Electrostatic Dust Transport Effects on Shaping the Surface Properties of the Moon and Airless Bodies across the Solar System

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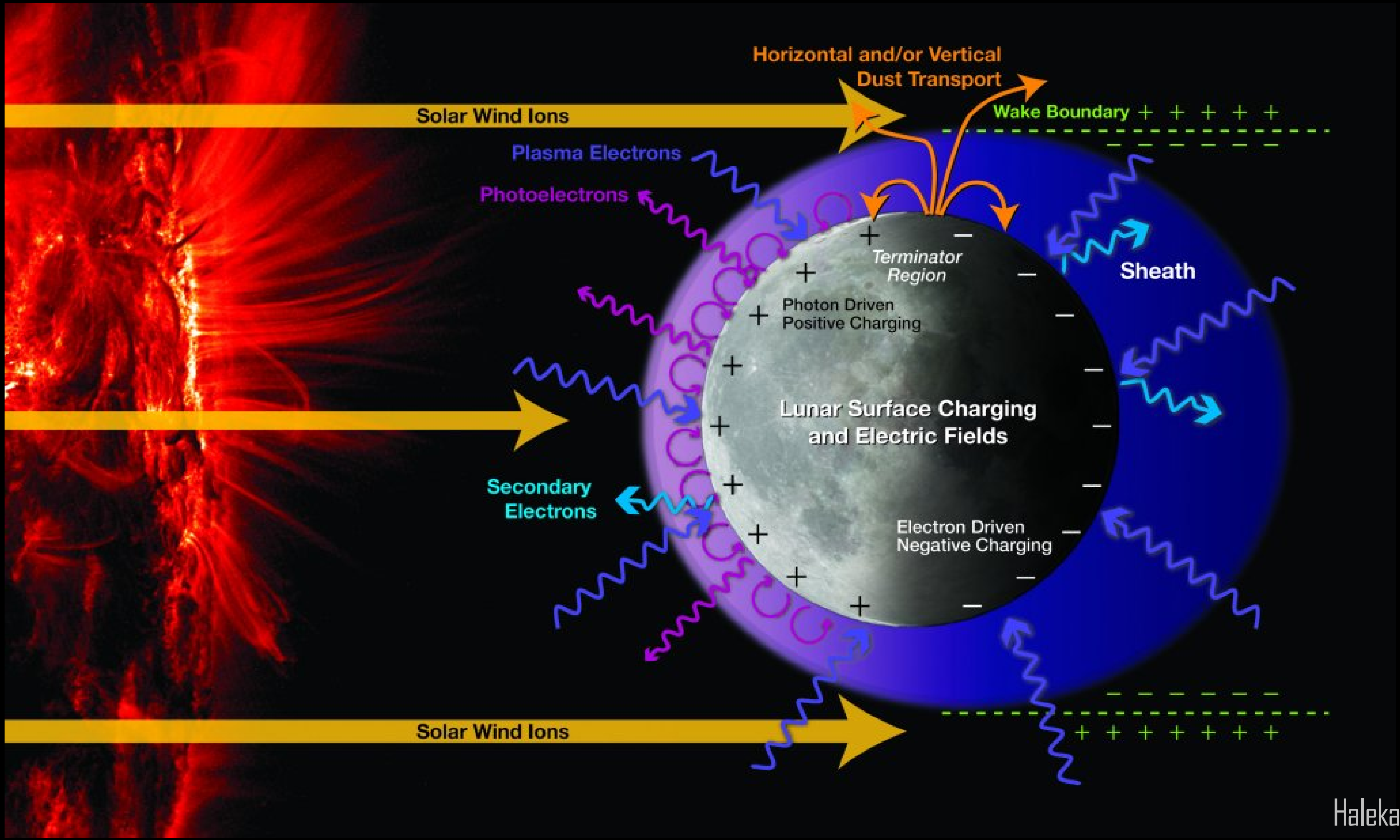
Unresolved Observation Puzzles related to Electrostatic Dust Transport

Plasma-Surface Interactions at Airless Bodies



Halekas et al

Dust particles on the regolith surface of airless bodies are charged, and may be mobilized, lofted and transported through electrostatic mechanisms.

