Electrostatic dust transport and its instrumentation on the lunar surface

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Hypothesis: Dust particles on the regolith surface of the Moon are charged and may be lofted or mobilized due to electrostatic forces.
Apollo Observations

Lunar Horizon Glow (LHG)

Lofted or levitated dust particles ~10 μm in diameter at height <30 cm

Criswell. 1973

Low-Speed Dust Detections across Terminator

However, later work analyzing different LEAM datasets (Grün and Horányi, 2013) found no significant rate enhancement during terminator crossings.

Berg et al., 1976

Enhanced electric field across lunar terminator due to differential charging has been thought to enhance dust lofting.
High-altitude streamers are thought to be nm-sized dust particles electrostatically lofted near the terminator (McCoy and Criswell, 1974; Zook & McCoy, 1991).

However, there are contradictory results:

High-altitude dust was indicated from the Apollo observations (McCoy, 1976; Glenar et al., 2011) and LADEE/UVS (Wooden et al., 2016) but not detected by Clementine (Glenar et al., 2014), LRO/LAMP (Feldman et al., 2014), and the in-situ measurements by LADEE/LDEX (Szalay and Horányi, 2015).
Dust Impact on Human Exploration

- Charged dust sticks to all exploration system surfaces, causing various issues:
  - Damage to spacesuits
  - Degradation of thermal radiators and optical components
  - Failure of mechanisms
  - Health risks for astronauts

- Understanding of electrostatic dust charging and transport is critical and imperative for assessing its impact on Artemis missions and future long-term, sustainable human exploration on the lunar surface.
A Long-standing Question

How do dust particles obtain enough charge to be electrostatically lofted from the regolith surface?
Macroscale Charging Models

**Shared Charge Model**

- **Plasma**
- **Sheath**
  - $Q = \varepsilon_0 \pi r^2 E$
  - $F_e = qE$
  - $F_g = mg$
  - $F_{co}$ (cohesive force)

**Charge Fluctuation Theory** (Stochastic process)

$Q_{dust}(t) = \bar{Q}_{dust} + \delta Q_{dust}(t)$

**Charge fluctuation magnitude is estimated as following**

$$\frac{\delta Q_{dust}^{rms}}{e} = \sqrt{\frac{CT_e}{e}}$$

These models cannot fully explain dust lofting on the lunar surface.

Flanagan and Goree, 2006

Sheridan and Hayes, 2011
Dust Lofting Experiments in the Laboratory

120 eV Electron Beam

38μm JSC-1A Lunar Simulant
Photo- or secondary electrons are absorbed within microcavities and collected by the surrounding dust particles, resulting in substantial negative charges on their surfaces.

Repulsive forces between the negatively charged particles cause them to be lofted from the surface.

According to Gauss’s law

\[ Q_b \propto \frac{(\phi_b - \phi_p)}{\lambda_{De}} \]
\[ Q_r \propto \frac{(\phi_r - \phi_b)}{r} \]
\[ Q_r \gg Q_b \text{ due to } r \ll \lambda_{De} \]

\[ Q \approx Q_r \approx -0.5C(\eta T_{ee}/e) \]

where, \( C = 4\pi\varepsilon_0\)

\( T_{ee} \) is the emitted electron temperature in eV.

\( \eta T_{ee} \) represents high-energy tail electrons.

\( \eta \): 4 ~ 10, empirical constant determined from experiments.
All lofted dust particles are charged negatively, even under UV radiation. This is contrary to the generally expected positive charge due to photoemission but agrees with the Patched Charge Model.
Characteristics of Lofted Dust Particles

Charge Magnitudes

Initial Velocities

Schwan et al., 2017

Size Distributions

Lofting Rates

Hood et al., 2022

Hood et al., 2018

Carroll et al., 2020

Characteristics of Lofted Dust Particles

Schwan et al., 2017

Size Distributions

Lofting Rates
It is time to find ground truth about electrostatic dust charging and transport on the Moon.
Findings on the Moon will help understand electrostatic dust transport and its role in surface evolution on other airless bodies in the solar system.

Dust ponds on asteroid Eros (Robinson et al., 2001)

Radial ‘spokes’ in Saturn’s rings (Smith et al., 1981)

Saturn’s icy moon Atlas (Hirata and Miyamoto, 2012)

Ponded dust deposits in Khepry on comet 67P (Thomas et al., 2015)
Electrostatic Dust Analyzer (EDA) to measure dust transport on the lunar surface (NASA – DALI: Development and Advancement of Lunar Instrumentation)

A Notional Measurement Configuration

EDA measures lofted dust particles that fall back to the lunar surface

EDA is inherited from Electrostatic Lunar Dust Analyzer (ELDA, Duncan et al., 2011)
Electrostatic Dust Analyzer (EDA)

Sensor Module:
- Dimensions: 21.6 cm X 17.0 cm X 17.9 cm
- Mass: 5.5 kg
- Power: 7.5 W

Functional Block Diagram:
- Sensor Module
- DSP Module

Power Services Board
- DAQ Board
- CSA Boards
- Wire Electrodes

Accelerometer

H/K ADC's
LVPS
Door Motor Drivers
Bias Voltage Power Supply
EDA Power Services

EDA Data Compress & CCSDS Packet
EDA Motor Controllers
Lander Interface
RS-422 Lander

FPGA
ARM CPU
Memory
Data Buffer Controller
Triggering
EDM Filter
In Rush

Tilt Motor Driver
Data Signal Processing (DSP)
A trajectory is reconstructed from induced charges on 4 wire-electrode arrays in two DTS as a charged dust particle flies through the sensor.

