Detection of spark discharges in an agitated Mars dust simulant isolated from foreign surfaces

Joshua Méndez Harper\textsuperscript{a}, Josef Dufek\textsuperscript{a}, George D McDonald\textsuperscript{b}

\textsuperscript{a}Department of Earth Science, University of Oregon, Eugene OR, 97403, USA
\textsuperscript{b}Department of Earth and Planetary Sciences, Rutgers, The State University of New Jersey, Piscataway NJ, 08854, USA

Abstract

Numerous laboratory experiments, starting in the Viking Lander era, have reported that frictional interactions between Martian analog dust grains can catalyze electrostatic processes (i.e. triboelectrification). Such findings have been cited to suggest that Martian dust devils and dust storms may sustain lightning storms, glow discharges, and other complex electrostatic phenomena. However, in many cases (if not most), these experiments allowed Martian dust simulant grains to contact foreign surfaces (for instance, the wall of an environmental chamber or other chemically dissimilar particles). A number of authors have noted that such interactions could produce charging that is not representative of processes occurring near the surface of Mars. More recently, experiments that have identified and corrected for collisions between dust simulants and chemically dissimilar laboratory materials have either failed to replicate near-surface Martian conditions or directly measure discharging. In this work, we experimentally characterize the triboelectrification of a Martian dust simulant resulting from both isolated particle-particle collisions and particle-wall collisions under a simulated Martian environment. For the first time, we report the direct detection of spark discharges under Martian surface conditions in a flow composed solely of natural basalt and isolated from man-made surfaces. The charge densities acquired by the fluidized grains are found to be of order $10^{-6}$ Cm$^{-2}$ (in excess of the theoretical maximum charge density for the near-surface Martian environment). Additionally, we demonstrate that the interaction of simulant particles with experimental walls can modulate the polarity of spark discharges. Our work supports the idea that small-scale spark discharges may indeed be present in Martian granular flows and may be qualitatively similar to small-scale
1. Introduction

Triboelectric charging—that is, electrification through frictional and collisional interactions—is extremely common in granular flows, both natural (Aplin et al., 2012; Gu et al., 2013; Méndez Harper and Dufek, 2016; Méndez Harper et al., 2017, 2018b) and man-made (Lowell and Truscott, 1986a; Lacks and Levandovsky, 2007; Apodaca et al., 2010; Lacks and Sankaran, 2011). The effects of tribocharging can be subtle, like the aggregation of fine volcanic ash high in Earth’s atmosphere (James et al., 2002; Telling and Dufek, 2012; Telling et al., 2013), or explosively dramatic—the lightning storms that accompany volcanic eruptions are perhaps the best examples (Thomas et al., 2007; Bennett et al., 2010; Arason et al., 2011; Behnke et al., 2013; Nicora et al., 2013; Aizawa et al., 2016; Cimarelli et al., 2016; Behnke et al., 2018; Méndez Harper et al., 2018a; Hargie et al., 2018). Given their ubiquity on Earth, triboelectric processes likely operate in other planetary environments with large dust and sand reservoirs, such as Mars and Titan (Krauss et al., 2003; Aplin et al., 2012; Forward et al., 2009b; Aplin et al., 2012; Helling et al., 2013; Méndez Harper et al., 2017, 2018b).

Theoretical, numerical, and experimental analyses suggest that the low-pressure (4.0 to 8.7 mbar), CO₂ atmosphere at the Martian surface breaks down under smaller electrical stresses than the near-surface terrestrial atmosphere (Helling et al., 2013; Kok and Renno, 2009; Wurm et al., 2019; Riousset et al., 2020). Indeed, spark discharges could occur at electric fields on the order of a few tens of kV m⁻¹ on Mars. Such fields are much smaller than those required to produce breakdown in Earth’s near-surface atmosphere of 3 MV m⁻¹. The theoretical Martian breakdown fields are also smaller than those that have been measured in terrestrial dust storms (100 kV m⁻¹; Stow, 1917; Crozier, 1964; Farrell et al., 2004). The interest in characterizing tribocharging of Martian materials stems from the hypothesis that, like on Earth, triboelectric charging on Mars may have the capacity to modulate a wide range of phenomena. Such processes could include enhanced dust lofting (Farrell et al., 2004; Zhai et al., 2006; Kok and Renno, 2009) the aggregation of charged grains (Krinsley and Leach, 1981; Merrison et al., 2004), the photochemical destruction and production of species with implications...
Figure 1: The setup used in this work to assess frictional electrification of a Martian dust simulant. The system consists of a glass environmental chamber capable of approximating near-surface Martian conditions. Particles in the chamber were charged by fluidizing a bed of basaltic material for periods of 20 minutes. Any discharges in the flow were detected by a fast antenna. We also used this setup to characterize the charging resulting from the interaction of particles with a plastic wall. A) Simulant grains undergo only particle-particle interactions. B) Simulant grains interact with an acrylic cylinder as well as with each other.
Figure 2: Fountain dynamics. a) High speed photograph showing fountain illuminated by a sheet laser. b) Velocity distribution in the fountain as measured through particle image velocimetry over 50 frames.

for the presence of organics and methane (Atreya et al., 2006a, Farrell et al., 2006b, Tennakone, 2016), and electrical discharges (Melnik and Parrot, 1998, Krauss et al., 2003, Wurm et al., 2019).

In the context of the Martian environment, putative near-surface triboelectricity has been hypothetically discussed since the observation of silts, clays, and aeolian bedforms by the Viking landers (Greeley, 1979). The subsequent discovery of dust devils by the Viking orbiters (Thomas and Gierasch, 1985) has led to speculation that, as on Earth, dust devils and large scale storms generate electrically charged grains (Stow, 1917, Crozier, 1964, Farrell et al., 2004). Indirect evidence for triboelectric charging on the Martian surface has continued to be reported, as well as revisited, over the years. The Wheel Abrasion Experiment (WAE) as part of the Mars Pathfinder mission’s Soujourner rover reported photographic evidence for the adhesion of dust to the rover’s wheels in Mars Year (MY) 23. The dust
was observed to have adhered preferentially to the aluminum and platinum components of the WAE based on reflectance measurements. An electrostatic origin for this adhesion was suggested but could not be verified since Sojourner did not have the capability to measure on-board electrical charge (Ferguson et al., 1999).