Lunar Horizon Glow (LHG)

First evidence observed by Surveyor 5, 6 and 7

Height < 30 cm, dust particles ~10 μm in dia.

Criswell, 1973; Rennilson & Criswell, 1974; Colwell et al., 2007

Dust Deposition on Lunar Rocks

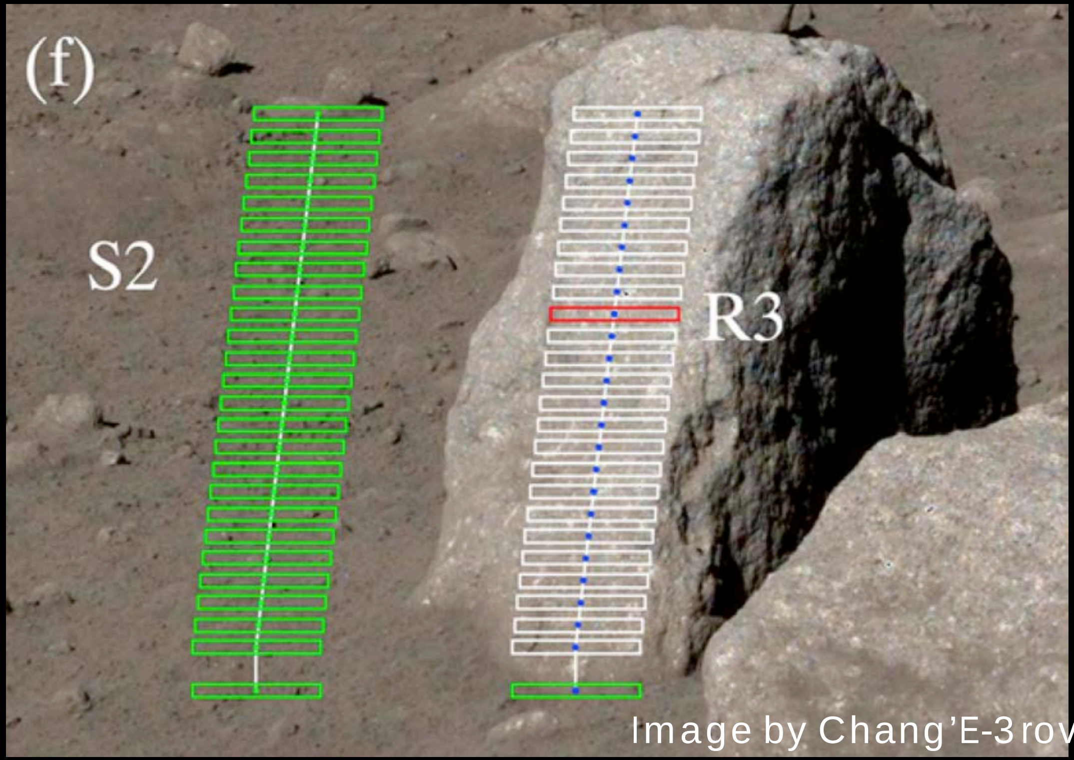


Image by Chang'E-3 rover

