The Electrostatic Environments of the Moon and Mars: Implications for Human Missions

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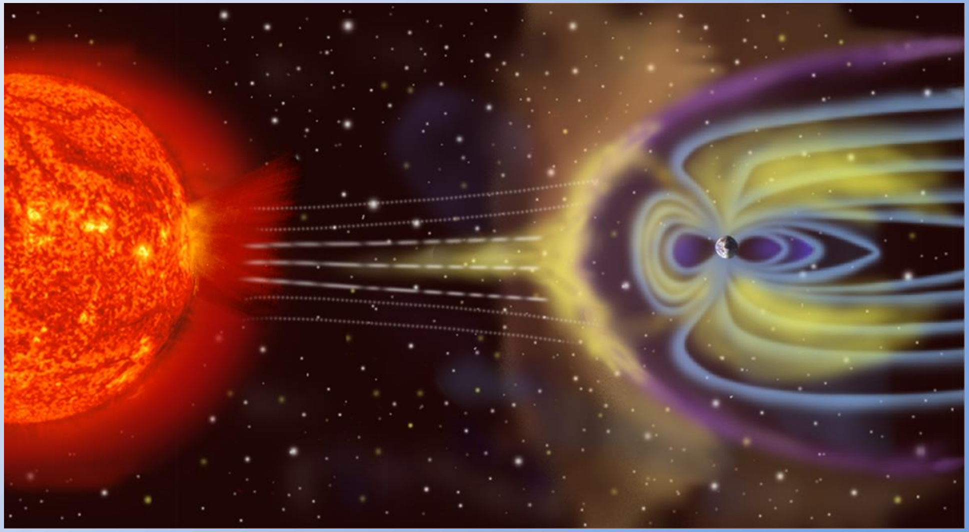
Electrostatic Environment of the Moon

- Extremely rarefied atmosphere (10^{-12} mbar)
- Directly exposed to solar wind, cosmic rays, solar UV
- Formalism to describe environment [1,2]: law of conservation of charge → lunar surface develops a charge so that Σ current fluxes=0
- Fluxes:
  - Solar wind electrons, protons, and ions (5 elementary charges/cm^3 at 400 km/s)
  - Cosmic ray protons (~90%) alpha particles (~9%) electrons (~1%) small fraction of heavy nuclei (~ 6 orders of mag. < than solar wind particles)
  - Photoelectrons
  - Reflected and backscattered electrons
  - Secondary electrons from the lunar surface due to GRC interacting with atoms in regolith
  - Solar wind ions and neutral particles reflected from the lunar surface
  - Neutrons generated in nuclear reactions with energetic incident radiation
  - Galactic cosmic rays partially reflected off the lunar surface



NASA GSFC image

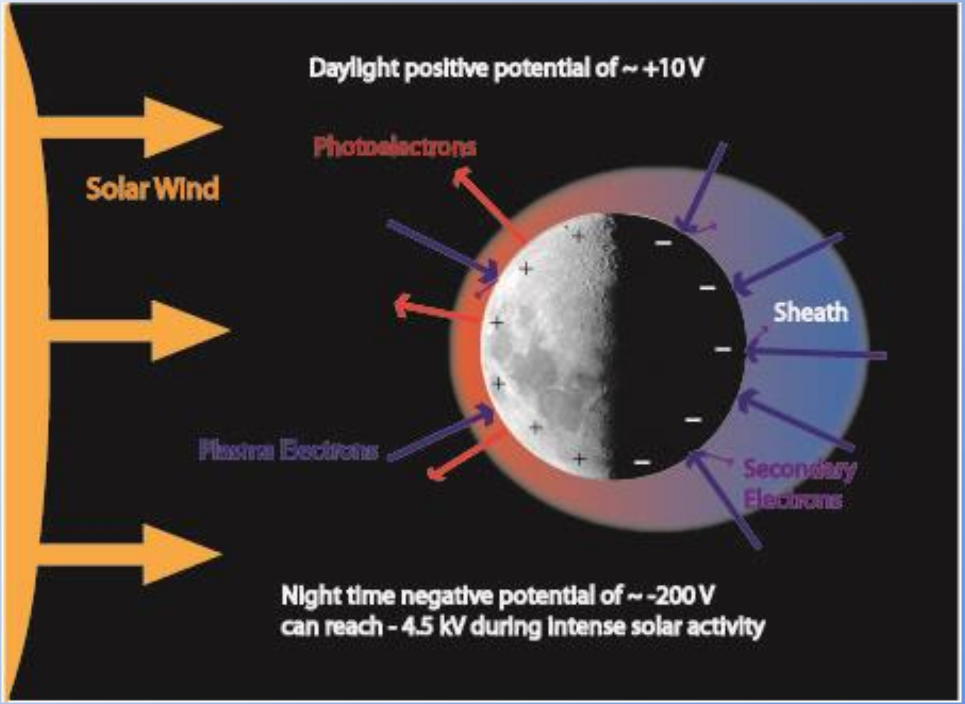
- Electron concentration and temperature data from *Electron Reflectometer* on Lunar Prospector
- Majority of contributions came from currents in red

[1] Manka R H 1973 Plasma and potential at the lunar surface *Photon and particle interactions with surfaces in space* (NY: Grard Springer) pp 347-361

[2] Halekas J S Bale S D Mitchell D L and Lin R P 2005 Electrons and magnetic fields in the lunar plasma wake *J. Geophys. Res.* **110** A07222

Electrostatic Environment of the Moon

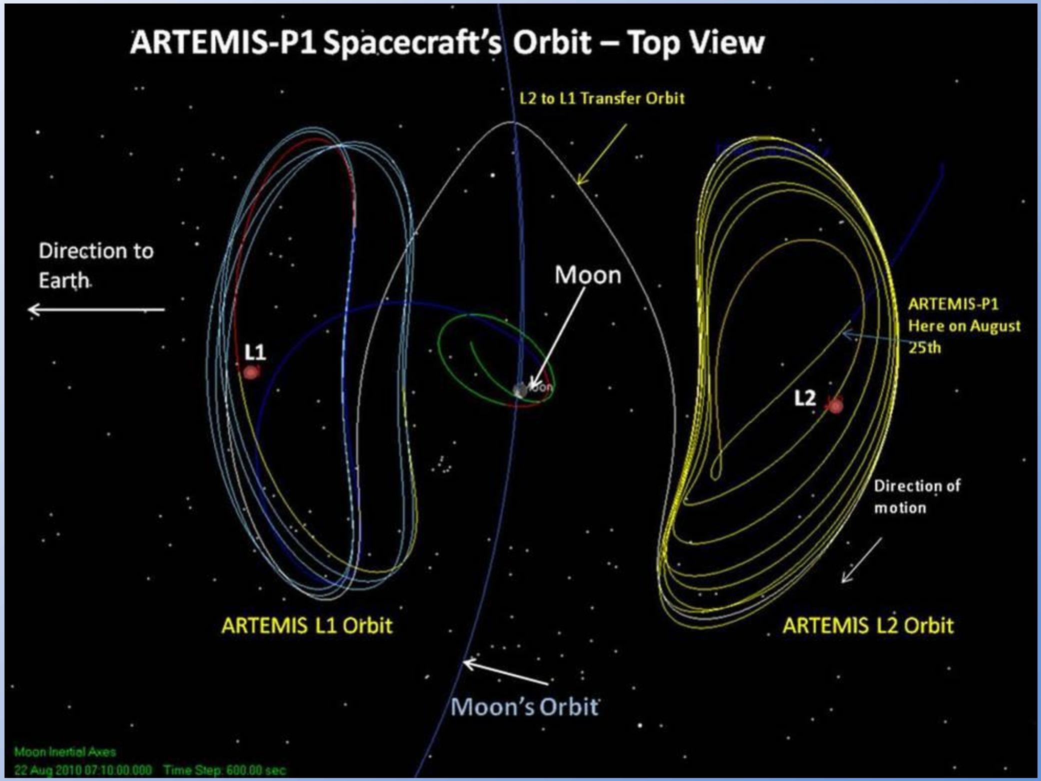
- **Daylight side**: Solar UV, X-rays→+ *Q* on surface (photoelectric effect)
- Photoelectrons form a *Debye sheath* of 10^3 to 10^4 cm^{-3} 1 m above surface → shields from plasma
- Currents: photoelectron & solar wind electrons
- Balance: surface charges to ~ 5 to 10 V
- **Night side**: Plasma density is reduced in solar wind wake. Thus higher electron energies → dominant current
- Balance: Surface charges to ~ -50 to -200 V
- When moon crosses Earth's plasma: ~ -kV
- During intense solar activity: -5.5 kV (Lunar Prospector)
- *Debye sheet* surrounds the moon → Dayside: meters Night side: km
- Debye distance *h* depends current energy and density:
- $h = \sqrt{\frac{\epsilon_0 \, kT}{2N_0 e^2}}$



- Near lunar terminator, outward photoelectron current balances inward solar wind electron current
- Potential is ~ -40 V
- Secondary electron emission increases during solar minimum (LRO mesurements)

Electrostatic Charging of the Lunar Regolith

- GCR particle radiation can generate deep dielectric charging down to a depth of ~1 m.
- Since the regolith has a very low electrical conductivity, electrostatic discharges can take place through the regolith.
- NASA's *Acceleration Reconnection Turbulence and Electrodynamics of the Moon's Interaction with the Sun* (ARTEMIS) mission, launched in 2010, is measuring the solar radiation incident on the Moon as it moves in and out the Earth's magnetic field.
- Winslow *et al* are applying ARTEMIS data to a deep dielectric charging model developed by Jordan *et al.* to estimate the subsurface electric field strength and dielectric breakdown.
- GCRs can also alter the chemical composition of the regolith