Despite tangential evidence, no dedicated electrostatic measurements have been performed in-situ on the Martian surface for verification of this phenomenon. However, a diverse set of experiments conducted across the last 40 years have successfully produced both glow and spark discharges in laboratory-scale flows of Martian dust simulants. Eden and Vonnegut (1973) investigated the triboelectric charging of silicates under an approximated Martian atmosphere by agitating sand in a glass flask. These investigators found that the motion of grains produced both small spark and glow discharges observable in a dark room. More recently, Krauss et al. (2003) performed experiments using the JSC-Mars-1 simulant (weathered basaltic volcanic ash from Mauna Kea) in a polycarbonate chamber. Glow discharges were recorded when the simulant was mobilized by a motorized stirrer. These authors also characterized the triboelectrification of mixtures of basaltic material and glass microspheres falling through a hopper. Mazumder et al. (2004) electrified JSC-Mars-1 simulant in a plastic vial and measured the charge on individual grains using laser Doppler velocimetry.

The insights provided by the laboratory studies summarized above are invaluable. Nevertheless, the direct applicability of the results to in-situ electrification on Mars is hindered by the fact that analog materials were allowed to contact surfaces that would not be expected on the Martian surface (the plastic or glass containers encasing the dust simulant or spherical glass beads). Collisions with container walls or the vanes of a stirrer can contribute significantly to the overall electrification through two principal mechanisms.

Firstly, the interaction of two dissimilar materials (for instance, a JSC-Mars-1 grain ricocheting off a polycarbonate wall or a glass microsphere) can produce more intense charge separation than the interaction between two chemically-identical materials (e.g. two colliding JSC-Mars-1 grains). Such an effect has been described empirically and compiled into a so-called triboelectric series by countless authors (e.g. Shaw (1917)). Thus, even if particle-particle collisions are more frequent than particle-wall collisions in an experiment, the particle-wall interactions may drive the overall electrification of the granular media (Matsusaka et al., 2010).

Secondly, the segregation and accumulation of charge can be much more
Figure 3: Schematic of the process used to estimate the charge density on particles in the flow. A Faraday particle trap (FPT) was suspended over the fountain in the vacuum chamber. After concluding the fluidization period (20 min), the inlet pressure was increased, launching particles into the narrow aperture in the bottom of the FPT. The internal sensing element (marked in blue) was small enough to detect the passage of individual grains with diameters down to 100 microns. Once traversed the sensing volume, particles are deflected into a discard bin by an inclined plane. This was done to prevent measured particles (which may have contacted the internal surfaces of the FPT) from becoming re-entrained into the fountain. The outside of the FPT was coated with grains of the same composition to minimize dissimilar material charging between the fountain and the FPT’s copper walls.
efficient during the interaction of surfaces with large discrepancies in size (consider micron-sized particles rubbing against the comparatively large inner surface of a flask) when compared to those produced by binary particle-particle collisions. Dozens of experiments have shown that the larger of the interacting surfaces tend to acquire positive charges while smaller surfaces concentrate negative charge. Thus, in the experiments described above, even if the container and the grains had been the exact same chemical composition, the container would have gained a positive charge relative to the small agitated particles (e.g. Lowell and Rose-Innes (1980); Lowell and Truscott (1986a); Lacks and Sankaran (2011)). Such size-dependent triboelectric charging may have set up coherent electric fields within experimental apparatuses, readily permitting the low-pressure CO₂ to reach breakdown conditions.

Together, the chemical and geometrical disparities between interacting grains and chamber walls could have produced the previously reported triboelectric effects in agitated Martian dust simulants. This has been verified for one of the aforementioned experiments by Aplin et al. (2012), who demonstrated that the results presented in Krauss et al. (2003) can be explained entirely by interactions between particles and the experimental apparatus. We note that understanding how Martian materials charge when interacting with man-made materials does provide useful insights given the numerous upcoming missions to Mars. However, because the electrification observed in many previous studies arose from experimental artifacts, the results of those works cannot be directly applied to understanding charging in natural Martian systems. Aplin et al. (2012) conclude their paper by encouraging the community to develop experiments that isolate Martian simulants from foreign objects to better understand endemic tribocharging.

Recently, the effects of walls were minimized, if not eliminated, in the charging experiments of JSC-Mars-1 by Forward et al. (2009b). These authors used a spouted bed to assess grain charging resulting from particle-particle collisions only. However, those experiments did not approximate the near-surface Martian environment (Forward et al. (2009b) used a nitrogen environment at 90 mbar), nor did the authors explore the viability of electrical discharges in the spouted bed. More recently, Wurm et al. (2019) performed careful experiments in a vibrated bed to assess the electrical properties of a simulated Martian environment. To minimize the effects of dissimilar material charging, the authors coated the walls of their setup with particles of the same composition and size. Wurm et al. (2019) found that particles ac-
quired charge densities of at least 7-11 µC m⁻². However, those authors used monodisperse samples with relatively large particles (1-2 mm) which provide limited insight into the charging dynamics of material mobilized by aeolian action.

Here, we investigate triboelectric processes under simulated Martian environments, with an experimental setup that eliminates boundary condition effects and allows for verification that particles are not only charging, but also actively discharging during fluidization. We conduct experiments in an 8 mbar CO₂ atmosphere using a Martian dust simulant similar to the Mojave Mars Simulant (Peters et al., 2008). Our experimental apparatus design allows us to characterize the electrification of micron-sized particles in isolated granular flows. We employ a set of sensors that allow us to both detect spark discharges in the flow, as well as directly measure the charge density on individual grains. Additionally, we conduct experiments in which particles are allowed to contact the walls to highlight the differences in charging behavior as compared to an isolated flow (which best mimics granular flows in natural settings). Our measurements suggest that the near surface Martian environment may support small-scale spark discharges resulting from the electrification due solely to particle-particle collisions. Our work also demonstrates that the configuration of the experimental setup is of critical importance when attempting to assess triboelectric processes in planetary environments.

2. Methods

2.1. Martian atmosphere simulator and fluidized bed apparatus

Electrification of a Martian dust simulant through frictional interactions was achieved using a fluidized bed apparatus comparable to that described in Forward et al. (2009b) and Méndez Harper and Dufek (2016). The device consists of a vertical glass tube (diameter ~ 10 cm) capped off at each end by an aluminum plate. This arrangement forms a pressure/vacuum chamber in which the environment can be finely tuned. Figures 1a and b show the system schematically. Approximately 100 g of a Martian dust simulant (described further on) was inserted into the chamber through a hatch in the top plate. The sample was then sprayed with an ExAir charge neutralizing air gun and allowed to sit for 24 hours at ambient conditions to permit any initial charge to dissipate. After this period of respite, the chamber was evacuated to 1-3 mbar and then purged by refilling the chamber with CO₂ gas to a
Figure 4: Typical output waveform from the integrator for the fast antenna (FA) setup experiment involving particle-particle collisions only (the setup in Figure 1b). Sharp transients are discharges in the flow.

pressure of 1 bar. Subsequently, the pressure in the chamber was brought down to 8 mbar, close to the average near-surface Martian pressure (4.0 to 8.7 mbar). A closed-loop control program running on an Arduino development board maintained a stable pressure in the chamber. All experiments were conducted at 25° C.