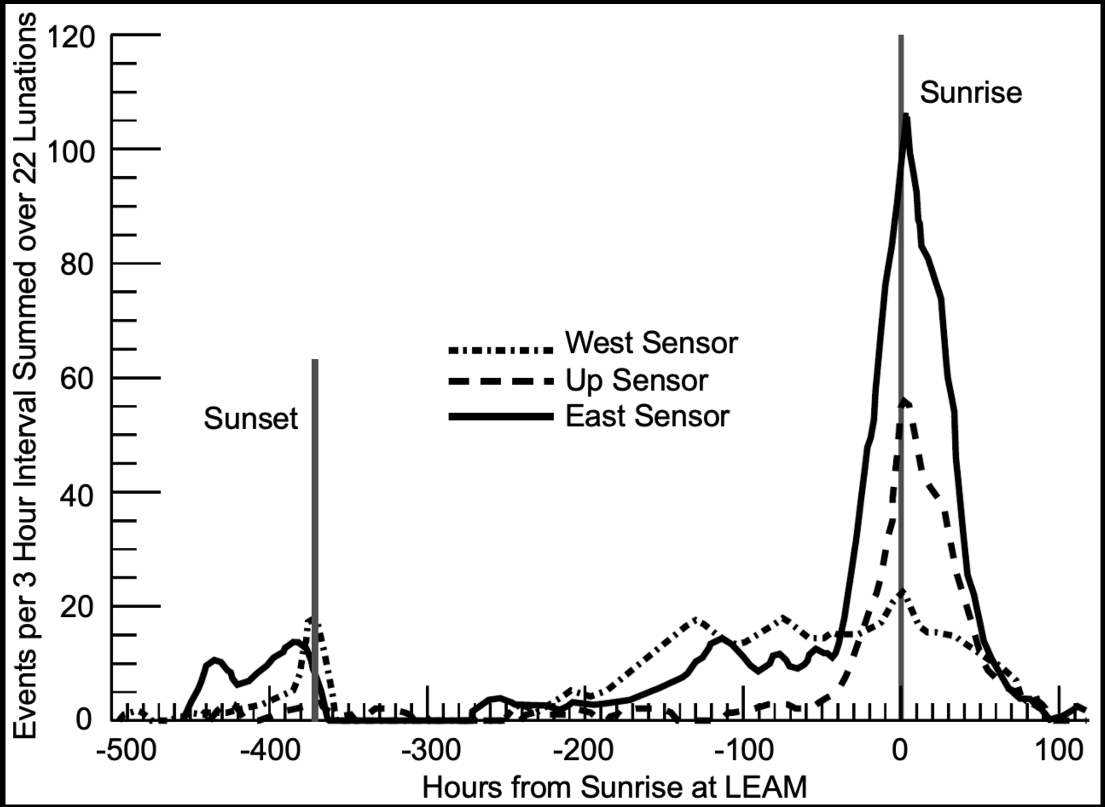
Yan et al., 2019

Dust deposition is found to be up to ~28 cm high on the rocks, which is a similar height to the LHG

Apollo Observations

Low-Speed Dust Detections at Terminator

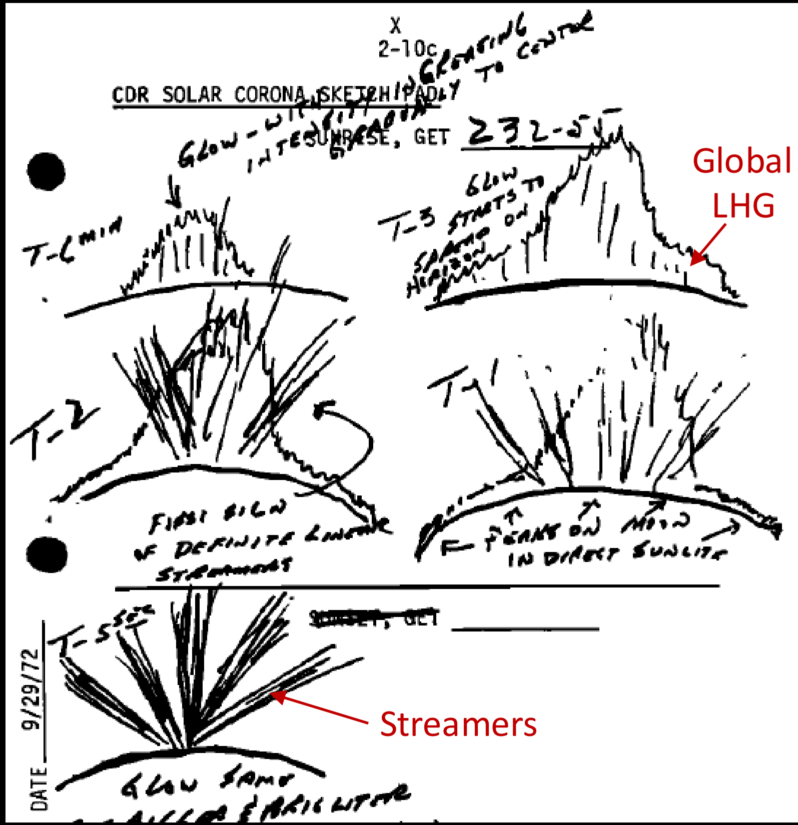
by the Lunar Ejecta and Meteorites (LEAM) experiment