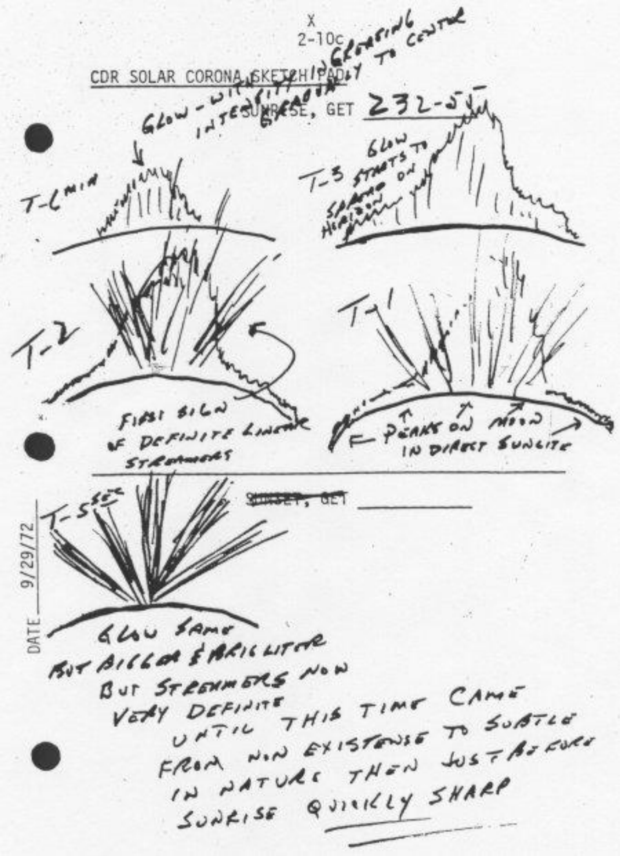
NASA Image

- Winslow R M *et al* 2015 Lunar surface charging and possible dielectric breakdown in the regolith during two strong SEP events *46th Lunar and Planetary Science Conference* 1261
- Jordan A P Stubbs T J Wilson J K Schwadron N A and Spence H E 2015 *J. Geophys. Res.* **120** 210-225

Horizon Glow on the Moon

NASA Kennedy Space Center

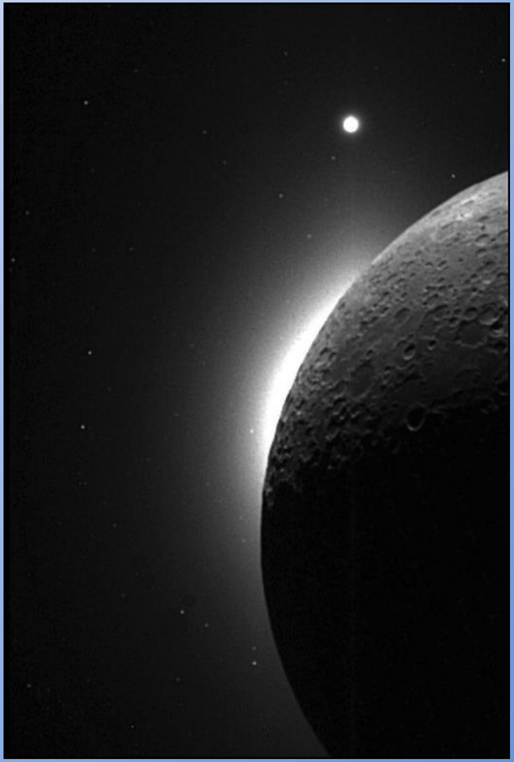
- Evidence of a horizon glow on the Moon that has been interpreted to be due to dust levitation and dust transport (concentration too high to be due to meteorite impacts)
- Lunar Surveyor 5 6 and 7 landers obtained television images of a glow just above the lunar horizon
- It was proposed that it was due to scattered sunlight from a cloud of submicron dust particles levitated by electrostatic forces up to ~ 1 m above the surface near the terminator.
- Apollo 17 astronauts sketched observations from orbit.
- The Lunar Ejecta and Meteorites (LEAM) experiment on Apollo 17 detected the presence of dust clouds as well as evidence of slow-moving highly charged dust particles.



GLOW SAME BUT BIGGER & BRIGHTER BUT STREAMERS NOW VERY DEFINITE UNTIL THIS TIME CAME FROM NON EXISTENSE TO SUBTLE IN NATURE THEN JUST BEFORE SUNRISE QUICKLY SHARP

NASA Image

- *Lunar Horizon Glow* experiment on the 1994 *Clementine* mission was not carried out due to conflicts with other experiments
- Clementine's tracker camera detected a faint glow above the brighter glow of zodiacal dust particles. Interpretation of these images is complicated and has never been completed satisfactorily [Hahn *et al*].
- NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE), launched in 2014 to study the moon from orbit until it was crashed on the lunar surface discovered that the moon is surrounded by a permanent dust cloud lofted from the surface by the impacts of interplanetary dust particles at 34 km/s, vaporizing part of the soil and releasing heat.
- A single interplanetary dust particle can kick up thousands of surface dust particles. Total estimated mass of the lunar dust cloud is 120 kg.
- However LADEE did not find evidence for the horizon glow.
- Submicron particle densities were measured at less than 100 particles/m^3, too low to produce a horizon glow
- Issue of the electrostatic lofting of submicron dust particles generating a horizon glow on the moon remains unresolved



NASA Image

- Hahn J M Zook H A Cooper B and Sunkara B 2002 Clementine observations of the zodiacal light and the dust content of the inner solar system *Icarus* **158** 360-378
- Szalay J R and Horanyi M 2015 The Search for Electrostatically Lofted Grains Above the Moon with the Lunar Dust Experiment *Geophys. Res. Lett.* **42** 5141–5146

Triboelectric Charging on the Lunar Surface

- Object moving on the surface of the moon will charge due to contact with the surface as well as to the exposure to the surrounding plasma environment
- On lunar dayside, rover will emit photoelectrons with energies that depend on the work function of the material
- Jackson *et al.* → modeling analyses with rubber tires on Apollo 14 Modular Equipment Transporter (MET) and with aluminum and titanium tires on Apollo 15, 16, and 17 Lunar Roving Vehicle (LRV)
- Calculations for the MET insulating wheel under lunar daylight conditions → it would charge to a potential similar to the ~5 V potential of the lunar surface.
- Metallic wheel on the LRV would charge to 4.62 V
- These potentials would decay in < 0.5 ms

NASA Image

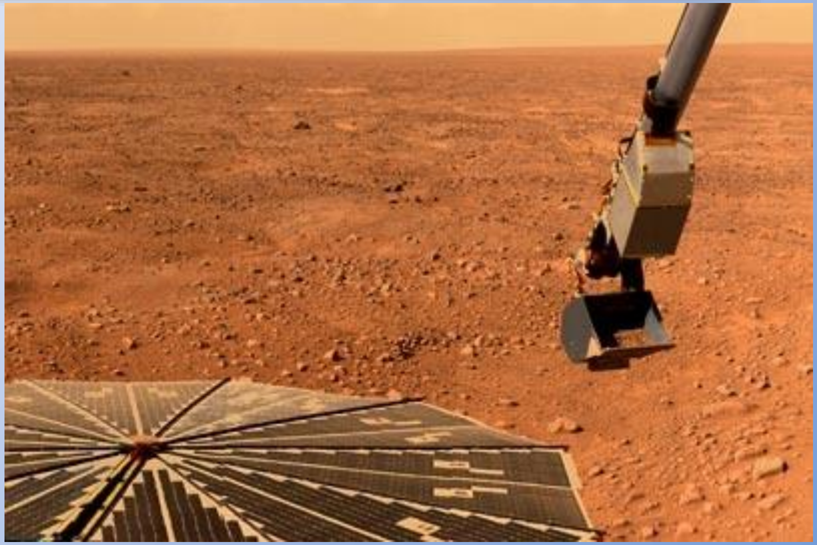
Jackson T L Farrell W M and Zimmerman M I 2015
Rover wheel charging on the lunar surface
Advances in Space Research **55** 1710-1720

Triboelectric Charging on the Lunar Surface

- Repeated wheel-regolith contact and separation would generate triboelectric charging on both surfaces
- Farrell *et al* modeled motion of the two wheels at 0.01 m/s to 3 m/s →
- In the photoelectron-dominated daylight plasma region the charge dissipates almost instantly in all cases.
- Thus charging on the lunar dayside is not an issue.
- On lunar night side (and on the shadowed polar crater region), where surface potentials reach -200 V, a rover will be exposed to the more energetic solar wind electrons and to secondary electron currents.
- At the higher speeds, both types of rover wheels would charge to -1 kV dissipating to equilibrium in ~ 10^7 to 10^8 s.
- These large potentials and long dissipation times will pose a hazard to astronauts and equipment during lunar missions.

