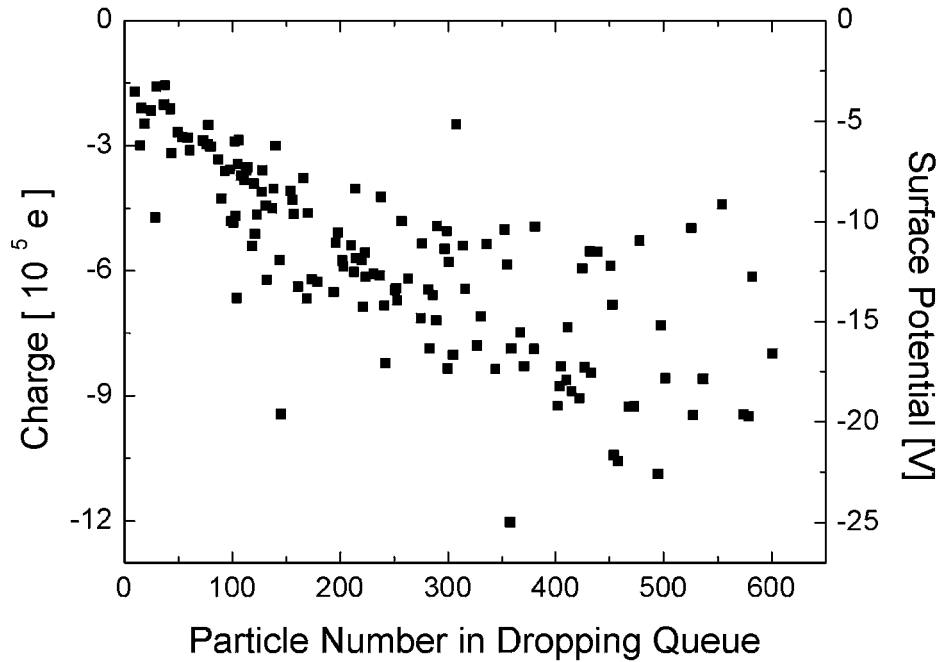


Figure 3. The evolution of the charge on JSC-1 lunar dust simulant particles after falling from a Ni surface in a queue. The particles were 125–150 μm in diameter. The right axis shows the equivalent dust surface potential assuming spherical shape.

suggested the work function of both samples to be larger than that of oxidized metals.

[17] From non-oxidizing metal surfaces (Co, Ni, Au, and Pt) the average charge was found to vary linearly with the work function of these metals. However, the charging of the JSC-Mars-1 on Au is an exception to this rule. This enhanced charging on Au is difficult to explain. Most probably, however, it is related to the nature of the dust sample rather than the Au surface. Au surfaces prepared by different methods charged the dust samples similarly, and thus we have a good reason to believe that both surfaces exhibited the work function of pure Au. The slope of the linear regression for both samples was $9.5 \times 10^5 \text{ e/V}$. By extrapolating the linear regression of the data for JSC-1 the effective work function of the dust can be obtained: 5.8 eV. Another set of measurements with smaller dust size range, 75–90 μm , gave essentially the same result (see Figure 4a). In case of JSC-Mars-1, the dust particles charged both negatively and positively on Pt. The occurrence of both polarities is ascribable to diversities in the chemical composition, shape, or surface properties of individual dust particles. Since both polarity charges occurred with the same magnitude and frequency, the resulting mean dust charge was close to zero. Hence it was concluded that the effective work function of JSC-Mars-1 is close to the work function of Pt, i.e. 5.6 eV. It is also interesting to note that the average dust charge from oxidized surfaces (horizontal dotted lines in Figure 4) fits the line of linear regression at 5.6 and 5.5 eV (vertical dotted line) for JSC-1 and JSC-Mars-1, respectively. This confirmed Harper's [1964] model on the effective work function of oxidized surfaces to be about 5.5 eV and only slightly dependent on the work function on the metal.

[18] The contact charge as a function of dust size was also investigated. Eight subsequent size ranges of JSC-Mars-1 spanning from 42 to 138 μm in mean diameter, $d_{\text{mean}} = (d_{\text{min}} + d_{\text{max}})/2$, have been studied as they charged from a Co surface. Figure 5 shows the results where a linear dependence on the dust size is observable. However, this range is too small to rule out other dependencies. Adhesion induced deformation theories [Rimai *et al.*, 1995] suggest the contact area between a dust particle and a planar surface to be proportional to the 4/3 power of the dust radius. However, this effect could not be verified in our experiments.