Berg et al., 1976

High-altitude Global LHG and Streamers

(Sketches by Apollo 17 commander E.A. Cerman)



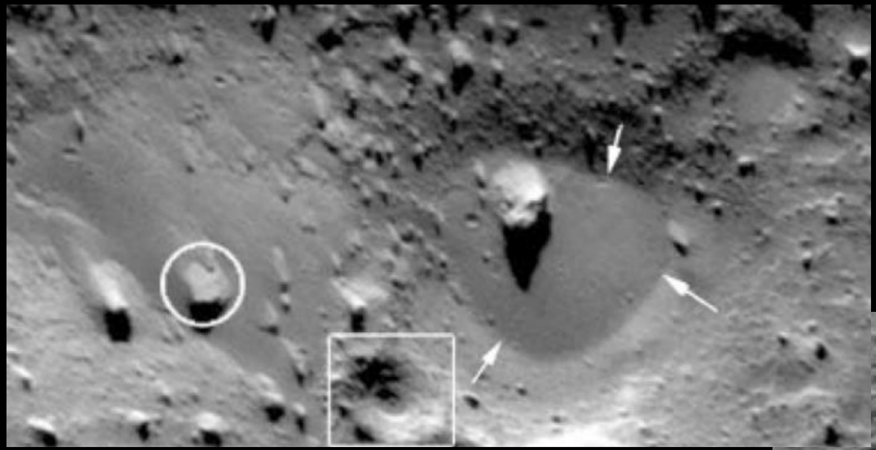
McCoy and Criswell, 1974

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

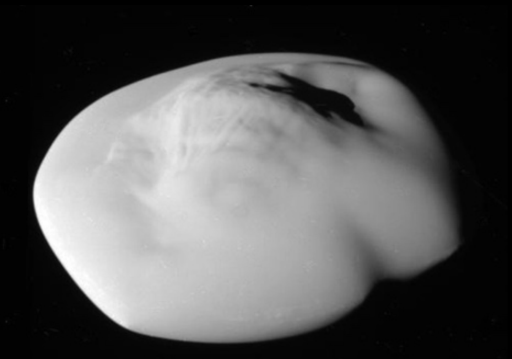
However, high-altitude dust was neither indicated by remote sensing observations by Clementine (Glenar et al., 2014) and LRO/LAMP (Feldman et al., 2014), nor by in-situ measurements by LADEE/LDEX (Szalay and Horányi, 2015).

Observations on Other Airless Bodies

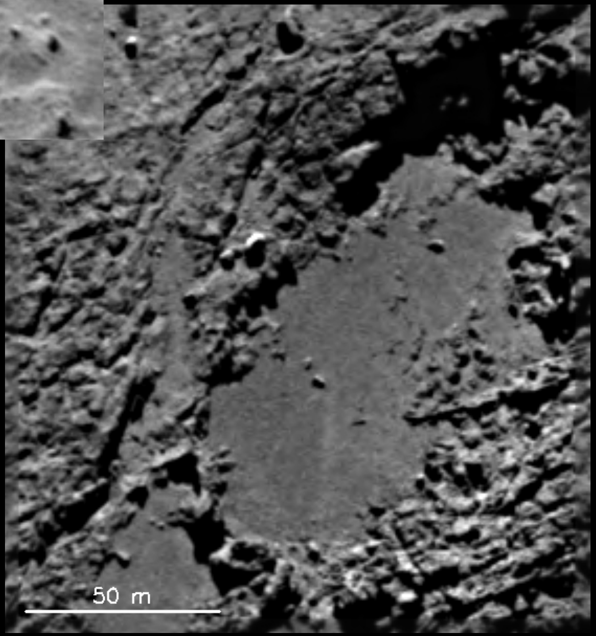
Radial ‘spokes’ in Saturn’s rings (Smith et al., 1981)