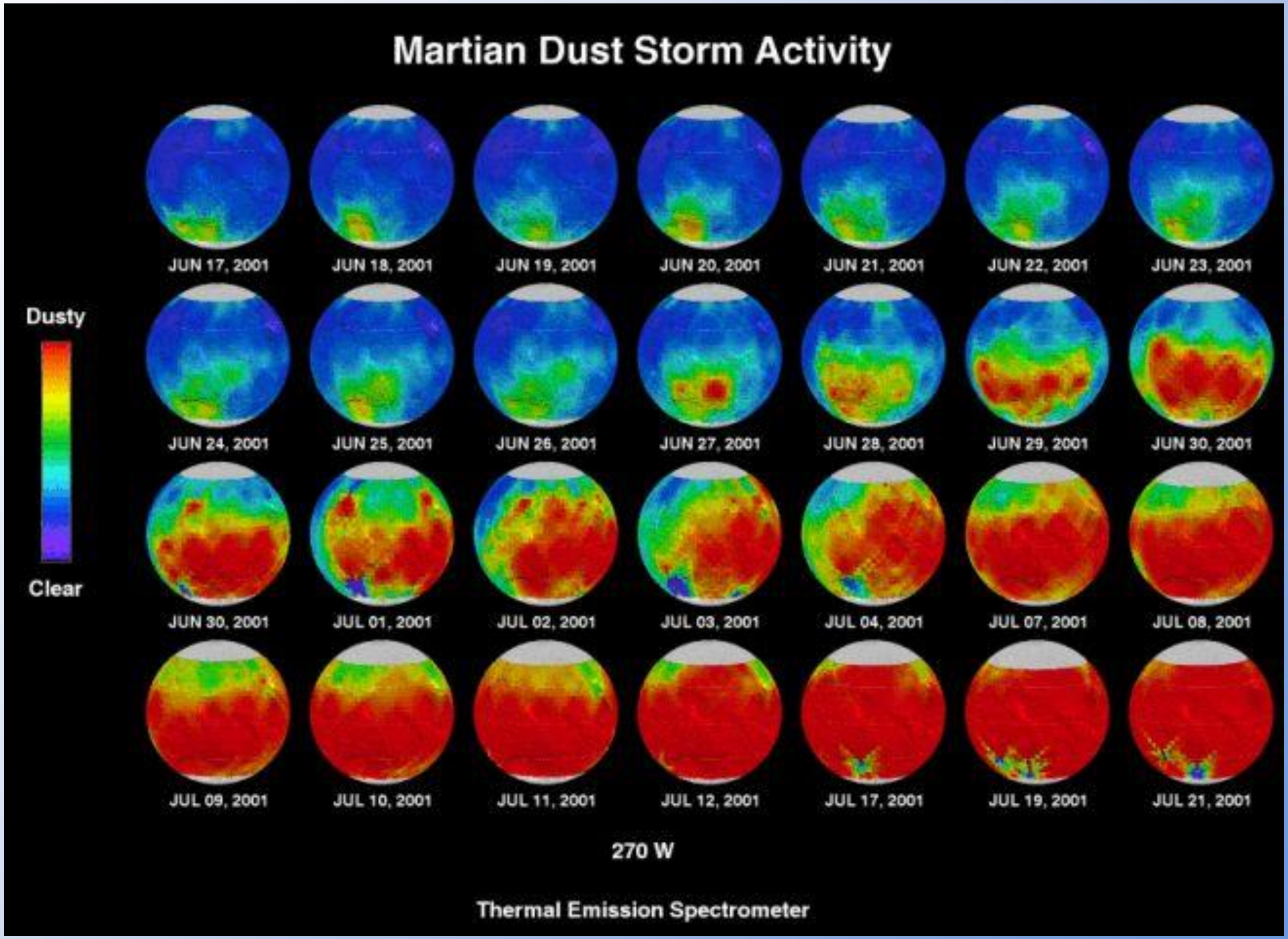
Farrell W M *et al* 2010 Anticipated electrical environment within permanently shadowed lunar craters *J. Geophys. Res.* **115** E03004

Atmospheric Dust

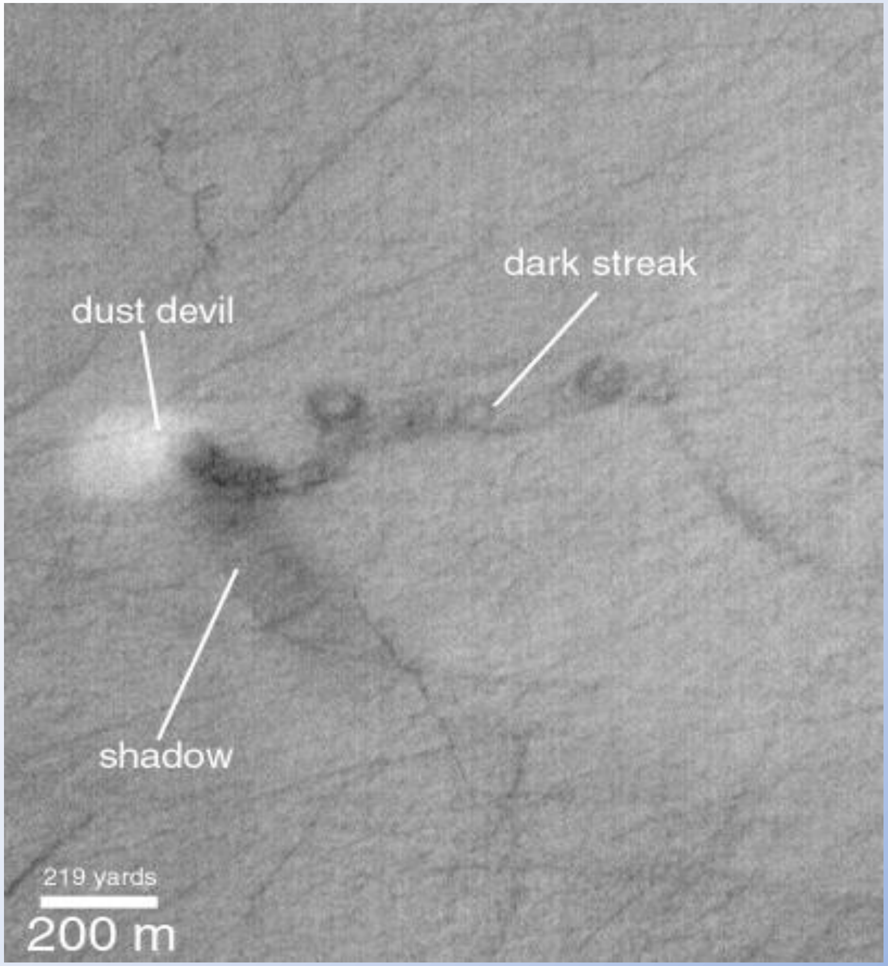


- Estimates from optical data: Average dust particle in the Martian atmosphere: 1.5 µm in diameter
- Average particle size changes with dust storm activity:
  - 2001: Derived particle data ranged from 2 to 5 µm
- Data from MI on Spirit & Opportunity (Landis et al 2006)
  - Suspended atmospheric dust: 2-4 µm
  - Settled dust uploaded by wind, diameter: ≤ 10 µm
  - Saltating particles: ≤ 80 µm
- Particle in soil (MI on Spirit on Scamander crater) ~ 220 µm

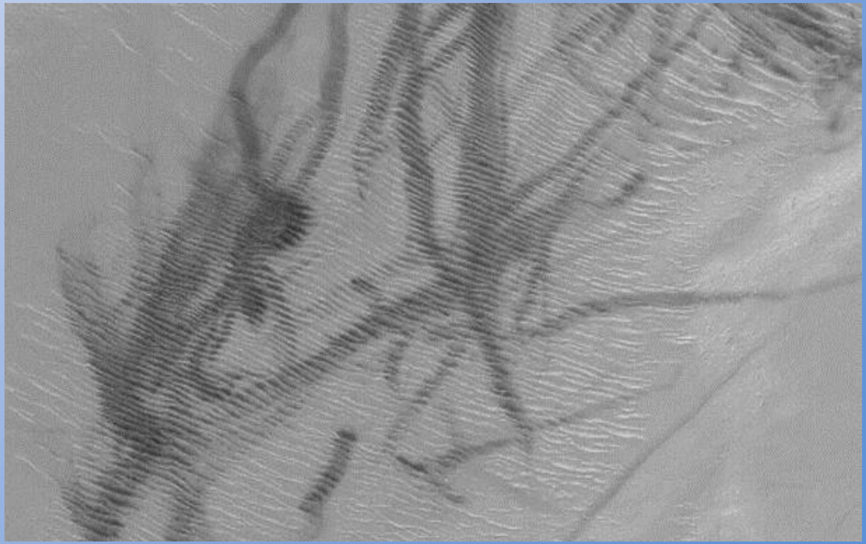
Martian Dust Storm



Dust Devils

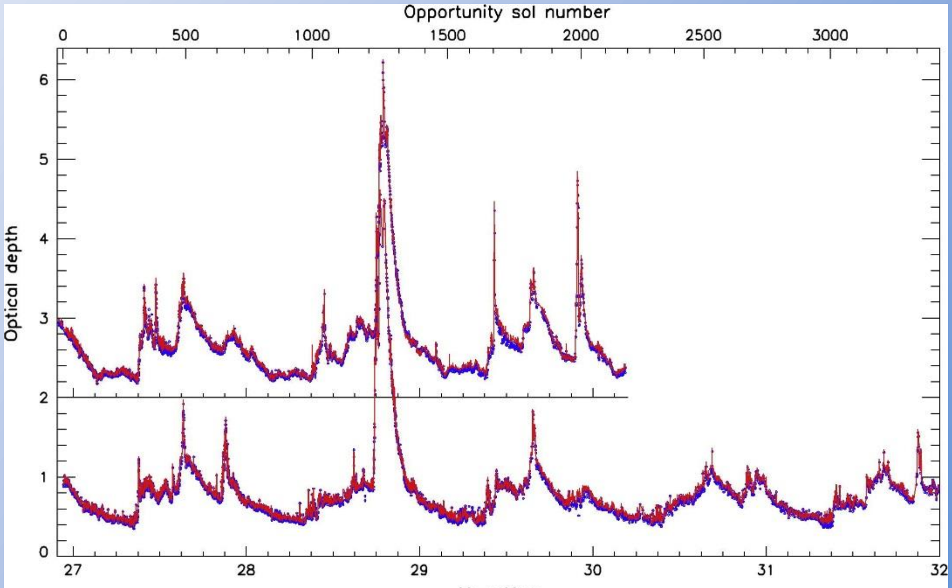


Martian dust devil (left) and dust devil tracks (below) photographed from orbit



Opacity of the Atmosphere

- Dust density in the Martian atmosphere has never been measured directly, they can be obtained from measurements of the opacity of the atmosphere that have been taken from landers.
- Opacity is measured in terms of the *optical depth τ*, which is a measure of the transmission of radiation through the atmosphere.
- *τ* is given by the logarithm of the ratio of transmitted to incident radiant power through the atmosphere.
- Typical values during non-dust storm conditions range from 0.2 to 1.
- During local dust storm conditions → from 1 to 6.
- Figure shows optical depths measured by the Mars Exploration Rovers (MER) Spirit and Opportunity during 5 years of their mission



[*] Lemmon MT *et al* 2014 Dust aerosol clouds and the atmospheric optical depth record over 5 Mars years of the Mars Exploration Rover mission *Icarus* **251** 96-111