[19] There were also experiments performed on contact charging from a glass surface. Glass, a nonconductor, represented a more realistic situation for dust charging on the surfaces of large planetary objects. The magnitudes of the measured contact charges were comparable to those observed for metal surfaces for the same dust size range (125–150 μm), i.e. on the order of several times $10^5 e$. The dust charge was observed to increase during the course of the experiment due to multiple contacts, similar to results in Figure 3. Both the JSC-1 and JSC-Mars-1 charged negatively on glass. For comparison, the charging of alumina and silica dust particles from glass has also been studied. These dust samples were investigated in a previous work [Sternovsky *et al.*, 2001], where their effective work functions had been determined: 5.25 eV and 5.5 eV for Al_2O_3 and SiO_2 , respectively. Figure 6 shows the overall results on dust charging from a glass surface for dust particles within the 125–150 μm size range. These four individual dust samples are represented on the x axis by their effective work function determined as described above. The mean charge clearly shows a dependence on the work function of the dust samples. The silica dust charged negatively on glass, but with a considerably lower rate than

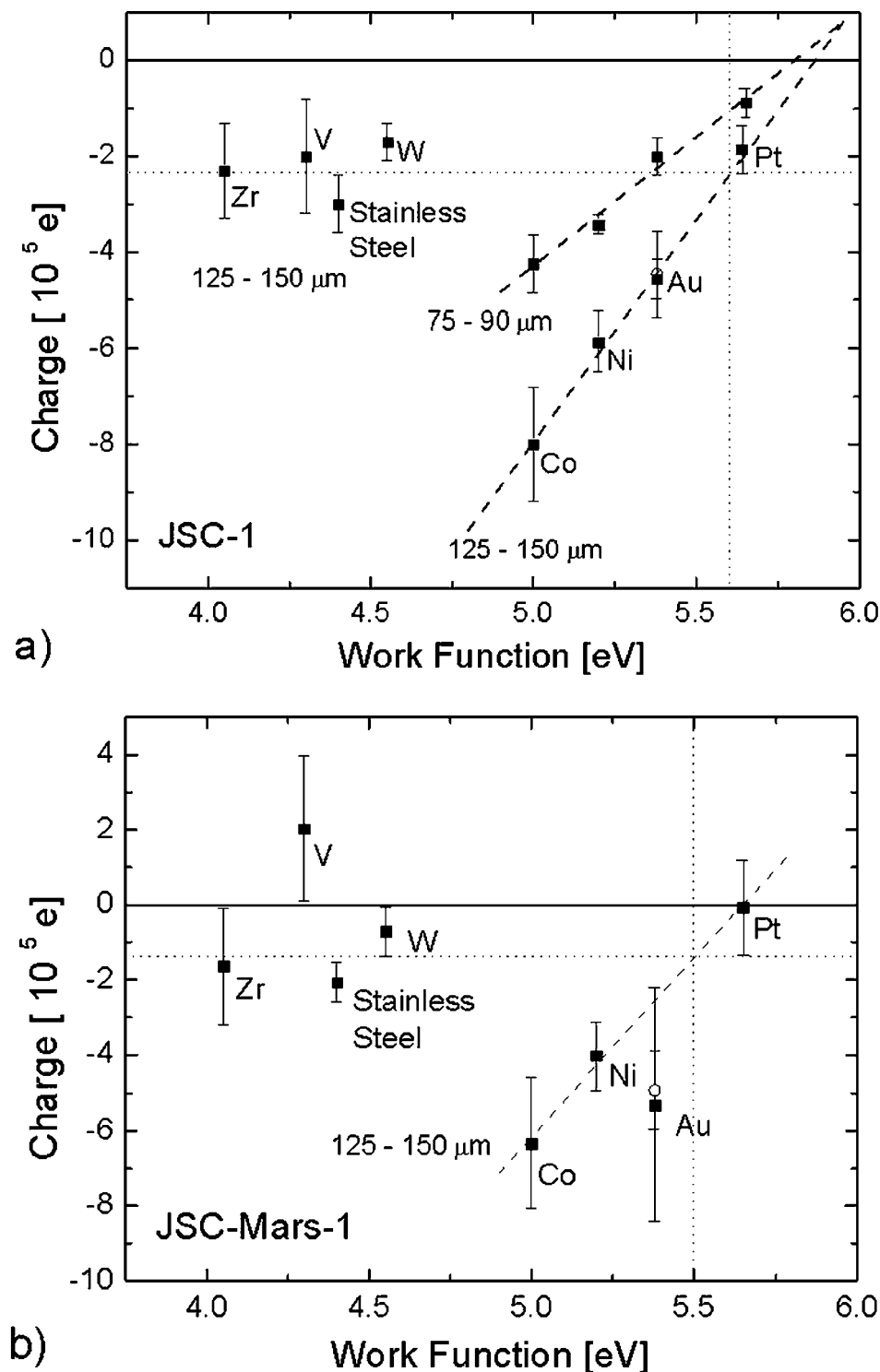