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



Highly smooth surface on Saturn’s icy moon Atlas (Hirata and Miyamoto, 2012)



Ponded dust deposits in Khepry on comet 67P (Thomas et al., 2015)

Recent Asteroid Missions

Unexpectedly, lack of regolith was observed on Ryugu and Bennu (Jaumann et al., 2019, Lauretta et al., 2019), which may be attributed to an electrostatic removal mechanism (Hsu et al., DPS, 2020)

Ryugu

Hyabusa2 (JAXA)

Bennu

OSIRIS-REx (NASA)

Electrostatic dust transport as a universal phenomenon, *if true*, may play an important role in the surface evolution of all airless bodies

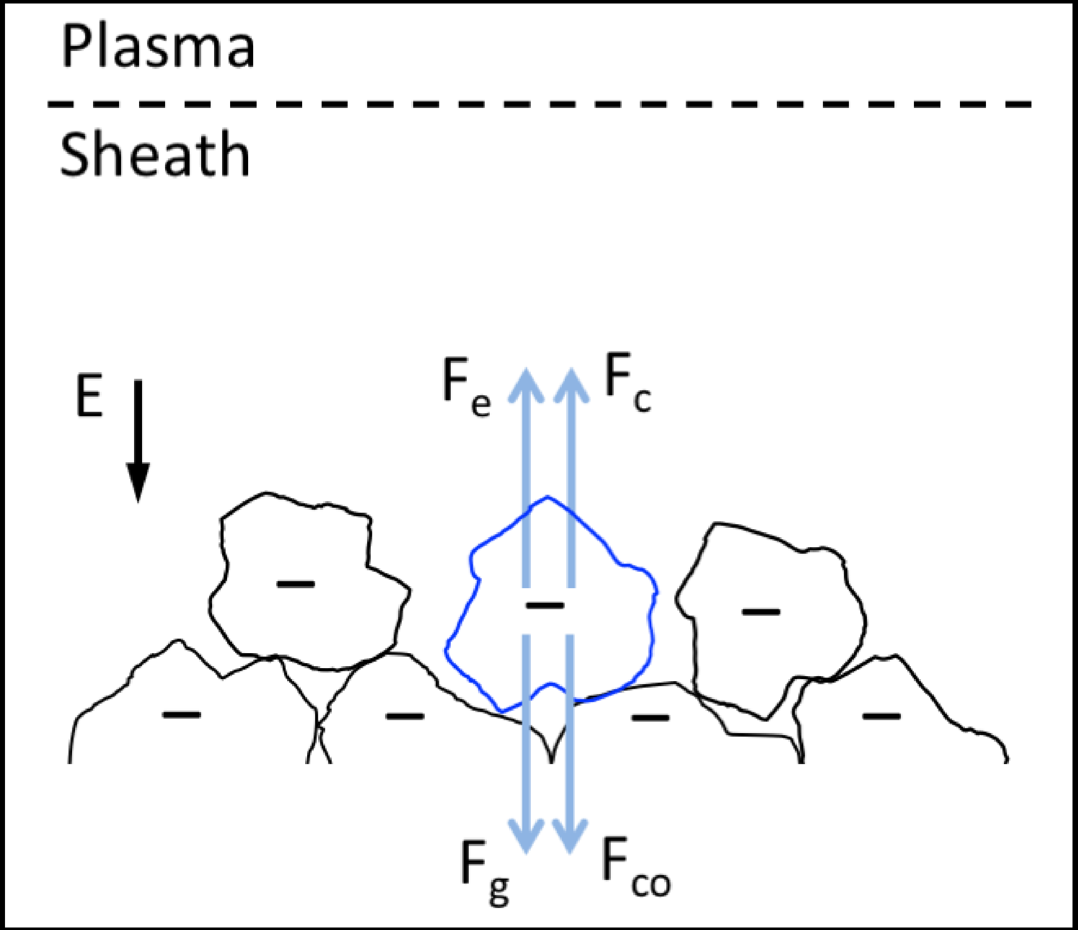
Current Understanding
of
Electrostatic Dust Transport

An increased interest has been attracted for lab, theoretical and computer simulation studies over the past decades in order to understand charging and lofting mechanisms of regolith particles and their dynamics on the Moon and other airless bodies to resolve the space observations.