Dust Content of the Atmosphere

- Using the MER optical depth data, we can calculate the expected atmospheric dust particle density for different conditions. The particle density as a function of height *z* can be approximated from

$$N \sim N_0 \tau e^{-\frac{z}{H}}$$

- where N_0 is the number density at the surface for an optical depth of 1 and *H* is the scale height, which has an average value of 11.1 km.
- For relatively clear atmospheric conditions, with the optical depth τ from 0.2 to 1, the average number of dust particles in the atmosphere near the ground (z = 0) ranges from about 5 to 24 particles/cm^3.
- For dust storm conditions, using $\tau = 6$, the expected particle density is about 140 particles/cm^3
- Typical terrestrial indoors environment (similar to a class 100,000 clean room)→ 100,000 particles of 0.5 µm and larger in diameter per ft^3 of air = 3.5 particles/cm^3
- Low end of the range of the atmospheric particle density during non-dust storm conditions on Mars.
- However, the Martian atmosphere has a density of 0.020 kg/m^3 near the surface, which is about 1.6% of the density of the terrestrial atmosphere near the surface. If we were to pump Martian atmospheric gas into a chamber and increase its density to match that of the Earth's atmosphere, the particle concentration would increase form an average of about 11 (taking the middle of the range for calm conditions) to about 670 particles/cm^3

Expected Electrical Environment

- Tribocharging of particles expected to generate E-fields up to Paschen breakdown ~ 20 kV/m
- Terrestrial dust devils ~ >120 kV/m (Jackson & Ferrell, 2006)
- 1973: Eden and Vonnegut performed lab experiments with sand in Martian-like atmosphere:
  - Dust particle $q \sim 10^4\ e^-$
  - Observed glow and filamentary discharges
- Recently, we observed glow discharges with Mars simulant
  - Showed alteration of known organics added to Mars simulant under simulated conditions
- 2001-2006: Fabian et al and Kraus et al: charging due to dust vertical motion; electrical discharges in atmosphere
- In dusty, turbulent Martian environment:
  - $E \sim 5$ kV/m

Electrical Discharges on Mars?

- Theoretical studies, laboratory, and terrestrial field experiments → atmospheric electrical activity on Mars (lightning or corona discharges) should be abundant
- However, years of direct observation from orbit and ground, including the recent MAVEN mission dedicated to the study of the Martian atmosphere, show no clear evidence of atmospheric electrical discharges.
- Triboelectric charging of dust grains during terrestrial dust storms or dust devils produces positive and negative charged grains
- On Mars, convective instabilities in the atmosphere should stratify similarly produced charged dust grains → lighter grains lifted to higher altitudes than more massive grains
- Since smaller particles charge negatively and larger particles charge positively, a macroscopic dipole moment is formed in the atmosphere that can produce an electrical discharges
- Fabian, Krauss and their collaborators demonstrated experimentally in a simulated Martian atmosphere that this type of dust vertical motion can generate electric fields strong enough for electrical discharges to occur [*].

*Fabian A Krauss C Sickafoose A Horanyi M and Robertson S 2001 Measurements of electrical discharges in Martian regolith simulant *IEEE Trans Plasma Sci* **29** 288–291

- Numerical models of dust electrification during Martian dust storms and dust devils predict that electric fields should have strengths up to the breakdown potential of carbon dioxide at the low atmospheric pressure of Mars
- Combined with experimental values of electron density in the Martian atmosphere, these models yield values of the electrical conductivity of the atmosphere that are several orders of magnitude higher than the values for the terrestrial atmosphere.
- Thus, charge dissipation in the Martian atmosphere would happen in seconds rather than minutes, as is the case for Earth
- Discharge mechanism, however, remains unknown. Whether it takes place violently (lightning) or gently (corona glow) is not known. No direct measurements have ever been made.
- However, there is experimental evidence for glow discharge in laboratory experiments →Eden and Vonnegut placed sand particles in a container with carbon dioxide at pressures in the range of the Martian atmospheric pressure and observed a glow as well as filamentary electrical discharges when the container was shaken.
- Our NASA laboratory conducted similar experiments where we were able to observe a visible glow and show that these discharges altered several organics known to exist on Mars.
- In contrast, a recent charging model → electric fields cannot reach levels up to breakdown because of charge dissipation in the saltation layer

- Farrell W M *et al* 2003 A simple electrodynamic model of a dust devil *Geophysical Research Letters* **30** 250
- Zhai Y, *et al* 2006 Quasielectrostatic field analysis and simulation of Martian and terrestrial dust devils *J. Geophys. Res. Lett.* **35** 16
- Eden H F and Vonnegut B 1973 Electrical breakdown caused by dust motion in low-pressure atmospheres: Considerations for Mars *Science* **180** 962
- Hintze P E *et al* 2010 Alteration of five organic compounds by glow discharge plasma and UV light under simulated Mars conditions *Icarus* **208** 749-757

- Searches for evidence of electrostatic discharges in the Martian atmosphere have been made with instrumentation aboard orbiting spacecraft.
- In 2009, Ruf and collaborators claimed that they had detected non-thermal electromagnetic emissions during a dust storm.
- Analyses of the modes of these emissions were interpreted to be Schumann Resonances. Some researchers attribute the presence of these resonances to lightning discharges.
- However, subsequent observations in the same electromagnetic region found no evidence of Schumann Resonances during a period that included dust storms.
- Detailed studies of over 5 years of observations by the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) yielded no evidence of high frequency radio emissions that would indicate the presence of electrical discharges.
- Moreover, the connection between Schumann Resonances and lightning has not been established yet, with only one research effort indicating it as a possibility

- Anderson M M *et al* 2012 The Allen Telescope Array search for electromagnetic discharges on Mars *Astrophys. J.* **744** 15
- Ondarkova A *et al* 2008 Peculiar transient events in the Schumann Resonance band and their possible explanation *J. Atmos. Sol-Terr. Phys.* **70** 937-946

- A key outstanding question related to the presence of lightning and glow discharges in the Martian atmosphere is the rate of charge dissipation in the more conductive Martian atmosphere.
- Some terrestrial examples of particle charging in volcanic ash clouds have shown that they remain electrified long after charge should have dissipated into the atmosphere.
- A similar phenomenon could happen on Mars that may influence electrical activity. Ions and electrons present in the atmosphere may also be a factor in limiting the strength of the electric fields and the conductivity of the atmosphere
- To shed light on this phenomenon, we are conducting experiments in a partially simulated Martian environment to tribocharge simulant dust particles in sizes that are representative of those in Martian dust storms and dust devils.
- Charging rates, charge polarity distribution, and charge decay rates will be measured. These experiments have never been performed under simulated Martian conditions.
- The proposed experiments should allow us to examine this possibility, providing new data that may help improve models for discharge events on Mars

- Delory G T 2012 Problems and new directions for electrostatics research in the context of space and planetary science *Proc. 2012 Joint Electrostatics Conference*
- Harrison R G *et al* 2010 Self-charging of the Eyjafjallojokull volcanic ash plume *Environ. Res. Lett.* **5** 024004
- Jackson T L *et al* 2010 Martian dust devil electron avalanche process and associated electrochemistry *J. Geophys. Res.* **115** E5

Electrostatic Precipitator

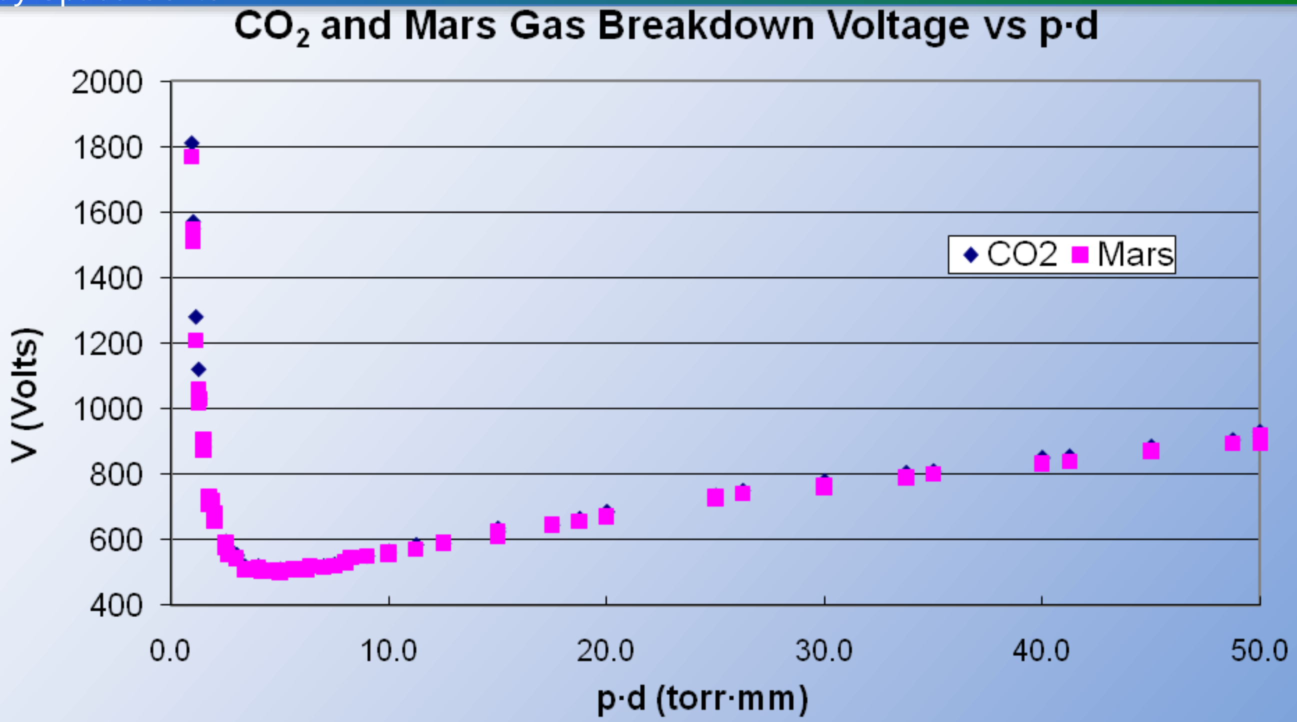
- Electrostatic Precipitator: two electrodes at a potential difference
- Townsend Breakdown: electron avalanches
- Weak *E* field: particles recombine
- Strong *E* field: avalanche region expands --> breakdown (Paschen)

Electrical Discharges on Mars?