To fluidize the bed of particles, a jet of CO₂ was forced through a 500 micron hole milled in the bottom end cap. By filming the fountain at high speed and processing the frames with a particle image velocimetry, we estimate that the particles had maximum velocities of 0.6 m/s—of the same order as the 2 – 7 m/s surface wind speeds measured by the Viking landers [Hess et al., 1977]. The resultant particle fountain had elevations of 4 cm above the bed surface (see Figure 2). The inner diameter of the glass tube
was large enough that particles did not contact the walls during fountaining. Thus, unlike most previously published experiments, triboelectric charging in this setup stems overwhelmingly from the interaction of chemically-identical surfaces (see Figure 1a). However, to demonstrate the spurious effect of experimental setup on the triboelectrification of the simulant, we also fluidized the sample in the presence of a foreign object. We placed a hollow acrylic cylinder (diameter 3.8 cm, length 2 cm) concentrically around the jet aperture. Here, particles interacted with each other and a plastic surface which may have produced spurious electrification (Figure 1b).

2.2. Measurement electronics

We employed two measurement devices to characterize the electrification in the fluidized bed: 1) A fast antenna (FA) capable of detecting spark discharges and 2) a miniature Faraday particle trap (FPT) to measure the charge on individual particles sampled from the flow. We note that the instruments were used in separate experiments.

The FA consists of a copper ring antenna running along the outside of the glass chamber. The ring is connected to an integrator circuit built around an LMC6001 precision operation amplifier. To make the system insensitive to the movement of charged particles in the fountain (which itself represents a current), we configured the time constant of the circuit to be on the order of 1 ms. Thus, only fast current transients are passed through to the output of the circuit. Similar designs are used to study atmospheric lightning. The output of the integrator is monitored for a period 20 minutes after the start of fluidization. We used the FA to characterize the discharge behavior in both the isolated fountain and the fountain with wall contacts (i.e. the experiments with the plastic insert). The FA is rendered schematically in Figure 1.

We employ the FPT to measure the charge density (with units of C m$^{-2}$) on individual particles in the fluidized particle bed. For these measurements, we replaced the FA and suspended a miniaturized inverted Faraday cup from the top end cap of the pressure chamber (See Figure 3). Here, we only characterized the charge density on particles in an isolated fountain. The granular sample was fluidized for twenty minutes at a constant inlet pressure. After this period, the inlet pressure was marginally increased for a period of 5 minutes, flinging particles near the dilute top of the fountain into the 5 mm-wide aperture of the FPT. This measurement process is capable of measuring the charge on individual particles and is similar to that reported in Watanabe.
Figure 5:  a) Time series of discharges as measured by the FA in an isolated fountain composed of our Xictli Mars dust simulant. Note the generally bipolar discharge behavior. b) Expanded section from a) to show that negative discharges are more frequent, but neutralize smaller amounts of charge than the large, less frequent positive discharges.
et al. (2006); Méndez Harper and Dufek (2016) and Méndez Harper et al. (2017). In contrast to the setup involving the FA, some particle-wall collisions do occur with the FPT setup. However we are able to minimize the effects of dissimilar charging while performing these measurements, by invoking two strategies: 1) we coated the exterior surface of the FPT with particles of the same size so that rebounding particles do not contact the copper body of the FPT; and 2) the internal geometry of the FPT is designed to trap particles once charge on them has been measured. Specifically, the top interior wall of the FPT is inclined so that over 80% of the particles that enter the sensing element are removed, and do not reflect back into the fountain (as quantified through high speed video). The precautions are depicted schematically in Figure 3. The sensing element of the FPT is connected to a charge sensitive preamplifier (built around an LMC6082 operational amplifier) which outputs a voltage proportional to the charge passing through the sensing element with a resolution of 1 pC/V. The fundamental principles of our FPT are based on the design described extensively in Watanabe et al. (2006).

2.3. Martian dust simulant

As a Martian dust simulant, we use crushed olivine basalt from the ≈300 AD eruption of the Xictli (Hispanicized as Xitle) volcano (Chichinauhtzin Volcanic Field, Distrito Federal, México) (Delgado et al., 1998). The sample corresponds to Flow 5 and was sourced from an outcrop near parking lot 4 of the Cultural Center of the National Autonomous University of Mexico (19°18′44.7″N, 99°11′02.2″W). In terms of composition, Xictli basalt is similar to the Mojave Mars Simulant (Peters et al., 2008; see Table 1).

For the experiments using the FA, the Xictli ash was sieved, washed, and dried to obtain a size distribution mimicking that of the JSC-Mars-1 simulant commonly used in other experiments (see Allen et al. (1998) and Table 2). For the FPT experiments, we used two samples: one with particles with nominal diameters between 150-250 µm and another with particles in the range of 250-500 µm. We did not employ the full polydisperse simulant described in Table 1 because 1) we found we could not determine whether or not grains smaller than ∼100 µm were being effectively trapped by the sensor; 2) the sheer number of small particles traversing the sensor prevented us from assessing the charge on individual grains and; 3) narrow size distributions reduced the uncertainty involved in estimating charge density.
Table 1: Chemical composition comparison between Mars dust simulants. Concentrations are in wt%. The values in parentheses denote the differences in composition of our Xictli sample from the most commonly used simulants. See Allen et al. (1998); Delgado et al. (1998) and Peters et al. (2008) for more details.

