IMPACT OF DUST ON LUNAR EXPLORATION

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ABSTRACT

All astronauts who walked on the Moon reported difficulties with lunar dust. These problems were likely worsened by the fact that the dust was electrically charged, which enhanced its adhesive properties. In order to develop strategies to tackle these issues it will be necessary to advance our theoretical understanding of the lunar dust-plasma environment, as well as comprehensively characterize it with in-situ measurements. Summarized here are the relevant properties of lunar dust and its impact on astronauts, together with a discussion of the three main problem areas: (1) Dust Adhesion and Abrasion, (2) Surface Electric Fields and (3) Dust Transport. Also discussed are recent calculations relating to some of the Apollo-era observations, together with necessary future in-situ measurements and suggested mission strategies.

1. INTRODUCTION

From the Apollo era it is known that dust on the Moon can cause serious problems for exploration activities. Such problems include adhering to clothing and equipment, reducing external visibility on landings, and causing difficulty to breathing and vision within the spacecraft [e.g. 1,2]. Eugene Cernan, commander of Apollo 17, stated that *"… one of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and it's restrictive friction-like action to everything it gets on"* [1].

NASA has recognised dust mitigation as being a priority in its Requirements for Lunar Exploration Program (RLEP) document (ESMD-RQ-0014), which states that the potential biological impacts of the lunar environment, including the micrometeoroid and dust environments, will be investigated (RLEP-M20 and RLEP-T20) [3]. Dust has also been highlighted as a priority by the Mars Exploration Program Assessment Group (MEPAG).

An important step in dealing with dust-related problems is to understand how dust grains behave in the ambient lunar environment. This will require both advances in our theoretical understanding together with a thorough characterization of the near-surface dust-plasma environment with comprehensive in-situ observations. This will be vital for the development of reliable mitigation strategies for lunar exploration.

We shall briefly describe the properties of lunar dust and its impact on the Apollo astronauts, followed by descriptions of the three main problems areas relating to electrically-charged dust: (1) Dust Adhesion and Abrasion, (2) Surface Electric Fields, and (3) Dust Transport. A summary is given in Table 1 of the impacts on exploration with relevant connections to existing scientific expertise.

2. PROPERTIES OF LUNAR DUST

"Lunar regolith" describes the layer of particles on the Moon's surface generated by meteoritic impacts, and is comparable to terrestrial volcanic ash [4]. The finest component is referred to as dust (<100μm).

Average regolith grain size is ~70μm, (too fine to see with the human eye), with roughly 10 to 20% by weight <20μm [4]. Recently, the dust component from Apollo samples has been directly observed to contain grains as small as 0.01μm [5]. Grain shapes are highly variable and can range from spherical to extremely angular; although, in general, they are somewhat elongated [4].

The low electrical conductivity of the regolith allows individual dust grains to retain electrostatic charge. On the lunar dayside conductivity can increase with surface temperature and infra-red and ultra-violet radiation [4]; therefore, this needs to be taking into account for surface and dust charging processes.

3. DUST IMPACT ON ASTRONAUTS

Outside the Lunar Module (LM) dust was kicked-up during landings which significantly reduced visibility [2]. Inside, dust would be brought in after moonwalks. It was reported by Alan Bean on Apollo 12 that *"After lunar liftoff … a great quantity of dust floated free within the cabin. This made breathing without a helmet difficult, and enough particles were present in the cabin atmosphere to affect our vision"* [2].

As mentioned, dust can make breathing difficult. It is very possible that chronic respiratory problems could arise in astronauts due to microscopic particulates in the lungs, especially after prolonged periods on the lunar surface [6]. It is also possible that lunar dust is toxic.

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Figure 1. Substantial amounts of lunar dust were clearly adhering to Jack Schmitt's spacesuit during Apollo 17.

Lunar dust resides in near-vacuum conditions, so the grain surfaces are covered in "unsatisfied" chemical bonds, thus making them very reactive. In an atmosphere, this "surface activity" would be pacified by reactions with the constituent gases (e.g. H_2O, O_2, etc, on Earth). In response to this potential hazard, NASA has formed the Lunar Airborne Dust Toxicity Advisory Group (LADTAG) to devise a strategy to evaluate this risk. Note that the Apollo astronauts were on the Moon for a relatively brief period of time, so it is not possible to fully assess the toxic effects of lunar dust. On Earth, such an assessment typically requires either chronic or intense exposures.