Stable positive corona at 2.2 kV and 150 µA on 0.64-cm diameter rod inside 9.6-cm diameter cylinder in 95% CO_2/ 5% humid air at 9 mbar taken using a 50 mm lens at F16 with 20 s exposure.

Same geometry just after transition from 200 µA positive corona to an unstable streamer discharge (F8, 10 s). Two stationary pink streamers are visible below the rod, as well as the recorded *dancing* motion of a dynamic blue streamer from the rod to the inner cylinder.

Electrical Breakdown on Mars



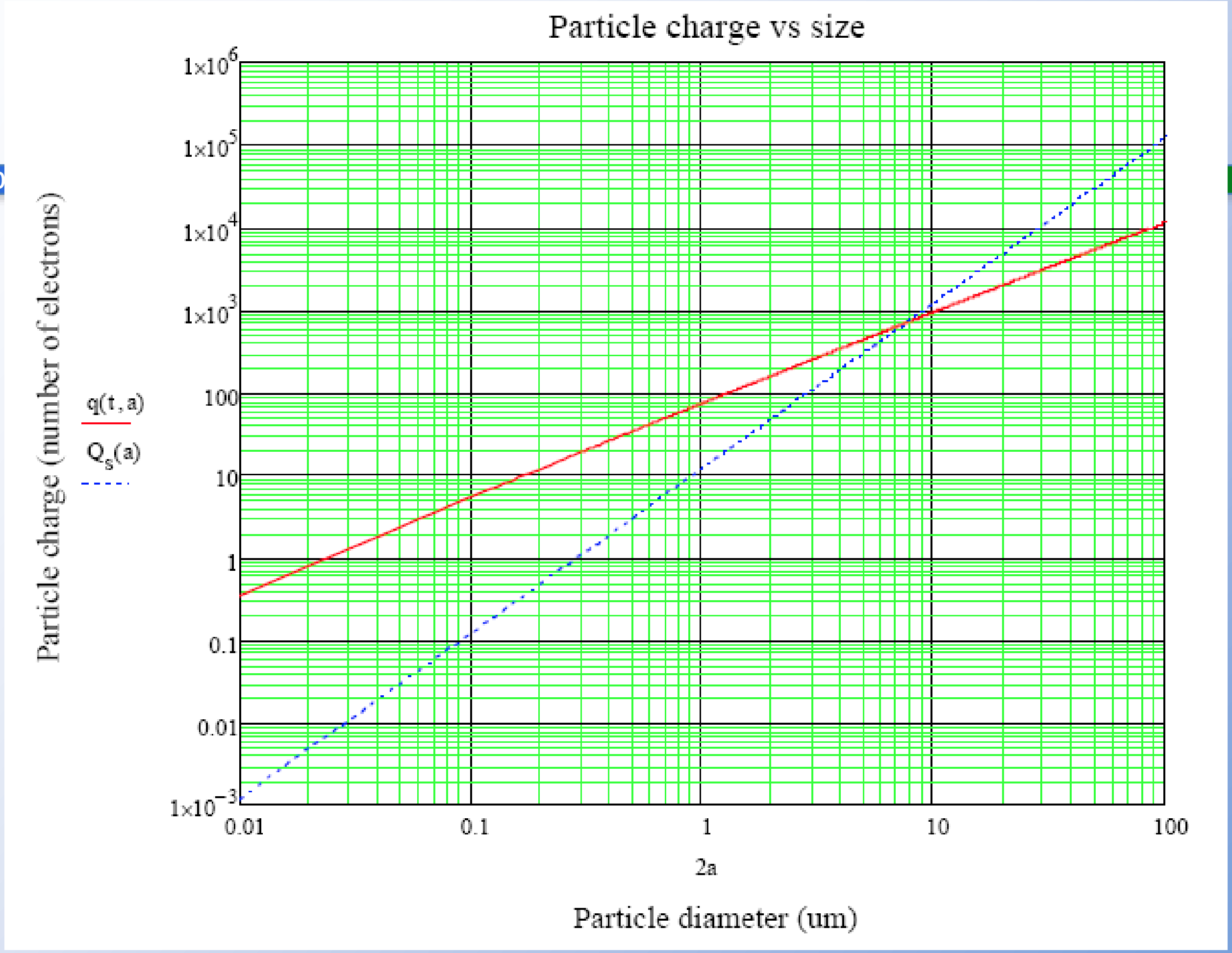
Paschen breakdown potentials versus pressure-distance for a Martian gas mixture (red squares) and for CO_2 (blue triangles)
This breakdown limits potentials required for an Electrostatic Precipitator

At 5 mbar in constant *E* field:
725 V for 5 mm gap
895 for 10 mm
2.8 kV for 5 cm
3.2 kV for 10 cm

- Dust particle charging depends on pressure
- Two types: Field (Pauthenier) and Diffusion Charging
- Field: ions accelerated in field attach to particles (depends on particle diameter)
  - Saturation Charge: $Q_s = 12(k/k+2)\pi\varepsilon_0 E a^2$
- Diffusion Charging: thermal ion motion

$$q(t) = \frac{4\pi\epsilon_0 kT}{e}\ln\left(\frac{aN_0 e^2 c_i t}{4\epsilon_0 kT} + 1\right)$$

Where *c* is the mean ion velocity = 362 m/s

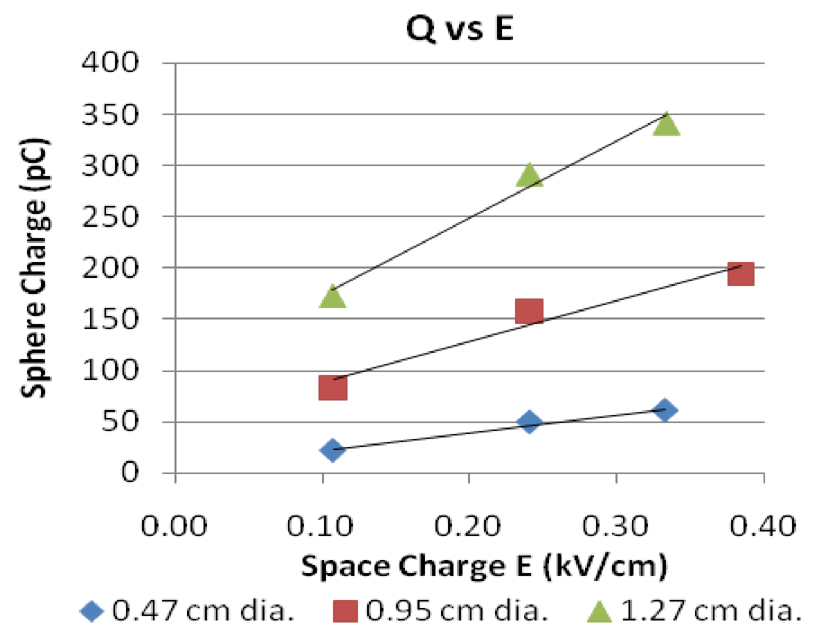


Continuum regime field (Pauthenier) saturation charge (dotted line) and diffusion charge (red line) for particles in CO_2 at 9 mbars with *E* = 0.23 kV/cm and an exposure time of 10 s

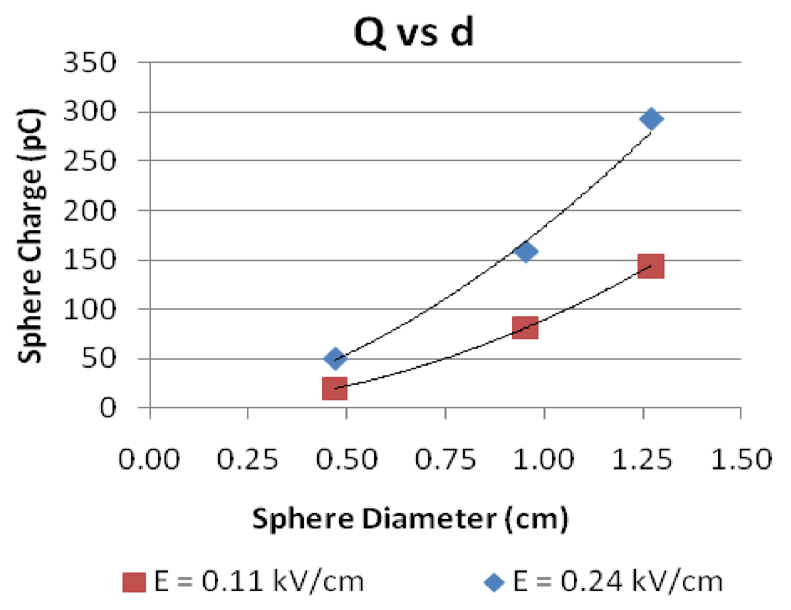
- Field charging contributes more to 4-10 micrometer diameter particles
- Both mechanisms contribute to 2-4 micrometer particles normally in atmosphere

Table 1. Corona Charging Experiments in 5 mBar CO_2.