| Oxide   | JSC-Mars-1 | MM1  | MGS-1 | Xictli, Flow 5 |
|---------|------------|------|-------|----------------|
| SiO$_2$ | 43.5 (-7.3) | 47.9 (-2.9) | 41.4 (-9.4) | 50.8           |
| Al$_2$O$_3$ | 23.3 (7.4) | 16.7 (0.8) | 11.2 (-4.7) | 15.9           |
| TiO$_2$ | 3.62 (1.82) | 1.09 (-0.71) | 0.2 (-1.6) | 1.8            |
| FeO$_2$ & Fe$_2$O$_3$ | 15.3 (6.0) | 10.6 (1.3) | 13.3 (4.0) | 9.3            |
| MnO     | 0.26 (0.1)  | 0.17 (0.01) | 0.1 (-0.06) | 0.16           |
| CaO     | 6.2 (-2.7)  | 10.45 (1.55) | 2.2 (-6.7) | 8.9            |
| MgO     | 4.2 (-4.5)  | 6.08 (-2.62) | 14.8 (6.1) | 8.7            |
| K$_2$O  | 0.7 (-0.32) | 0.48 (-0.54) | 2.3 (1.28) | 1.02           |
| Na$_2$O | 2.34 (-0.99)| 3.28 (-0.05) | 4.3 (0.97) | 3.33           |
| P$_2$O$_5$ | 0.78 (0.3) | 0.17 (-0.31) | 0.3 (-0.18) | 0.48           |

Table 2: Particle size distribution of the crushed Xictli ash used in the experiments with the fast antenna based on the particle size distribution of JSC-Mars-1 (Allen et al., 1998). Boxed distributions were used in experiments with the FPT.

| Grain size (µm) | Wt% |
|-----------------|-----|
| 500-1000        | 21.4|
| 250-500         | 29.5|
| 150-250         | 20.8|
| 90-150          | 12.9|
| 45-90           | 9.2 |
| 20-45           | 5.4 |
| <20             | 1.3 |
3. Results and Discussion

3.1. Discharges in the flow and the effect of experimental setup

While we did not optically detect discharges (either glow or spark), our fast antenna detected spark discharges in all experiments—i.e. discharges occurred in both the experiments involving isolated particle fountains and those with particle-wall contacts. Discharges produce step-wise potential changes in the fountain environment and these are amplified by the fast antenna circuitry. Because of the small preamplifier time-constant, the voltage in the circuit’s feedback network rapidly decays back to zero. Thus, discharges manifest as sharp pulses at the output of the antenna’s circuit. Four discharge signals are exemplified in Figure 4.

Figure 6: Typical output waveform from the FA circuit in the experiment involving collisions of the particles with an acrylic cylinder wall (the setup in Figure 1b). Note the overwhelmingly monopolar discharge behavior.
Discharge events began within a few minutes of the start of fluidization. The magnitude of the signals increased with time and eventually saturated the integrator circuit (the voltage pulses were clipped at the integrator’s voltage rails). In experiments with isolated fountains (in which charging resulted from particle-particle collisions only), we observe events that neutralize both negative and positive charge. Neutralization of negative charge produces a positive change in potential, whereas neutralization of positive charge leads to a negative potential change.

A 20 minute recording of the fast antenna’s output for a typical isolated fountain experiment is rendered in Figure 5a. Note the overall bipolarity of the discharges. Interestingly, however, negative discharges (that is, discharges resulting in positive potential changes) are more frequent than positive discharges, but have overall smaller magnitudes (see Figure 5b, which shows an expanded section of Figure 5a). This behavior may have to do with how charge carriers (potentially electrons) are partitioned among particles in a polydisperse flow. As mentioned previously, numerous authors have reported that negative charge becomes preferentially concentrated on the smaller particles in a granular material (including JSC-Mars-1; see Forward et al. (2009b)). Larger particles are left with positive charges. Because of their relatively inextensive surface areas, smaller particles are able to sustain comparatively smaller amounts of net charge than large particles before the weak Martian atmosphere breaks down (Wurm et al., 2019). We posit that the asymmetry in magnitudes between positive and negative discharges are underpinned by these geometrical considerations.

Discharges occurred at maximum rates of 0.1-1 Hz, lower than those reported by Krauss et al. (2003). Possibly, the lower discharge rates and the absence of optical signatures in our experiments result from the smaller gas velocities (a maximum of 0.6 m/s) as compared to other experiments, the dilute nature of the fountain, and the absence of contacts with chemically dissimilar surfaces. These three parameters control the rate of charge transfer by modulating the particles’ collision rates as well as allowing for chemically dissimilar tribocharging. Thus, flows in which particles collide often with each other and foreign surfaces charge faster than those in flows with low collision rates and only chemically identical interactions. Presumably, faster charging rates also imply more frequent discharges as the breakdown limit (discussed below) is reached quicker. Future experiments should explore the effect of gas speed on the triboelectrification of isolated Martian dust simulants.
As mentioned in the Methods section, we conducted a second set of spouted bed experiment in which we allowed our simulant to contact a foreign object, specifically an acrylic cylinder. The voltage trace rendered in Figure 6 exemplifies the discharge behavior in these experiments. In contrast to the bipolar discharging observed in the free-fountaining experiments, discharges in the experiments with the plastic insert were overwhelmingly negative (i.e. they produced positive voltage changes). This finding is unsurprising given the documented charging behaviors when two or more dissimilar materials are brought into contact (see Matsusaka et al. (2010) and Lacks and Sankaran (2011) for comprehensive reviews). When the fountain is isolated, charge exchange occurs exclusively between constituent grains. Thus, while the charge on any individual grain may be very large, either positive or negative, the net charge of the fountain is zero. Conversely, when the flow is exposed to a boundary of different composition, there is a preferred direction of charge flow determined by the surface work functions of the ash and plastic. In other words, negative charge tends to collect on one of the surfaces, leaving the other with a net positive charge. The direction of charge flow (i.e. which substance will be positive or negative) during frictional or contact interactions has been summarized empirically in the triboelectric series (Shaw, 1917). Silicates tend to be at the top of the series, whereas hydrocarbon-based materials dominate the lower portion. Thus, in the experiments involving the plastic insert, ash particles likely charge positively, whereas the acrylic cylinder accumulates negative charge. The difference in charge accumulation between experiments with and without the plastic insert is presented conceptually in Figure 7b and a. The effective segregation of charge in experiments with the plastic insert likely accounts for the monopolar discharge behavior shown in Figure 6. Interestingly, the discharge rate did not change significantly as compared to the isolated fountain experiments (in contrast with the polarity). This finding may suggest that ash-plastic contacts here involve similar rates of charge exchange as that in particle-particle contacts.