Figure 4. The charging of the two dust simulants (a) JSC-1 and (b) JSC-Mars-1 from different metals. The dust sizes were from the ranges 75–90 and 125–150 μm , respectively. The points represent the average dust charge from six individual measurements with the standard deviations indicated. The dashed lines are the linear regressions calculated for the non-oxidizing surfaces Co, Ni, Au, and Pt. For the JSC-Mars-1 the data point on Au is left out from the linear regression. The horizontal dotted lines represent the average dust charge from oxidized surfaces except V. The vertical dotted lines indicate the effective work function of oxidized metals. The hollow circles represent the charge measured on Au surfaces deposited by a magnetron.

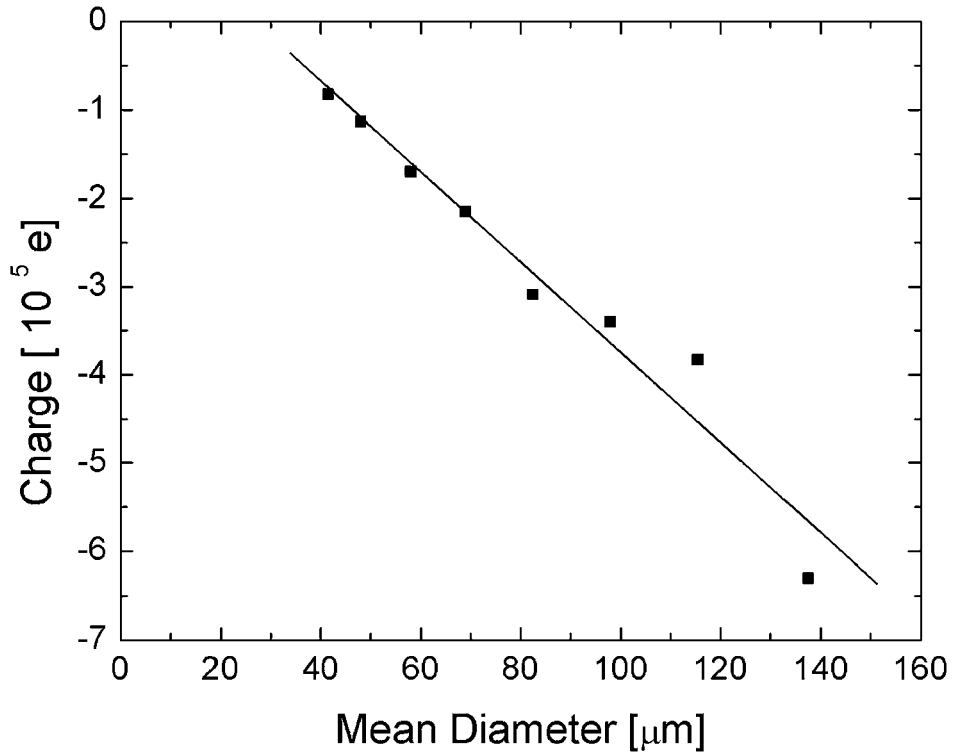


Figure 5. The charge on JSC-Mars-1 from a contact with a Co surface for different dust sizes.

the two planetary analog samples. This low charging rate could also be due to the fact that silica and glass are similar in composition. Alumina, the dust sample with the lowest effective work function, charged positively from glass. The

mean dust charge exhibited approximately a linear dependence on the work function with a slope of about 10^6 e/V, which is close to that observed for planetary regolith simulants charging from metal surfaces.