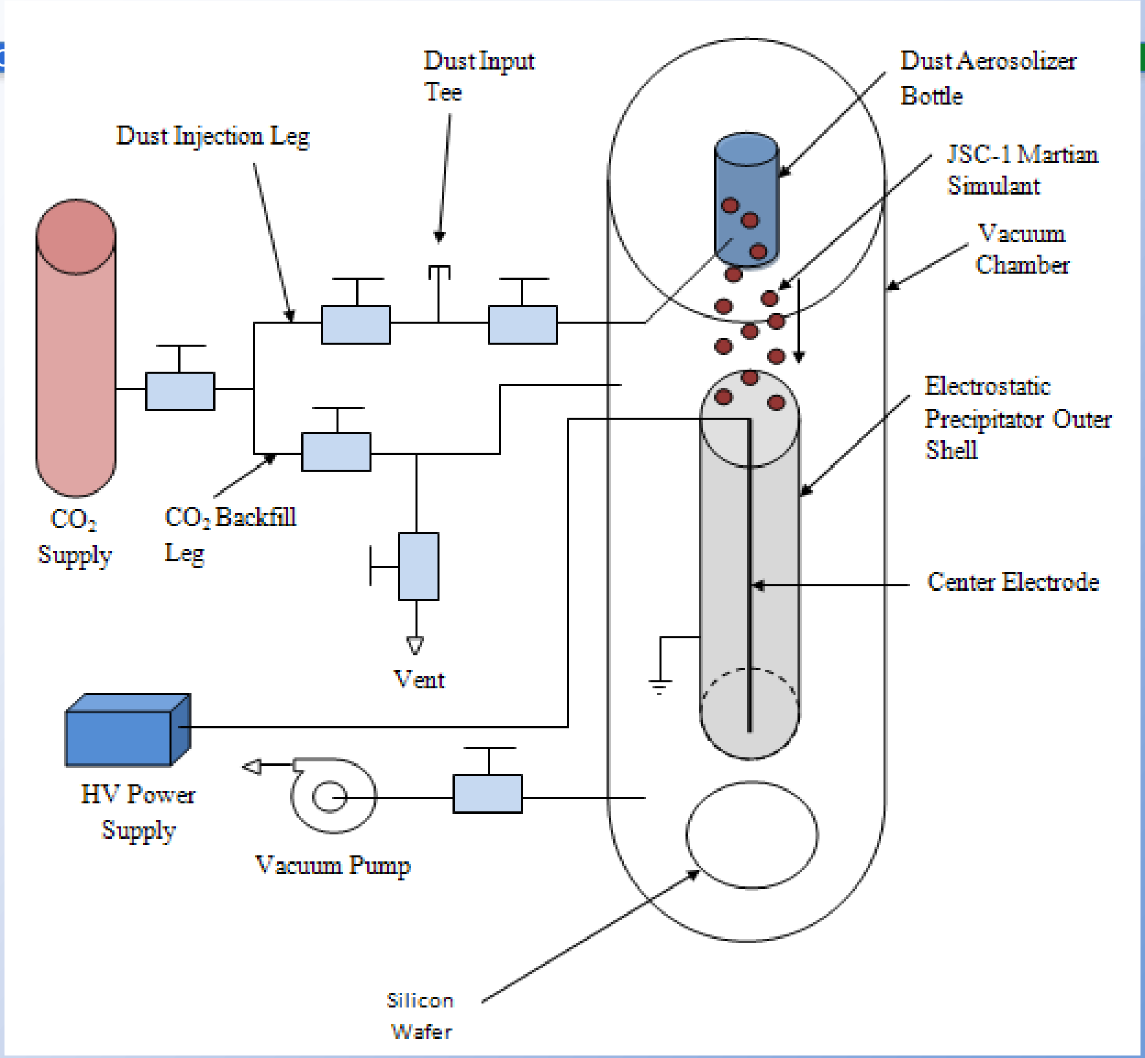
Outer Cylinder Inner Diameter (cm)	Inner rod/wire (cm)	Ball Diameter (cm)
5.26	70×10^{-4}	0.95
5.26	100×10^{-4}	0.95
7.0	70×10^{-4}	0.95
7.0	100×10^{-4}	0.47, 0.95, 1.27
7.0	0.3	0 95
9.6	70×10^{-4}	0 95
9.6	100×10^{-4}	0 95



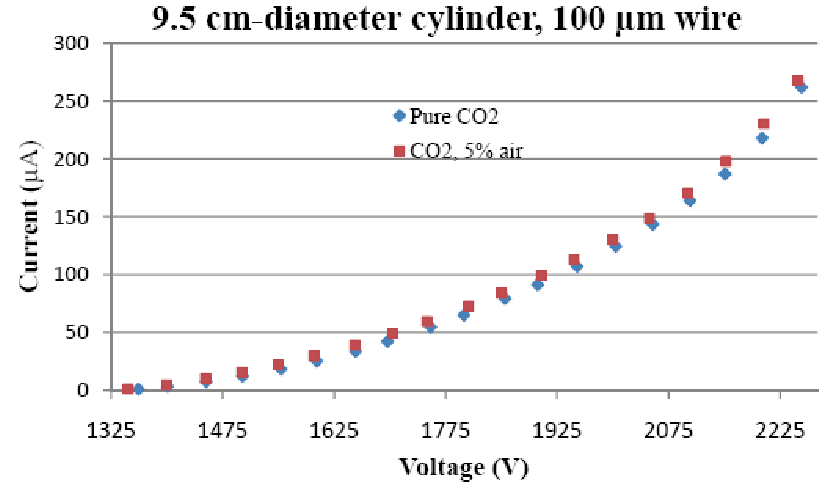
Experimental values of the charge on 0.47, 0.95 and 1.27 cm diameter brass sphere vs *E*

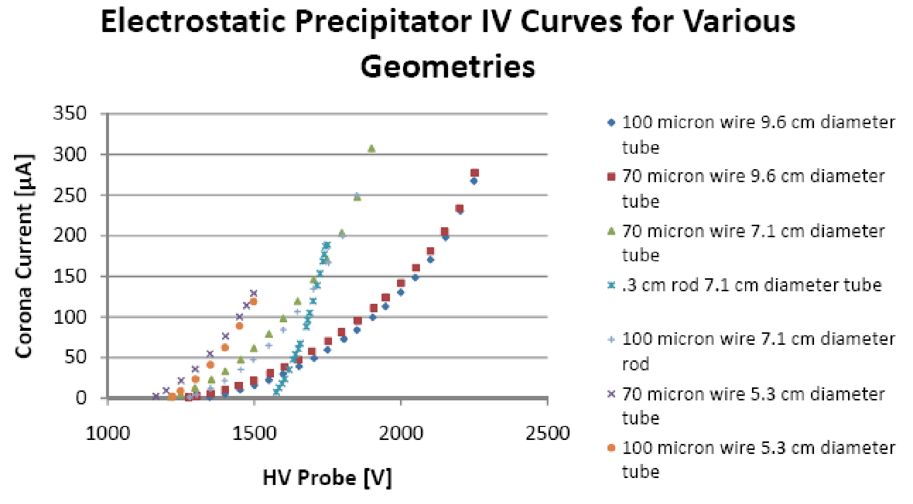


Experimental charge vs. sphere diameter for *E* fields of 0.11 and 0.24 kV/cm. Data taken at 5 mbar in CO_2



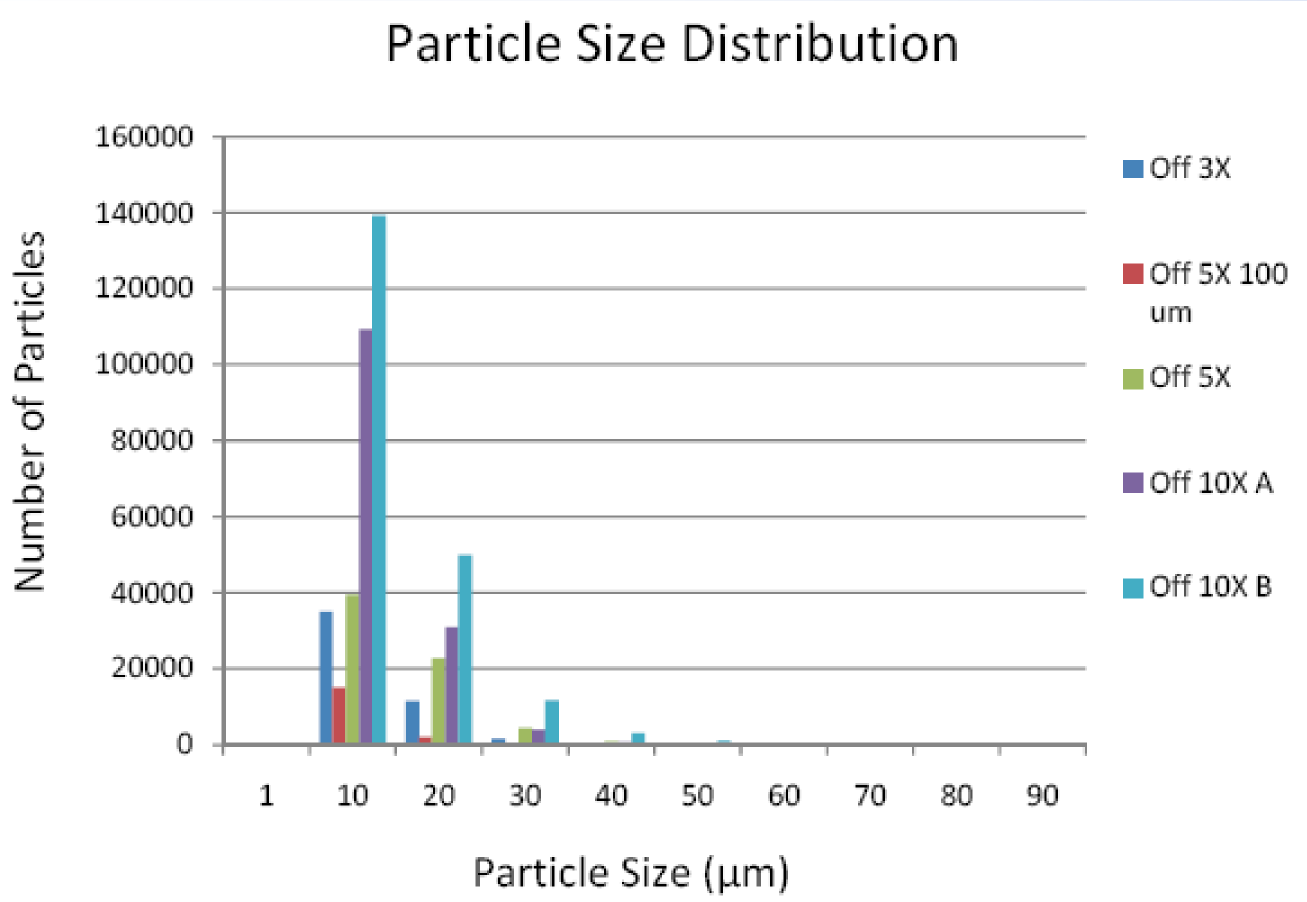
Schematic diagram of the experimental apparatus