To close this section, we would like to highlight two main findings: 1) As far as we are aware, this is the first work to report spark discharges in an agitated bed of Mars dust simulant particles isolated from both wall contacts and interactions with particles of dissimilar compositions. Our work, thus, lends credence to the idea that small scale discharges are plausible in the near-surface Martian dust and sand systems. 2) As in Aplin et al. (2012), our experiments demonstrate that boundary effects can have profound impacts on
Figure 7: Conceptual representation of charge partitioning in a) an isolated particle fountain and b) a flow of particles in which grains are allowed to contact a foreign wall. When the flow is isolated, particles exchange charge only with each other (i.e. some particles become positive while others concentrate negative charge). Conversely, when the flow is allowed to interact with a plastic wall, the direction of charge flow is dominated by relative differences in the materials’ work functions. In the present case, silicates tend to charge positively whereas plastics charge negatively. This difference in charge accumulation likely underpins the differences in discharge behavior we observe in our spouted bed experiments (See Figures 5 and 6).

the charging and discharge behaviors of Mars dust simulants. Specifically, our experiments show that a bipolar discharge behavior in an isolated fountain readily switches to an overwhelmingly monopolar one when a passive acrylic wall is introduced in the system. Together, our findings stress that future investigations of Mars dust charging should take appropriate precautions to minimize contacts with foreign objects.

3.2. Charge density on particles

The second set of experiments involve the Faraday particle trap (FPT), allowing us to directly estimate the charge density on individual grains in the flow. As mentioned in the methods section, we only assessed the charge on flows composed of particles with diameters of 150-250 µm and 250-500 µm. The time series rendered in Figure 8 shows the output voltage of the
Figure 8: Voltage trace exemplifying the output of the charge amplifier circuit connected to the FPT. Each pulse represents the passage of a single particle through the sensing volume of the circuit. Symmetric pulses are representative of particles that traversed the sensing volume without impacting the interior wall of the FPT. Overlapping pulses are representative of more than one particle passing through the sensing volume at a time. We discard asymmetric pulses and overlapping pulses from our dataset.
charge amplifier. Each peak is representative of a single particle entering the FPT. Asymmetric peaks indicate situations in which particles may have contacted the interior walls of the sensing element (thus, the charge entering the FPT is different than the exiting charge). Overlapping peaks result from the passage of more than a single particle through the sensor at a time. We exclude these peaks (indicated in Figure 8) from further analysis. Overall, we analyzed the charge on \( \sim 100 \) particles for each distribution. We note that while the FPT can measure charges as small as 1 fC, electromagnetic noise from our vacuum pump prevented us from reliably detecting charges smaller than 0.01 pC.

The ability of a material to charge is often assessed by computing its surface charge density \( \sigma \) (that is, the charge divided by a particle’s surface area). The distributions of charge densities for the two granulometries are shown in Figure 9. In order to compare two size distributions, the charge densities here were calculated using the mean, spherical-equivalent particle diameter of each sample (200 \( \mu \)m for the 150-250 \( \mu \)m sample and 375 \( \mu \)m for the 250-500 \( \mu \)m sample). Under these assumptions, both size distributions gained maximum charge densities on the order of \( 10^{-6} \) Cm\(^{-2}\). Numerous authors have noted that charging is enhanced in flows with broad particle size distributions (e.g. Duff and Lacks (2008); Forward et al. (2009a)). Because our FPT setup restricted us to using narrow size distributions in the experiments where we measure charge density, the values we obtained for \( \sigma \) may underestimate the range of charge densities in our full Martian dust simulant (which has particles smaller than 10 microns and as large as several millimeters). As discussed above, in an isolated flow, particles only exchange charge with each other. Thus, some grains gain net positive charge whereas others gain negative charge. This conservation of charge is reflected by the fact that the distributions are essentially Gaussian with zero means (See Figure 9). The troughs near the middle of the distributions (i.e. where the charge was very small) are artifacts of the high noise floor in our experiments. They do not represent true features of the distributions.

3.3. Implications for Martian atmospheric electricity

Electrical discharges have not been incontrovertibly detected on Mars. Lacking field data, most work has focused on determining i) a viable electrification mechanism capable of charging Martian materials, ii) establishing criteria for the breakdown of the Martian atmosphere, and iii) gaining insight from terrestrial dust systems. Given the lack of precipitation on Mars, any
Figure 9: Charge density distributions for particles of two nominal distributions a) 150-250 microns and b) 250-500 microns. Note that the troughs near zero are artifacts of a high noise floor.
electrical activity would likely be underpinned by electrification mechanisms other than those believed to operate within conventional thunderstorms (i.e., those involving ice and graupel; Keith et al. (1990); Saunders et al. (1991)). Tribocharging has been proposed repeatedly as a viable electrification mechanism on Mars given its generally accepted roles in terrestrial dust flows (It is interesting to note, however, that while numerous authors report large electric fields associated with terrestrial dust systems, only a handful describe electrical discharges—the most prominent among these is Kamra (1972). This dearth in reporting may stem from the more stringent breakdown criteria associated with the near-surface terrestrial atmosphere).

Yet, even if triboelectric processes can statically charge aeolian materials, some work has cast doubt as to whether frictional interactions are efficient enough to cause atmospheric breakdown on Mars. For instance, Kok and Renno (2009) have suggested that locally generated plasma in dust storms may increase the conductivity of the gas, therefore "short-circuiting" the electric field set up by charged particles. This quenching could prevent electric fields from rising above the breakdown threshold, complicating the production of arc discharges. Farrell et al. (2015) has countered by showing that the current densities associated with pre-spark Townsend discharge (electron avalanche) are generally smaller than the triboelectric charging currents. Although the "short-circuiting" currents may become comparable to the charging currents when the electric fields in the dust storm become large, they appear to be incapable of shutting off the discharge completely. Quite recently, Riousset et al. (2020) coupled a Boltzmann solver with standard Global Reference Atmospheric Models to estimate the breakdown conditions at every altitude for realistic gas mixtures on Mars. These authors find that the low pressure Martian atmosphere does indeed favor discharges.