4. DUST ADHESION AND ABRASION

Dust adhered to spacesuits (see Fig. 1) both mechanically and electrostatically. Mechanical adhesion was due to the barbed shapes of the dust grains, which allowed them to work into the fabric. Alan Bean also noted that *"… dust tends to rub deeper into the garment than to brush off"* [2]. Electrostatic adhesion was caused by charging of objects by the solar wind plasma, photoionization and triboelectric charging (see Section 5). During Apollo, it was found that the abrasive effect of adhered dust can wear through the fabric of a spacesuit, drastically reducing its useful lifetime [1,2].

Problems were experienced during Lunar Roving Vehicle (LRV) excursions, with much dust being kicked-up and covering exposed areas [1,4], leading to increased friction at mechanical surfaces. The resulting abrasive effect of dust increased wear and tear, which significantly limited the lifetime of surface equipment.

From the recovery and examination of parts from Surveyor 3 during Apollo 12, it was found that dust accumulation and adhesion were greater than anticipated [4] on both aluminum and painted surfaces.

5. SURFACE ELECTRIC FIELDS

Charged dust adhesion and transport on the Moon are strongly linked to the environmental electric fields. The lunar surface electrostatic potential can be calculated by balancing the incident electric currents to the Moon's surface (i.e., in equilibrium the net current is zero) [7]. Using this approach it can be shown that the lunar dayside charges positive, as photoelectron currents caused by solar UV and X-rays dominate; and the lunar nightside charges negative, since plasma electron currents dominate, as illustrated in Fig. 2. It is also possible for the global-scale transition from positive to negative surface potential to occur dayside of the terminator [8,9].

A wake or "void" forms downstream of the Moon when it is immersed in the solar wind flow, as indicated by the

Table 1. Examples of lunar dust-related phenomenon, their impact on exploration and connection with existing scientific expertise (particularly in the field of space plasma physics).

Lunar Phenomenon:	Impact on Exploration:	Connection:	Relevant expertise:
Dust Adhesion	- Abrasion of surfaces. - Thermal Effects. - Health Risks.	- Determining how charged particulates in a plasma interact with a surface.	- Surface physics. - Plasma-surface interactions, e.g. sputtering.
Surface Electric Fields	- Causes dust to electro-statically adhere to objects. - Drives dust transport.	- Understanding how objects charge in a plasma and under solar illumination.	- Spacecraft charging. - Probe physics. - Plasma wake physics.
Dust Transport	- Coats exterior surfaces with fine layer of charged dust. - Compromise optical observations from the Moon.	- Understanding how particulates interact with a plasma. - Knowing how the dust and plasma are modified by this interaction.	- Dusty plasma physics. - Planetary Rings.
Surface Composition	- Locating Resources. - Identifying landing sites.	- Understanding the source and composition of sputtered ions.	- Pick-up ions, e.g. from comets.

dashed lines behind the Moon in Fig. 2. This complicated interaction creates large electric fields at the terminator [10], amongst other phenomena.

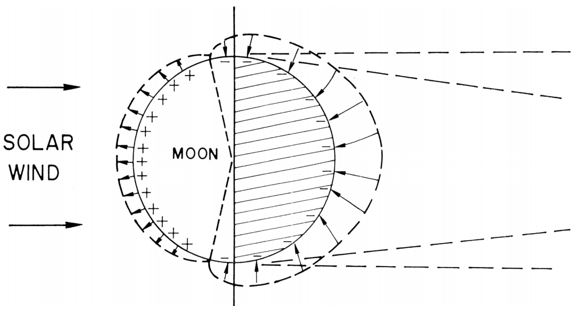

Figure 2. Sketch showing the global-scale charging of the lunar surface in the solar wind [7]. Also indicated is the sheath that acts to shield the ambient solar wind plasma from the lunar surface charge (not to scale).

It is also important to realize that the Moon spends about a quarter of its orbit traversing the magnetosheath and the tail of the magnetosphere when it passes nightside of the Earth [9]. Within the magnetosphere the plasma environment is typically much hotter and more tenuous than in the solar wind flow, so surface charging differs significantly [9].