A key fundamental question remained as a challenge to answer:

How do dust particles obtain enough charges to initiate their mobilization and lofting on airless bodies?

Previous Charging Theories



F_e: Sheath electric field force
F_c: Coulomb repulsive force
F_g: Gravitational force
F_{co}: Cohesive force

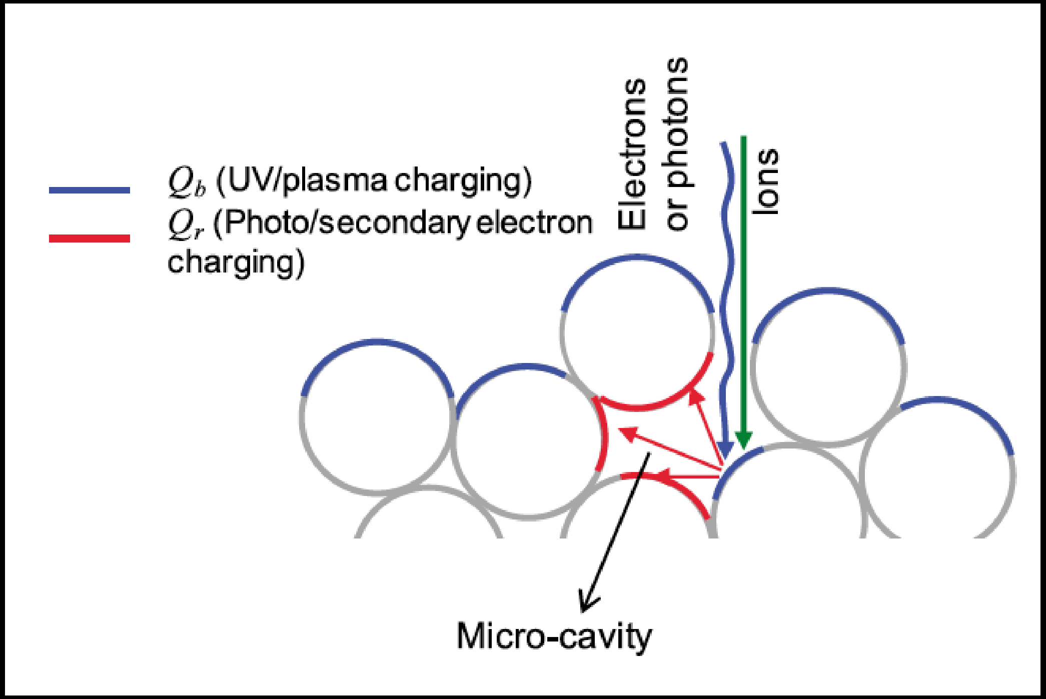
Study of charging on the regolith has been mainly based on the electric field above the regolith surface (i.e., regolith is treated like a solid surface).

The electrostatic force, which is the product of the predicted charge and electric field, is too small for dust particles to be lofted, off by several orders of magnitude required to overcome the lunar gravitational force.

Wang et al., 2016

ed Charge Model"

cale charging)



Wang et al., 2016

- Photo- or secondary electrons are emitted and re-absorbed inside a microcavity, and deposit substantial negative charges on the surrounding particles due to a large E-field across the small cavity.
- Strong repulsive forces between these negatively charged particles eject them off the surface.

More and more lab and modeling studies have produced results in support of the patched charge model and provided new insight into the characteristics of dust charging and lofting, including initial dust charge and velocity, size range and lofting rate.