Our experiments allow us to address some of these open questions. While electrification processes other than tribocharging could operate in global dust storms and dust devils, the presence of discharges in our fluidized bed experiment supports the hypothesis that triboelectrification alone may meet the criteria for the production of small spark discharges under Martian conditions. Furthermore, the charge densities we compute by directly measuring the charge on individual grains is generally consistent with the theoretical criteria for breakdown. At the surface, the maximum electric field $E_{\text{max}}$ that can be sustained by the tenuous Martian atmosphere has been estimated to fall between 20-50 kV/m (Melnik and Parrot 1998, Kok and Renno 2009). From the electric field, the maximum charge density can be computed to a
first order as:

\[\sigma_{\text{max}} = \epsilon_0 E_{\text{max}},\]  

(1)

where \(\epsilon_0\) is the permittivity, and \(E_{\text{max}}\) is the breakdown electric field. Thus, theoretically, \(\sigma_{\text{max}}\) ranges between 2.8 and \(5 \times 10^{-7}\) Cm\(^{-2}\) (for comparison, the \(\sigma_{\text{max}}\) on Earth is \(27 \times 10^{-5}\) Cm\(^{-2}\)). Note that the charge densities we measure in both granulometries meet this discharge criteria (see Figure 9). In fact, a large fraction of the particles we characterized carried charge densities that exceed these theoretical values by up to a factor of 5. [Hamamoto et al. (1992) argues that charge densities that exceed the theoretical limit are to be expected on on sub-millimeter particles because the region of high electric field in which electron avalanche occurs becomes thinner as the rate of curvature (as grains get smaller) increases. Indeed, those authors find that particles around 1 micron may sustain charge densities several orders of magnitudes larger than that predicted by equation 1. This may also explain why the charge density distribution for the 150-250 \(\mu\)m sample is broader than that for the 250-500 \(\mu\)m sample.

Both the presence of discharges in the active fountain and the elevated charge densities on individual grains suggest that triboelectric charging is indeed capable of meeting the breakdown criteria for near-surface Martian conditions. This conclusion is consistent with the Paschen Law limit model discussed in [Wurm et al. (2019)]. [Wurm et al. (2019) hypothesized that minute discharges between grains occurred to limit the amount of charge collected by grains. Here, we have explicitly shown that such small-scale discharges do indeed occur in isolated flows of natural silicate materials under a simulated Martian environment, as well as quantified the charge densities that the Mars simulants reach.

We stress, however, that the presence of small-scale discharges does not imply the existence of large-scale lightning on Mars. Lightning not only requires an efficient charging mechanism to electrify particles, but also processes by which negative and positive charge become separated over distances of hundreds to thousands of meters. Perhaps the best terrestrial analog to putative Martian discharges are the small volcanic vent discharges that occur in the rarefied barrel shock region of a supersonic volcanic jet ([Behnke et al., 2013] [Méndez Harper et al., 2018a]). These small discharges (less than 10 m in length) are only present within the region of low pressure just upstream of a Mach disk. Because vent discharges involve low energies, they are in-
visible to global lightning detection systems, but can be detected from a few kilometers away using specialized equipment like a lightning mapping array. Even close to the source, vent discharges manifest not as discrete pulses in radio frequency, but rather as a continual RF “hum” (see figure 1 in Thomas et al. (2007)). If discharges in Martian dust storms are comparable to volcanic vent discharges, they would likely be undetectable from orbit. Positive detection would require dedicated instruments on the ground.

4. Summary

In this work, we have investigated the capacity of a Martian dust simulant to charge triboelectrically in an isolated granular flow. Unlike previous work, our experiments were designed to minimize particle contacts with foreign surfaces, as well as designed to measure individual spark discharges.

We have demonstrated that:

(i) Natural basaltic grains in an isolated (i.e. with no wall contacts) spouted bed under near-surface Martian conditions can indeed produce spark discharges.

(ii) The distribution of charge densities on the particles were measured, with maximum charge densities on the order of $10^{-6}$ Cm$^{-2}$.

(iii) Grains coming into contact with a chemically-dissimilar laboratory container affects the polarity with which dust grains charge and influences discharge behavior.

Forty years of laboratory experiments and modelling have suggested that the small-scale discharges may occur within Mar’s near-surface dust system. Nevertheless, most of those experiments involved interactions between Martian dust simulant grains and container walls. Such contacts could have produced electrification behaviors different from those on Mars. Here, we have directly accounted for these concerns and shown that spark discharges do indeed still occur within an isolated flow of basaltic grains. These discharges are small in scale and we suggest an analogy to volcanic vent discharges on Earth. Given their low energies, we will likely have to wait for on-ground electrical measurements to unequivocally ascertain whether discharges occur in granular flows on the actual Martian surface. If electrical discharges do exist on Mars, it will be interesting to quantify whether the sizes of discharges scale with the size of the dust devil or storm and whether or not they can catalyze chemical reactions.
5. References

References

Allen, Carlton C and Jager, Karen M and Morris, Richard V and Lindstrom, David J and Lindstrom, Marilyn M and Lockwood, John P. (1998). JSC Mars-1: a Martian soil simulant. *Space 98* 469–476.

Aizawa, K., Cimarelli, C., Alatorre-Ibarguengoitia, M., Yokoo, A., Dingwell, D., and Iguchi, M. (2016). Physical properties of volcanic lightning: Constraints from magnetotelluric and video observations at Sakurajima volcano, Japan. *Earth and Planetary Science Letters* 444:45–55.

Aplin, Karen L. (2006) Atmospheric electrification in the solar system *Surveys in Geophysics* 27(1):63–108.

Aplin, KL and Goodman, T and Herpoldt, KL and Davis, CJ. (2012). Laboratory analogues of Martian electrostatic discharges. *Planetary and Space Science*. 69(1):100–104.

Apodaca, Mario M, Paul J Wesson, Kyle JM Bishop, Mark A Ratner and Bartosz A Grzybowski. (2010). Contact electrification between identical materials. *Angewandte Chemie* 122(5):958–961.

Arason, P., Bennett, A. J., and Burgin, L. E. (2011). Charge mechanism of volcanic lightning revealed during the 2010 eruption of Eyjafjallajökull. *Journal of Geophysical Research: Solid Earth*. 116(B9).

Atreya, Sushil K. and Wong, Ah San and Renno, Nilton O. and Farrell, William M. and Delory, Gregory T. and Sentman, Davis D. and Cummer, Steven A. and Marshall, John R. and Rafkin, Scot C.R. and Catling, David C. (2006). Oxidant enhancement in Martian dust devils and storms: Implications for life and habitability. *Astrobiology*. 6:439-450.

Behnke, Sonja A., Ronald J. Thomas, Stephen R. McNutt, David J. Schneider, Paul R. Krehbiel, William Rison and Harald E. Edens. (2013). Observations of volcanic lightning during the 2009 eruption of Redoubt Volcano. *Journal of Volcanology and Geothermal Research* 259:214–234.
Behnke, Sonja A., Harald E. Edens, Ronald J. Thomas, Cassandra M Smith, Stephen R. McNutt, A. R. Van Eaton, Corrado Cimarelli. (2018). Investigating the Origin of Continual Radio Frequency Impulses during Explosive Volcanic Eruptions. *Journal of Geophysical Research*

Bennett, A. J., Odams, P., Edwards, D., and Arason, P. (2010). Monitoring of lightning from the April-May 2010 Eyjafjallajökull volcanic eruption using a very low frequency lightning location network. *Environmental Research Letters* 4(5):1748–9326.