6. LUNAR DUST TRANSPORT

The Lunar Ejecta and Meteorites (LEAM) experiment was placed on the lunar surface by Apollo 17 to detect hypervelocity impacts from meteoroids. Surprisingly, the measurements were dominated by high velocity impacts (up to 1 km s^{-1}) from electrostatically charged dust [11]. Interestingly, the counts registered by LEAM peaked around the terminator, especially at sunrise, as shown in Fig. 3.

Horizon glow (HG) and “streamers” from forward scattered sunlight were observed above the terminator by both surface landers and astronauts [e.g., 12,13]. It was suggested that near-surface HG (<1m) was caused by scattering from levitating dust grains with radii of ~5μm, with line-of-sight column dust concentrations of ~50 cm^{-2} [12,14]. This was likely due to electrostatic charging of the lunar surface and dust grains, which caused the dust to be repelled from the like-charged surface [e.g., 12,13,14]. Note that HG was ~10^7 too bright to be explained by meteoroid-generated ejecta [12,14].

There was also evidence for 0.1μm-scale lunar dust present sporadically at much higher altitudes (~ 100km) [15] (see also Figs. 1 and 3 in [16]). Observations from the Lunokhod-2 astrophotometer of the “twilight” lunar sky (when the Sun was ≈1° below the horizon) were about 20 times brighter at visible wavelengths than anticipated [17]. This brightness was likely caused by light scattering from dust above the edge of the lunar shadow (≥260 m) [17]. McCoy’s model “0” for dust concentrations in the lunar exosphere – inferred from “excess brightness” in Apollo 15 and 17 coronal photography – showed a decrease with altitude to: ~10^{-1} cm^{-3} at 1 km, ~10^{-2} cm^{-3} at 10 km and possibly ~10^{-5} cm^{-3} at 100 km [13]. The scale height for this dust population was determined to be ~10 km, which is too short to be caused by sodium or potassium gas in the lunar exosphere (also these gases are too dim to be seen by the unaided human eye) [18]. An unexpected diffuse background brightness was also seen in images taken from the lunar surface during the Apollo 16 mission by the Far-Ultraviolet Camera/Spectrograph [19]. It was speculated that this background brightness could have been caused by electrostatically suspended dust [19], which also suggests that electrostatic transport of dust can occur during the lunar daytime [8].

It has been proposed that dust observed at high-altitudes is electrostatically “lofted” by the “dynamic dust fountain” effect [8,16], as opposed to the static levitation mechanism used to explain heavier grains nearer the surface [12,14]. In the dynamic dust fountain model charged dust grains follow ballistic trajectories, subsequent to being accelerated upwards through a narrow sheath region by the surface electric field. These dust grains could affect the optical quality of the lunar environment for astronomical observations and interfere with exploration activities [e.g., 20].

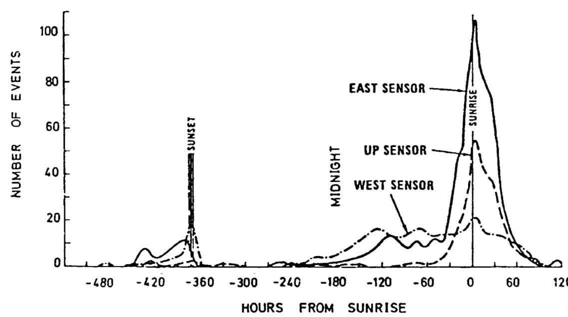

Figure 3. Number of dust impacts registered by the 3 sensors of the Lunar Eject and Meteorite (LEAM) experiment per 3-hour period (integrated over 22 lunations) as a function of time from sunrise [11].

Under certain conditions it is likely that triboelectric charging plays an important role in causing dust grains to become highly charged at the lunar surface [21]. Triboelectric charging is caused by both differences in contact potential and frictional transfer of charge between grains in contact. Laboratory experiments using JSC-1 lunar simulant have shown that individual grains of r_d ≈ 50 μm can acquire a triboelectric charge of ~10^5 electrons via inter-grain contacts [21]. Dust grains on the lunar surface would acquire triboelectric charge when separated by a disturbance, such as a meteoritic impact.