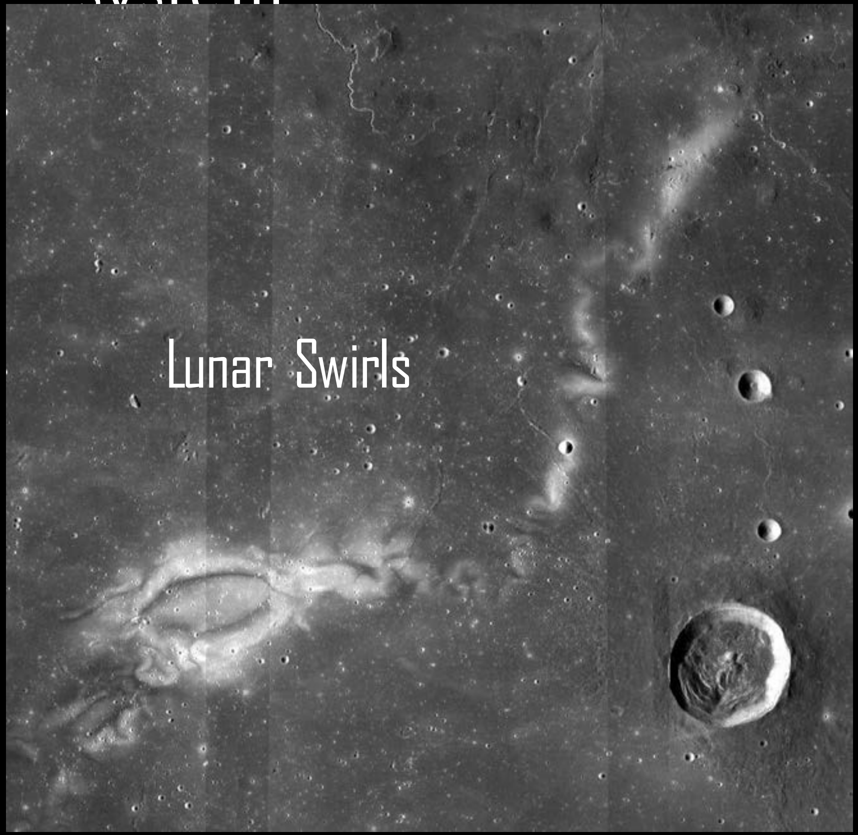
References: Zimmerman et al., 2016; Schwan et al., 2017; Hood et al., 2018; Dove et al., 2018; Orger et al., 2019 ; Carroll et al., 2020.

These lab and modeling studies, in combination with previous observations, show strong support for the occurrence of electrostatic dust transport on the surfaces of the Moon and other airless bodies

In-situ measurements are needed in order to determine the ground truth

Significance

- Surface evolution of the Moon and other airless bodies across the solar system



Dust size re-sorting may cause the formation of high albedo patterns (Garrick-Bethell et al., 2011)

- Resurfacing process due to electrostatic dust mobilization and transport may change the surface physical properties, including surface porosity (e.g., 'fairy castle' Hapke and Van Horn, 1963; Mendell and Noble, 2010), dust size distribution and even regolith loss due to dust escape on small bodies
- Both thermal and spectral properties may be significantly altered as a result of the changes in the surface physical properties. *A possible example is shown on the left.*
- This electrostatic process potentially adds a new dimension, in addition to impacts and space weathering, for understanding the surface evolution of the Moon and other airless bodies.

Relevance to NASA Strategic Goals in Previous Reports: PSDS 2012-2023 and NASA Science Plan 2014: *How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?* Lunar SCEM 2007 and LEAG's ASM-SAT reports: Science Goal 8b - *Determine the size, charge, and spatial distribution of electrostatically transported dust grains*; and Transformative Lunar Science 2018: 2f) *Evaluate the extended record of space weather and fundamental processes of plasma interactions with surfaces.*

- # Dust hazards to future surface exploration

Mobilized dust due to natural mechanisms and/or human activity poses potential risks to future lunar surface exploration, as recognized by the Lunar Surface Innovation Consortium (LSIC) as one of the major technical challenges.

Dust hazards learned from the Apollo missions (Afshar-Mohajer et al., 2015) include

- Damage to spacesuits
- Degradation of thermal radiators and optical devices
- Failure of mechanisms
- Health risks for astronauts

Electrostatic dust is also of concern to asteroid space resource utilization (Graps, et al. 2016; Graps et al., 2019).