Cimarelli, C., M. A. Alatorre-Ibarguengoitia, K. Aizawa, A. Yokoo, A. Diaz-Marina, M. Iguchi and D. B. Dingwell. (2016). Multiparametric observation of volcanic lightning: Sakurajima Volcano, Japan. *Geophysical Research Letters* 43(9):2015GL067445.

Crozier, W. D. (1964). The electric field of a New Mexico dust devil. *Journal of Geophysical Research*, 69(24), 5427-5429.

Cimarelli, C., M. A. Alatorre-Ibarguengoitia, U. Kueppers, B. Scheu and D. B. Dingwell. (2014). Experimental generation of volcanic lightning. *Geology* 42(1):79–82.

Delgado, H., Molinero, R., Cervantes, P., Nieto-Obregón, J., Lozano-Santa Cruz, R., Macías-González, H. L., ... & Silva-Romo, G. (1998). Geology of Xitle volcano in southern México City—a 2000-year-old monogenetic volcano in an urban area. Revista Mexicana de Ciencias Geológicas, 15(2), 115-131.

Duff, N. and Lacks, D. J. (2008). Particle dynamics simulations of triboelectric charging in granular insulator systems. *Journal of Electrostatics*, 66(1-2), 51-57.

Eden, H. F. and Vonnegut, B. (1973). Electrical breakdown caused by dust motion in low-pressure atmospheres: Considerations for Mars *Science* 180(4089):962–963.

Farrell, WM and Smith, PH and Delory, GT and Hillard, GB and Marshall, JR and Catling, D and Hecht, M and Tratt, DM and Renno, N and Desch, MD and others. (2004). Electric and magnetic signatures of dust devils from the 2000–2001 MATADOR desert tests. *Journal of Geophysical Research: Planets*. 109(E3).
Farrell, W. M. and Delory, G. T. and Atreya, S. K.. (2006). Martian dust storms as a possible sink of atmospheric methane. *Geophysical Research Letters*. 33(21).

Farrell, W. M., McLain, J. L., Collier, M. R., Keller, J. W., Jackson, T. J. and Delory, G. T. (2015). Is the electron avalanche process in a martian dust devil self-quenching? *Icarus* 254:0019-1035.

Ferguson, Dale C. and Kolecki, Joseph C. and Siebert, Mark W. and Wilt, David M. and Matijevic, Jacob R. (1999). Evidence for Martian electrostatic charging and abrasive wheel wear from the Wheel Abrasion Experiment on the Pathfinder Sojourner rover *Journal of Geophysical Research: Planets*. 104(E4).

Forward, Keith M., Daniel J. Lacks and R. Mohan Sankaran. (2009a). Charge Segregation Depends on Particle Size in Triboelectrically Charged Granular Materials. *Physical Review Letters* 102(2):028001.

Forward, Keith M., Daniel J. Lacks and R. Mohan Sankaran. (2009b). Particle-size dependent bipolar charging of Martian regolith simulant. *Geophysical Research Letters* 36(13):L13201.

Gilbert, J. S., S. J. Lane, R. S. J. Sparks and T. Koyaguchi. (1991). Charge measurements on particle fallout from a volcanic plume. *Nature* 349(6310):598–600.

Greeley, Ronald. (1979). Silt-clay aggregates on Mars *Journal of Geophysical Research: Solid Earth*. 84(B11).

Gu, Zhaolin, W. Wei, J. Su and C. W. Yu (2013) The role of water content in triboelectric charging of wind-blown sand *Scientific reports* 3:1337

Hamamoto, N., Nakajima, Y., & Sato, T. (1992). Experimental discussion on maximum surface charge density of fine particles sustainable in normal atmosphere. *Journal of electrostatics*, 28(2), 161-173.

Hargie, K., Van Eaton, A., Mastin, L. G., Holzworth, R. H., Ewert, J., and Pavolonis, M. (2018). Globally detected volcanic lightning and umbrella dynamics during the 2014 eruption of Kelud, Indonesia. *Journal of Volcanology and Geothermal Research* 0377-0273.
Hatakeyama, H. (1947). On the Variation of the Atmospheric Potential Gradient caused by the Cloud of Smoke of the Volcano Asama. (The Fourth Report.). *Journal of the Meteorological Society of Japan. Ser. II* 25(1-3):39–39.

Hatakeyama, H. and K. Uchikawa. (1951). On the Disturbance of the Atmospheric Potential Gradient caused by the Eruption-smoke of the Volcano Aso. *Papers in Meteorology and Geophysics* 2(1):85–89.

Helling, C., Jardine, M., Stark, C., and Diver, D. (2013). Ionization in atmospheres of brown dwarfs and extrasolar planets. III. Breakdown conditions for mineral clouds. *The Astrophysical Journal*. 767(2), 136.

Hess, S L and Henry, R M and Leovy, C B and Ryan, J A and Tillman, J E. (1977). Meteorological Results From the Surface of Mars: Viking 1 and 2. *Journal of Geophysical Research*, 82(28):4559-4574.

James, M. R., J. S. Gilbert and S. J. Lane. (2002). Experimental investigation of volcanic particle aggregation in the absence of a liquid phase. *Journal of Geophysical Research: Solid Earth* 107(B9):2191.

James, M. R., S. J. Lane and J. S. Gilbert. (2000). Volcanic plume electrification: Experimental investigation of a fracture-charging mechanism. *Journal of Geophysical Research: Solid Earth* 105(B7):16641–16649.

James, Mike R, SJ Lane and JS Gilbert. (1998). SPECIAL: Volcanic plume monitoring using atmospheric electric potential gradients. *Journal of the Geological Society* 155(4):587–590.

Kamra, A. (1972). Physical Sciences: Visual Observation of Electric Sparks on Gypsum Dunes. *Nature* 240, 143144

Keith, W. D., and Saunders, C. P. R. (1990). Further laboratory studies of the charging of graupel during ice crystal interactions. *Atmospheric research*, 25(5), 445-464.

Kikuchi, K. and T. Endoh. (1982). Atmospheric electrical properties of volcanic ash particles in the eruption of Mt. Usu Volcano, 1977. *Journal of the Meteorological Society of Japan* 1(60):548–561.
Kok, Jasper F. and Renno, Nilon O. (2009) Electrification of wind-blown sand on Mars and its implications for atmospheric chemistry. Geophysical Research Letters, 36(5).