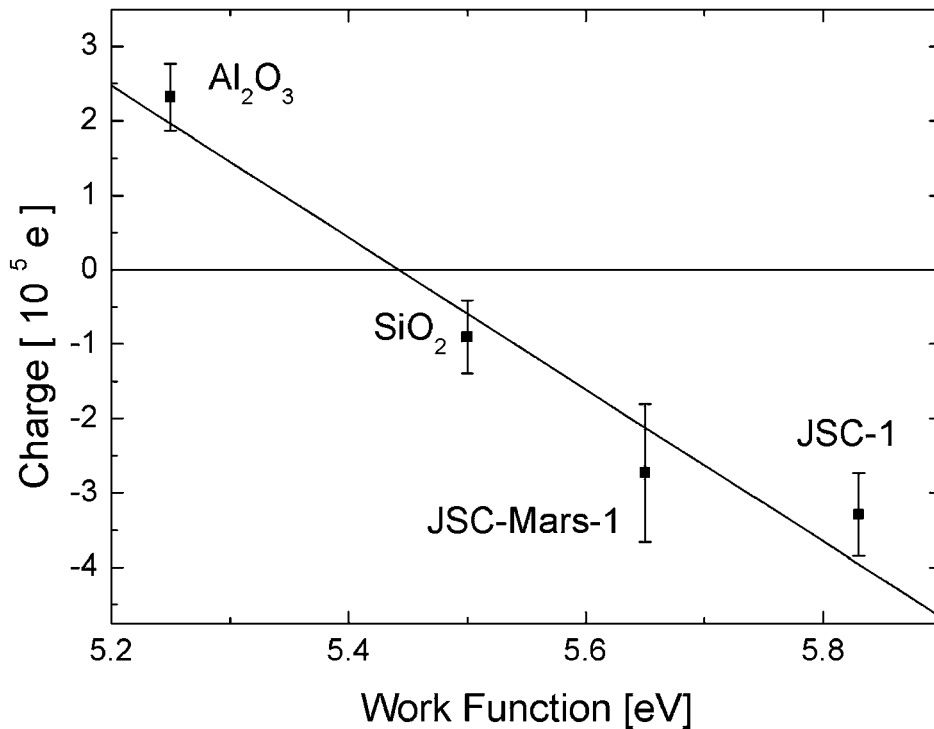


Figure 6. Contact charge from a glass surface on different dust compositions (alumina, silica, JSC-1 and JSC-Mars-1). The dust samples were from a 125–150 μm size range.

5. Summary

[20] The contact charging properties of two regolith analog samples (JSC-1 and JSC-Mars-1) have been investigated. The experiments demonstrated that both can become highly charged from a contact with either an insulating or conducting surface. The dust charge from contacts thus can be comparable or even exceed the charge a dust particle collects in a typical low temperature space plasma environment where the equilibrium charge is on the order of the electron temperature, T_e , which is typically few eV [Horányi, 1996].

[21] The acquired dust charge depends on the work functions of the surface and the contacting species, on the size of the dust and also on the degree of dust migration upon the surface. Based on these investigations of the charging properties of the JSC-1 and JSC-Mars-1 it is possible to predict both the polarity and the magnitude of the expected dust charge. Materials with an effective work function lower than 5.8 eV (5.6 eV) will charge the JSC-1 (JSC-Mars-1) negatively and vice versa. However, one needs to keep in mind the diversity of the individual dust grains and expect variations as our results show. On planetary objects dust particles charge from a surface with a similar composition and electrical properties as the dust itself. Due to compositional diversities, however, extended dust charging can be expected with both polarities, as observed by Sickafoose et al. [2001]. Oxidized metal surfaces can be considered to have about 5.5 eV effective work function. The longer the dust may migrate on the surface, the larger the contact charging effect. When single bouncing contacts of dust from surfaces are considered, the resulting dust charge may depend on additional conditions, e.g. the angle or speed of the impact [Matsuyama and Yamamoto, 1995].

[22] The observed contact charging properties of lunar and Martian dust particle simulants will help the design of future planetary surface experiments, possibly leading to the use of surface coatings of sensitive electronics or optical components. The large contact charges described here for planetary regolith analogs JSC-1 and JSC-Mars-1 suggest that grains lifted off airless planetary surfaces will carry a significant charge, regardless of ambient plasma conditions. The ambient magnetospheric or solar wind plasma can create a plasma sheath near the surface with strong electric fields, and photoelectrons produced by solar ultraviolet radiation can lead to a photoelectron sheath, also producing a strong local electric field [e.g., Sickafoose et al., 2001]. Once levitated in these low gravity environments (electrostatically or by an external disturbance, such as an impact), the charged grains may be transported by strong local electric fields leading to redistribution of dust on asteroidal surfaces and within planetary rings.

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