Apollo 17 Astronaut Harrison "Jack" Schmitt coated by lunar dust during his field investigations. NASA photo.

Relevance to NASA Strategic Goals in Previous Reports: 1) Science Goal 8b in Lunar SCEM 2007 and LEAG's ASM-SAT reports; 2) HEOMD Lunar SKG-III-D-2: *Regolith adhesion to human systems and associated mechanical degradation*; 3) Strategic Objective 2.2 in the NASA 2018 Strategic Plan: *Conduct human exploration in Deep Space, including to the surface of the Moon*, and 4) Global Exploration Roadmap: *Enable sustained living/working around and on the Moon.*

- Planetary defense for Near-Earth-Objects (NEOs)

Fine dust particles significantly contribute to the regolith thermal properties, which plays a role in determining orbital and rotational dynamics of small bodies. Studies in this topic are potentially applicable to NASA’s NEO survey programs for planetary defense.

Relevance to NASA Strategic Goals in Previous Reports: NASA’s 2018 Strategic Objective 1.1: *Understand The Sun, Earth, Solar System, And Universe - Safeguarding and Improving Life on Earth*; and NASA’s Explore Science 2020-2024 Priority 1 Exploration and Scientific Discovery, Strategy 1.1 – Planetary Science: *Advances in planetary science, coupled with leading efforts to detect, track, and characterize near-Earth objects, will continue to improve planetary defense*.

Outstanding Questions

- **What are the dynamics of dust charging and subsequent lofting and transport in the near-surface plasma and electric field environment on different types of airless bodies?**

  Lab studies have shown that electrostatic dust transport largely depends on ambient plasma conditions, as well as the regolith and dust properties, including regolith compaction and microstructure, dust size, shape and composition, and inter-particle cohesion.

- **How does electrostatic dust transport play a role in shaping the surface physical and spectral properties on different types of airless bodies?**

Recommendations
for
Next Decadal Studies

- Synergy of in-situ measurements, laboratory experiments and theoretical modeling

  In-situ measurements complemented by lab and modeling investigations are recommended to

  - Unambiguously confirm the occurrence of the electrostatic dust phenomenon on airless bodies.
  - Quantify dust charging and lofting processes on different types of airless bodies.
  - Explain and predict remote sensing and sample return measurements of the surface properties of airless bodies due to electrostatic dust transport.

- Lunar landed missions

  - Both robotic and crewed lunar landed missions are recommended, enabled by Commercial Lunar Payload Services (CLPS) and large-lander missions as part of the Artemis program.
  - Recommended instruments include in-situ dust and plasma instruments at various locations, as well as remote sensing instruments for global-scale observations.

- Asteroid and/or comet missions with small landers/rovers
  - Small landers or rovers carrying dedicated dust instruments are recommended to be deployed by large asteroid or comet missions. Examples of this type of mission implementation include Rosetta, Hayabusa2 and upcoming Martian Moons eXploration (MMX) missions.
  - Standalone smallsat missions (e.g., SIMPLEx) that deploy small landers/rovers are also recommended to measure electrostatic dust transport on NEOs.

- Dust Mitigation
  - Characterizations of charged dust mobilized by natural mechanisms and/or human activities are recommended to be investigated.
  - Collaborations between SMD, HEOMD and STMD are recommended to tackle this challenge.

Concluding Remarks

- Electrostatic dust charging and transport, as a five-decade long problem, has been suggested to explain a number of phenomena observed on airless bodies.

- Recent laboratory experiments have made a breakthrough in understanding the fundamentals of dust charging and lofting.

- This electrostatic process has important implications for the surface evolution of the Moon and other airless bodies, dust hazards for future surface exploration, as well as planetary defense of NEOs.

- In order to ultimately understand this electrostatic phenomenon and its science and exploration impacts, synergy of in-situ measurements, laboratory experiments and theoretical modeling, lunar landed missions, asteroid and/or comet missions with small landers/rovers, as well as dust mitigation studies are recommended for next decadal studies.