- **Charge** is measured from the induced charges on all wire-electrodes in a DTS.
- **Velocity** is determined from the time shift of the charge signals between the two wire-electrode arrays.
- **Mass (and size)** is derived from the trajectory deflection by DFE.

### Measurement Quantities

<table>
<thead>
<tr>
<th></th>
<th>Dust size accuracy</th>
<th>Velocity accuracy</th>
<th>Charge accuracy</th>
<th>Flux accuracy</th>
<th>FOV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 &lt; r &lt; 20 μm</td>
<td>0.8 &lt; v &lt; 20 m/s</td>
<td>1.2 &lt; Q &lt; 64 fC</td>
<td>0 &lt; F &lt; 1.7 particles cm⁻² s⁻¹</td>
<td>54° (for size meas.)</td>
</tr>
<tr>
<td></td>
<td>15%</td>
<td>15%</td>
<td>20% positive/negative</td>
<td>20% continuous</td>
<td>135° (for flux meas.)</td>
</tr>
</tbody>
</table>

**FOV**: 54° (for size meas.)  
135° (for flux meas.)
EDA – Engineering Model (TRL 6)

Sensor
First Dust Drop in Air

First Signals

6/7/2022
Dust Campaign in Vacuum Chamber

![Image of dust campaign setup]

Diagram showing:
- JSC-1A Lunar Simulant
- 2-axis translation stage
- EDA
- Vacuum Chamber
- Dust Dropper
- Pickup Tube
Data Analysis Flow Chart

ADC data

Conversion to physical quantities

Convert and correct waveforms to charge signals using CSA impulse response

Correct charge w/ loss due to wall effect and determine particle locations using a modeled lookup table

Fit trajectories with determined particle locations to derive mass (size)
Example Data (Large Charge w/o Deflection)

**Data Numbers:**
- DatNum: 3-17--9-44

**Entry and Exit Particle Identification:**
- A1, B1
- A2, B2

**Graphs:**
- Corrected Charge Signals
- Pickup Tube Charge Signal

**Estimated Dust Size:**
- 100 – 112 μm

**Velocity (at two DTS locations):**
- 2.2 & 2.6 m/s
- 2.17 & 2.5 m/s

**Charge:**
- 24 ± 0.8 fC
- 11.5*2 = 23 fC

**Additional Information:**
- Particle: 1

**EDA:** N/A

**Estimated Dust Size:**
- 100 – 112 μm

**Velocity (at two DTS locations):**
- 2.2 & 2.6 m/s
- 2.17 & 2.5 m/s

**Charge:**
- 24 ± 0.8 fC
- 11.5*2 = 23 fC
Example Data (Small Charge w/o Deflection)

Corrected Charge Signals

<table>
<thead>
<tr>
<th></th>
<th>EDA</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust Size</td>
<td>N/A</td>
<td>35 – 48 μm</td>
</tr>
<tr>
<td>Velocity (at two DTS locations)</td>
<td>2.1 &amp; 2.5 m/s</td>
<td>2.17 &amp; 2.5 m/s</td>
</tr>
<tr>
<td>Charge</td>
<td>4.6 ± 0.5 fC</td>
<td>2.0*2 = 4 fC</td>
</tr>
</tbody>
</table>

DatNum: 2-8-23--14-34
Example Data (Deflection)

Corrected Charge Signals

- A1
- B1
- A2
- B2

Particle

DTS | DFE | DTS
---|---|---
1 | + | *
* | * | *
7 | * | *
A1 | B1 | A2

Velocity (at two DTS locations)
- 2.2 & 2.5 m/s
- 2.17 & 2.5 m/s

Charge
- 11 ± 0.8 fC
- 3.6*2 = 7.2 fC

EDA Dust Drop Deflection Trajectories
- Drop height: 0.20 m
- Entry speed: 1.98 m/s
- phi: 6.0 V
- Q: 11.1 fC

Estimated Dust Size
- 33 μm
- 35 – 48 μm
Concluding Remarks

• Charging and lofting of dust particles on the lunar surface is a long-standing problem, which has important implications for planetary science and human exploration.

• Recent laboratory breakthroughs have improved our understanding of the underlying physics, paving a road for in-situ measurements on the Moon.

• EDA developed under the NASA-DALI program will provide direct measurements of electrostatically lofted dust on the lunar surface to ultimately solve this five-decade-old problem.