It has recently been suggested that fusing the lunar regolith together using a microwave sintering technique may, to some extent, alleviate the dust problem in the area local to a lunar habitat [22]. This sintering process would have to be regularly reapplied, since dust from elsewhere would be transported onto treated surfaces by both natural and artificial means.

7. IN-SITU MEASUREMENT REQUIREMENTS

All the existing observations of the electrostatic transport of dust were acquired by instruments designed to measure something else (e.g., LEAM was set-up to detect hypervelocity impacts). Therefore, it is necessary to make targeted in-situ measurements of dust-plasma-surface interactions on the Moon in order to fully understand this alien environment. This will be an important precursor to human exploration, which will allow our new understanding to be applied to the development of systems and equipment, particularly critical systems such as life support.

Future necessary measurements include:

- Determining the size and concentration of dust in the lunar exosphere. This will show exactly how much dust gets ejected from the surface.
- Finding the surface electric field height profile. This will reveal both the surface potential and the shielding scale length (probably of order the local Debye length). The surface electric field is a driver behind the electrostatic transport of dust. Observations can be correlated with upstream conditions (e.g., in the solar wind) to determine their effect on surface charging.
- Direct detection of the mass, velocity and charge of dust grains above the surface. A future instrument will need to be sensitive to grains with energies below the threshold of LEAM, since this will likely allow the detection of the bulk of the transported dust population.

Characterizing the near-surface plasma will also be important. For mathematical convenience, it is often assumed that this plasma is quasi-Maxwellian [e.g., 7].

In Table 2 we list instruments that could measure the key dust-plasma parameters discussed above. All of these instruments come with significant spaceflight heritage, and so provide a highly reliable means of characterizing the lunar dust-plasma environment in situ. These instruments can each be built with a mass of roughly 2 – 3 kg and requiring between about 2 – 5 W to operate (excluding heaters). The electron and ion spectrometers would typically weigh slightly more at around 5 kg, while a LIDAR would likely have significantly greater mass and power requirements. The above estimates are based on instruments that can satisfy the most basic observational requirements; naturally, with a greater mass and power budget a more comprehensive set of measurements can be achieved. These observations would provide vital environmental information for experiments testing dust mitigation strategies, particularly if an active response is required.

Table 2. Required measurements, and examples of instrumentation with the necessary spaceflight heritage.

Measurement:	Instrumentation:
Exospheric dust concentrations	Photometer (passive) CCD imager with filters (passive) LIDAR (active)
Surface electric fields	Electric fields boom (and maybe magnetometer)
Dust mass, velocity and charge	Microphone-type impact sensor (similar to LEAM)
Plasma characteristics	Electron spectrometer Ion spectrometer

If a suite of dust-plasma instrumentation, such as that listed in Table 2, were flown on a surface lander and deployed at a single location, this would certainly provide invaluable new data. However, a better option might be to deploy a rover with instrumentation on both its landing platform and the rover itself (as has been done with the imagers on the Mars Exploration Rover platforms). The observations from the platform would act as a control, while the rover investigated dust-plasma-surface variations due to, for example, changes in topography and surface composition. Such a lander/ rover combination could also accommodate many other science investigations relevant to future exploration.

Another option would be to make these observations from orbit, which would permit a global view of the lunar electrostatic environment. In particular, this would help us better understand the effect of the lunar wake on surface charging and dust transport, as well as gauge the extent and location of dust in the Moon's exosphere. A combination of orbiter and lander-based observations would provide both the global perspective and the precise local measurements necessary for understanding the underlying physical processes.

8. CONCLUSIONS

In order to fully assess the potential hazards posed by electrically-charged dust to lunar exploration it will be necessary to:

1. Take targeted in situ measurements of dust and plasma in the lunar environment with modern instrumentation, and
2. Develop theory and simulations to model the highly complicated lunar surface-dust-plasma interactions [8].

Required measurements include:

- Concentration of dust in the exosphere as a function of altitude and zenith angle [cf, 13];
- Mass, velocity and charge distributions of transported dust [cf, 11];
- Electric field and plasma (density and temperature) profiles above the surface.

This can be achieved with fairly basic spaceflight-proven instrumentation, as listed in Table 2. These measurements would resolve the ambiguities and uncertainties associated with Apollo-era observations. Further development of our theoretical work will be vital in order to interpret these important and exciting new results [8, 9, 16].

9. ACKNOWLEDGMENTS

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