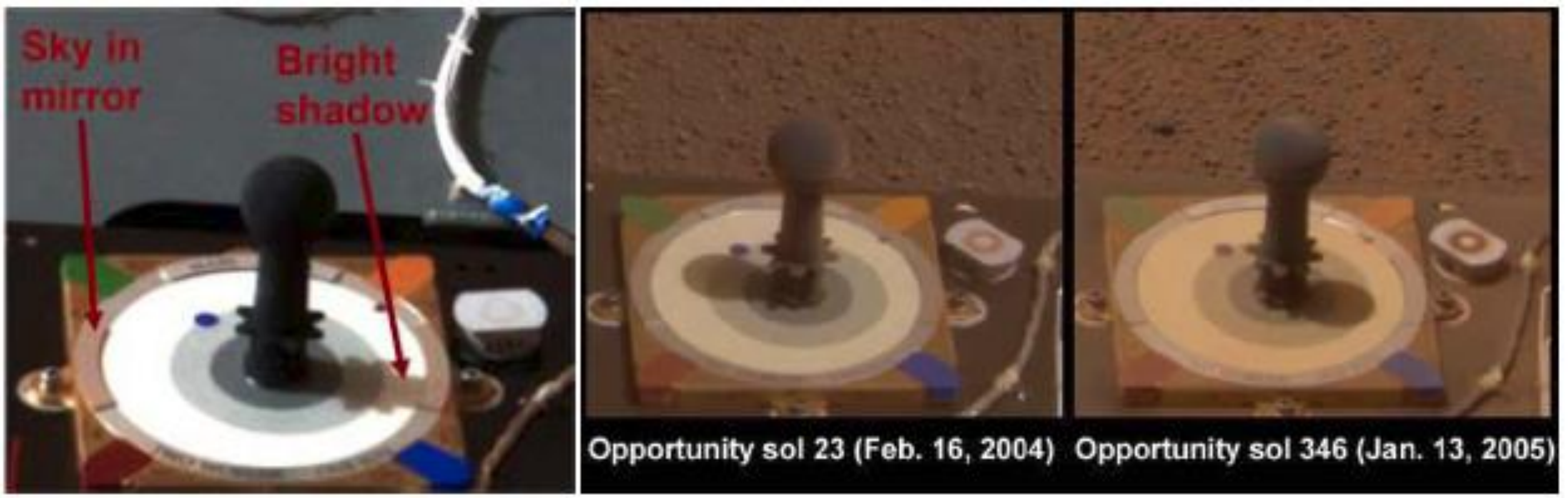
I-V curves for one configuration of the precipitator. Data taken at 5 mbar in pure CO_2 and in a 95% CO_2-5% air mixture, show that there is little difference in the *I-V* characteristics between the two environments at this pressure.

I-V curves for seven configurations of the precipitator. Data taken with clean electrodes and positive polarity at 5 mbar in CO_2.



- Particle size distribution of JSC Mars-1 simulant dust particles introduced into the chamber with short puffs of CO_2 gas and aerosolized before falling through the precipitator with the field off
- Three, five, and ten puffs, each carrying about 2 mg of simulant dust, were supplied
- Dust was collected on silicon wafers 7 cm in diameter
- Four runs were performed with the 7.0 cm-0.3 cm rod outer-inner electrode configuration and one with the 7.0 cm-100 μm configuration

Microscope images at 100× of JSC Mars-1 dust simulant particles aerosolized in the vacuum chamber and sent through the precipitator with the field off (left) and with the field on (right). The largest particles seen on the image with the field on are outside the range of particles expected in the Martian atmosphere.

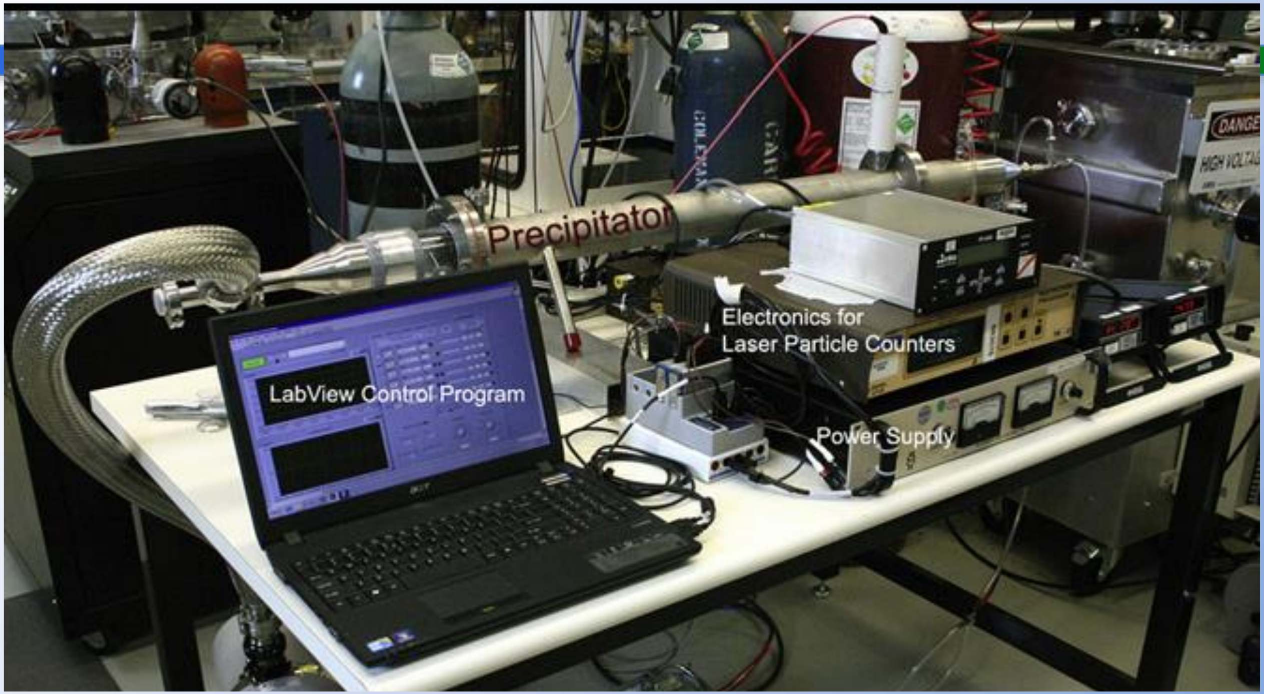


(Left): Clean color calibration target on Mars Exploration Rover Spirit. The target's mirror and the shadows cast on it by the Sun help scientists determine the degree to which dusty Martian skies alter the panoramic camera's perception of color. **(Center)**: Calibration target on the missions' twin rover Opportunity after 23 Martian days (sol). **Right):** Target after 346 sols.

To calculate precipitator efficiency:

- Ten CO_2 puffs carrying 5 g each of <10 µm vacuum oven-dried simulant
- Unprecipitated simulant was collected with Whatman 542 filter paper
- Precipitated dust was picked up with 2 sheets of filter paper
- These two sets, plus a control, were burned in crucibles at 900 °C
- Efficiency = 99%

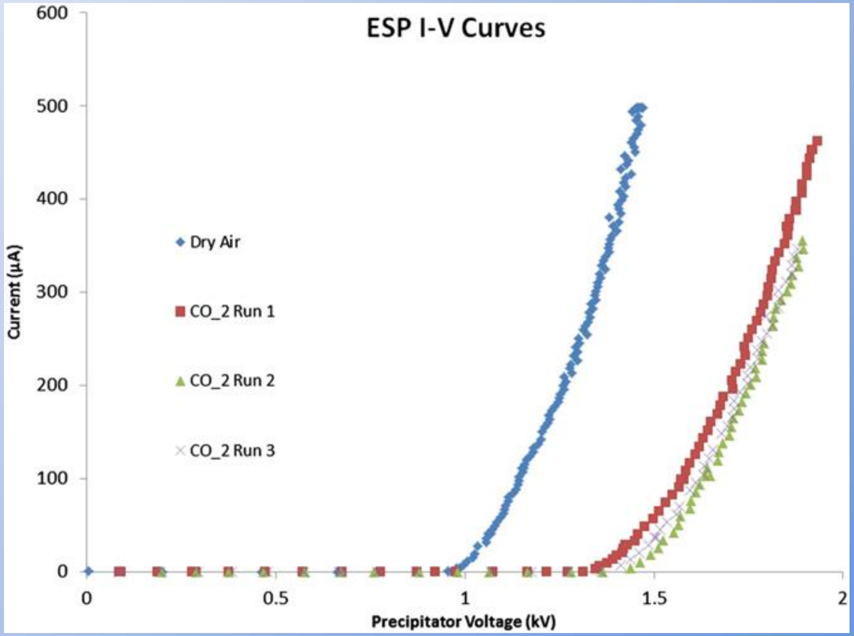
Precipitator in a Flow-Through



- A prototype precipitator with a controlled CO_2 flow of 9.4 LPM at 9 mbars was designed and constructed.
- Particle counters provide particle counts before and after precipitation.
- Design is a 1/10 scale intended for possible demonstration on the NASA Mars 2020 mission.
- A full scale unit, with a flow of 88 g/h or 0.74 SLPM, corresponding to 94 LPM at 8 mbar, will be proposed for NASA’s Mars Sample Return Mission in 2024.