Krauss, C. E., Horányi, M. and Robertson, S. (2003). Experimental evidence for electrostatic discharging of dust near the surface of Mars New Journal of Physics 5(1):1367-2630.

Krinsley, D. and Leach, R. (1981) Properties of electrostatic aggregates and their possible presence on Mars. Precambrian Research. 47(3-4):167–189.

Lacks, Daniel J. and Artem Levandovsky. (2007). Effect of particle size distribution on the polarity of triboelectric charging in granular insulator systems. Journal of Electrostatics 65(2):107–112.

Lacks, Daniel J. and R. Mohan Sankaran. (2011). Contact electrification of insulating materials. Journal of Physics D: Applied Physics 44(45):453001.

Lowell, J. and Rose-Innes, A. C. (1980). Contact electrification. Advances in Physics. 29(6), 947-1023.

Lowell, J. and W. Truscott. (1986a). Triboelectrification of identical insulators. I. An experimental investigation Journal of physics D: Applied physics 9(7):1273.

Lowell, J. and Truscott, W. S. (1986b) Triboelectrification of identical insulators. II. Theory and further experiments. Journal of Physics D: Applied Physics. 19(7):1281

Matsusaka, S. and Maruyama, H. and Matsuyama, T. and Ghadiri, M. (2010). Triboelectric charging of powders: A review. Chemical Engineering Science 65(22).

Mazumder, MK and Saini, D and Biris, AS and Sriama, PK and Calle, C and Buhler, C. (2004). Mars dust: characterization of particle size and electrostatic charge distribution Lunar and Planetary Science Conference, KSC-2004-032, 2004.

Melnik, O., & Parrot, M. (1998). Electrostatic discharge in Martian dust storms. Journal of Geophysical Research: Space Physics. 103(A12), 29107-29117.
Méndez Harper, Joshua and Josef Dufek. (2016). The effects of dynamics on the triboelectrification of volcanic ash. *Journal of Geophysical Research: Atmospheres* p. 2015JD024275.

Méndez Harper, J. S., McDonald, G. D., Dufek, J., Malaska, M., Burr, D., Hayes, A., McAdams, J., and Wray, J. (2017). Electrification of sand on Titan and its influence on sediment transport. *Nature Geoscience*. 10(4), 260.

Méndez Harper, J. S., Cimarelli, C., Dufek, J., Gaudin, D., and Thomas, R. J. (2018a). Inferring compressible fluid dynamics from vent discharges during volcanic eruptions. *Geophysical Research Letters*. 45(14), 7226-7235.

Méndez Harper, J. S., Helling, C., and Dufek, J. (2018b). Triboelectrification of KCl and ZnS particles in approximated exoplanet environments. *The Astrophysical Journal*, 867(2), 123.

Merrison, J., Jensen, J., Kinch, K., Mugford, R. and Nørnberg, P. (2004). The electrical properties of Mars analogue dust *Planetary and Space Science* 52(4):279–290.

Miura, Toshiro, Takehiro Koyaguchi and Yoshikazu Tanaka. (1996). Atmospheric electric potential gradient measurements of ash clouds generated by pyroclastic flows at Unzen Volcano, Japan. *Geophysical Research Letters* 23(14):1789–1792.

Miura, Toshiro, Takehiro Koyaguchi and Yoshikazu Tanaka. (2002). Measurements of electric charge distribution in volcanic plumes at Sakurajima Volcano, Japan. *Bulletin of volcanology* 64(2):75–93.

Nicora, M. G., Búrgesser, R. E., Rosales, A., Quel, E. J., and Ávila, E. E. (2013). Actividad eléctrica asociada a la erupción del complejo volcánico Cordón Caulle durante 2011. *Meteorológica*. 38(2), 121-131.

Pahtz, T., H. J. Herrmann and T. Shinbrot. (2010). Why do particle clouds generate electric charges? *Nature Physics* 6(5):364–368.

Peters, G. H., Abbey, W., Bearman, G. H., Mungas, G. S., Smith, J. A., Anderson, R. C., ... & Beegle, L. W. (2008). Mojave Mars simulant Characterization of a new geologic Mars analog. *Icarus*, 197(2), 470-479.
Riousset, J. A., Nag, A., and Palotai, C. (2020). Scaling of conventional breakdown threshold: Impact for predictions of lightning and TLEs on Earth, Venus, and Mars. *Icarus*, 338, 113506.

Saunders, C. P. R., Keith, W. D., and Mitzeva, R. P. (1991). The effect of liquid water on thunderstorm charging. *Journal of Geophysical Research: Atmospheres*, 96(D6), 11007-11017.

Shaw, P. E. (1917) Experiments on tribo-electricity. I. The tribo-electric series *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* 94(656): 16–33.

Stow, C. D. (1969). Dust and sand storm electrification. *Weather*, 24(4), 134-144.

Tennakone, K (2016). Contact electrification of regolith particles and chloride electrolysis: synthesis of perchlorates on Mars. *Astrobiology*. 16(10):811–816.

Telling, J. and Dufek, J. (2012). An experimental evaluation of ash aggregation in explosive volcanic eruptions. *Journal of Volcanology and Geothermal Research* 209-210 (0377-0273): 1–8.

Telling, J., Dufek, J., and Shaikh, A. (2013). Ash aggregation in explosive volcanic eruptions. *Geophysical Research Letters*. 40(10), 2355-2360.

Thomas, Peter and Gierasch, Peter J. (1985). Dust Devils on Mars. *Science* 230(4722):175-177.

Thomas, R. J., P. R. Krehbiel, W. Rison, H. E. Edens, G. D. Aulich, W. P. Winn, S. R. McNutt, G. Tytgat and E. Clark. (2007). Electrical Activity During the 2006 Mount St. Augustine Volcanic Eruptions. *Science* 315(5815):1097–1097.

Watanabe, Hideo and Samimi, Abdolreza and Ding, Yu Long and Ghadiri, Mojtaba and Matsuyama, Tatsushi and Pitt, Kendal G. (2006) Measurement of Charge Transfer due to Single Particle Impact. *Particle & Particle Systems Characterization* 23 (2): 133–137

Wurm, G., Schmidt, L., Steinpilz, T., Boden, L., and Teiser, J. (2019). A challenge for Martian lightning: Limits of collisional charging at low pressure. *Icarus*, 331, 103-109.
Zhai, Y. and Cummer, S. A. and Farrell, W. M. (2006). Quasi-electrostatic field analysis and simulation of Martian and terrestrial dust devils. *Journal of Geophysical Research: Planets*, 111(6), 1-8.