I-V Curves

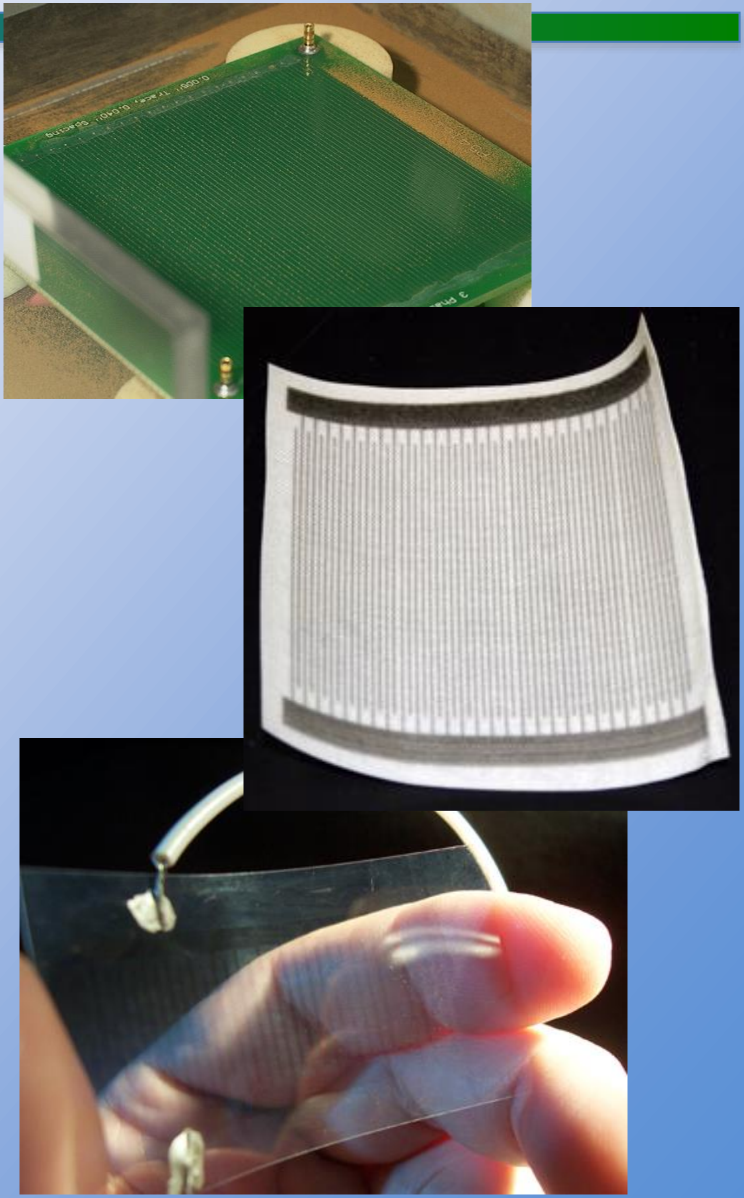
- Current-Voltage (*I-V*) curves at 9 mbars in air and in CO_2 were obtained.
- Voltage started at 100 V and increased by 50 V until the corona current reached 500 µA (higher than the 250 µA in previous design due to longer tube).
- We performed one single particle collection experiment with aerosolized 4 µm diameter Martian simulant particles.
- Obtained significant counts upstream with essentially no counts downstream
- Laboratory move did not allow us to perform additional experiments
- Current proposal for Mars 2020 mission, if approved, will allow us to resume experiments.



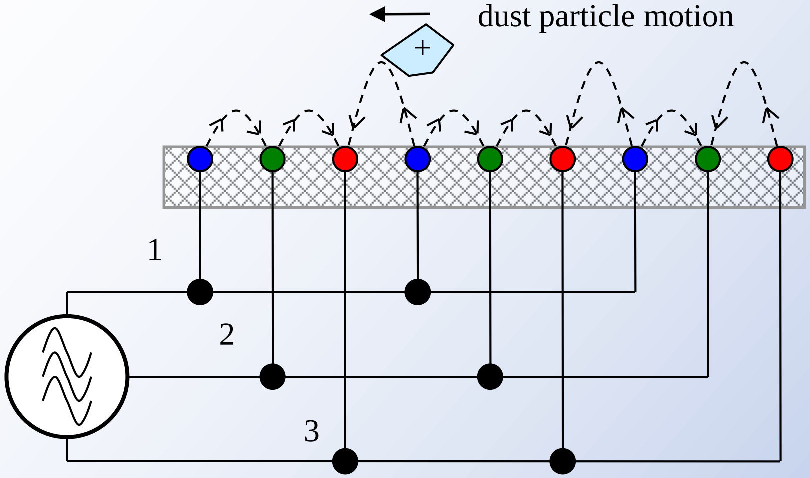
Current-voltage curves for the precipitator in a flow through configuration under 9 mbar no flow conditions

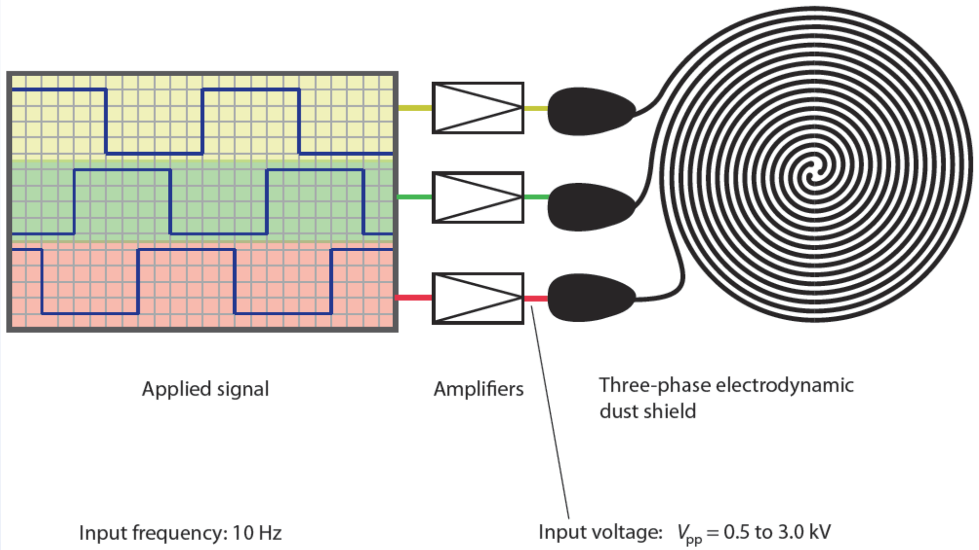
Electrodynamic Dust Shield

- With the EDS, Particles are removed by applying a multi-phase traveling electric field to electrodes that are embedded in the surface
- Electrodes:
  - Thin wires on opaque surfaces
  - CNT electrodes on fabric
  - Transparent, flexible electrodes on transparent surfaces for optical devices, windows, visors
- Applications developed:
  - Solar panels
  - Optical systems
  - Thermal radiators
  - Flexible films
  - Fabrics



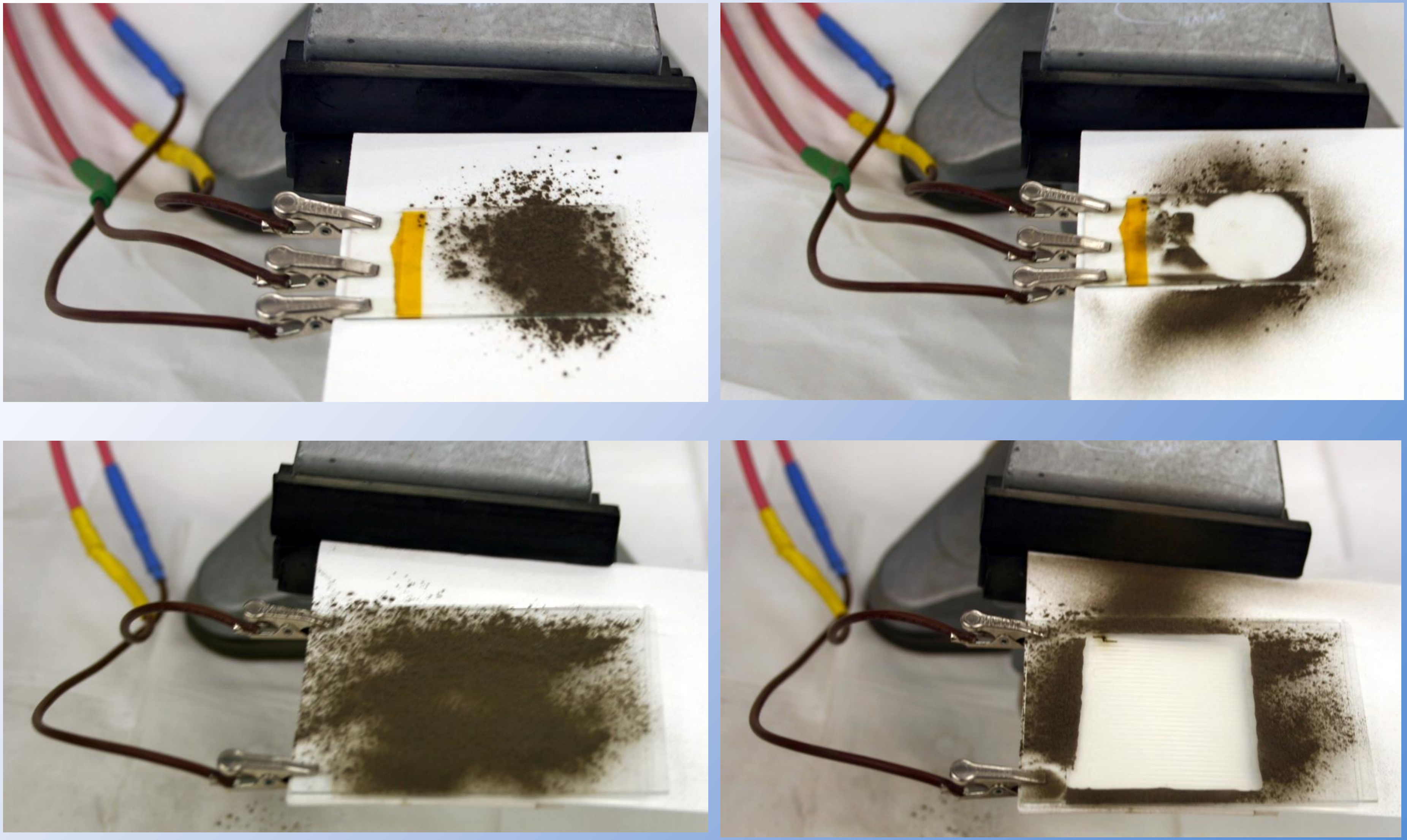
What's Under the Hood





Three-phase dust shield with indium tin oxide transparent electrodes in a spiral pattern configuration on a glass substrate

Transparent EDS for Optical Systems



Living Off the Land

- NASA's ISRU Project: production of
  - mission consumables
  - surface construction
  - manufacturing and repair
  - space utilities and power
- Oxygen, methane, and water production from Martian atmospheric gas requires prior dust removal
- Electrostatic Precipitator that works at 1/100 of an atmosphere

ISRU plant for vehicle propellant production