Lunar Dust and Regolith: Outstanding Questions and Important Investigations

1. Overview and definitions

Lunar regolith is the broken up rock that comprises most of the lunar surface down to several meters) that has been generated over eons due primarily to impacts and micrometeorite bombardment. Any systems operating on the lunar surface will interact with the regolith, and most remote-sensing systems interrogate primarily the upper mm of the surface. Our current understanding of lunar regolith characteristics comes from samples returned from the Apollo missions, some *in situ* measurements, and remote sensing data. Significant questions remain relating to the properties and behavior of regolith on the lunar surface, and to how it interacts with human and robotic systems. Much of this can be learned with returned samples, but many of the interactions are best studied *in situ* and will require characterization on the surface in future lunar missions.

This report summarizes the discussion of the broad themes and open questions that were identified during the Lunar Surface Science Workshop (LSSW): Dust and Regolith Virtual Session, held on August 20, 2020. Additional discussion during the outbrief and breakout group at the Lunar Exploration and Analysis Group (LEAG) meeting on September 15, 2020 was also captured.

In this report, the term "regolith" is used when discussing the general characteristics of the material on the lunar surface, especially as it is considered for lunar surface science. Key technology areas concerned with regolith properties include mobility, trafficability, and sample acquisition.

The term "dust" is typically used to refer to the finest parts of the lunar regolith. In this report we use the term "dust" to refer to the finest particulates, and generally in discussions related to the phenomenology related to lofted and blowing dust (including exospheric/orbital species). *Dust mitigation*, as well as some rocket exhaust/plume interaction effects, is the key technology area focused on dust properties and interactions. We note that there is overlap between the key areas of dust and regolith, but do our best to distinguish between questions related to each throughout this report.

2. Outstanding Questions

The LSSW presentations identified several outstanding questions about lunar regolith characteristics and surface processes, as well as dust and regolith interactions that will arise due to surface operations. Those questions are sorted and included here, but this list is by no means comprehensive. Questions in italics are directly relevant to Artemis systems.

Bombardment and surface modification

- What are the details of the processes by which impacts create and continually shape the lunar regolith?
- How large is the area affected by a newly formed impact event and what are the emplacement mechanisms in the affected area?
- How important is micrometeroid bombardment in modifying and redistributing dust on the lunar surface?
- At what depth are sparse distal secondaries able to churn the regolith?
- *Has the lunar surface been modified by the action of gas, dust, or other comet-related effects?*

Regolith Production and Characteristics

- How do volatiles migrate through the lunar regolith?
- What details of lunar and Solar System history are contained in the Feldspathic Highlands Terrane regolith/paleoregolith/megaregolith?
- What is the 3D microstructure of undisturbed regolith? Does this structure change in permanently shadowed regions?

Space Weathering

- What is the dominant space weathering process for the Moon?
- How do local environmental conditions (e.g., temperature, presence of volatiles) influence space weathering effects?
- How important are micrometeroid bombardment and solar-wind ion exposure in the optical space weathering of the lunar surface, and what are the implications for space weathering on other airless silicate bodies?
- How does space weathering manifest itself at the lunar poles?
- What role does space weathering play in generating the low porosity upper layer in permanently shadowed regions (PSRs)?
- What process forms the larger microphase (>50 nm) iron in agglutinates?
- Is there a unifying model of space weathering that can connect all airless bodies?
- To understand the record of the ancient Sun, can we find regolith samples of known age and solar exposure?

Electrostatic/magnetic dust behavior:

- *What are the electrical and magnetic properties of lunar dust?*
- How does electrostatic dust transport play a role in shaping the physical and spectral properties on the surfaces of the Moon and airless bodies across the solar system?
- *What are the charging state and behavior of dust particles lofted naturally or by human activity in the near-surface plasma environments on the Moon?*
- Magnetic anomalies are predicted to have especially active surface dust environments. Can such activity be observed in-situ, and what can the processes at work in the

magnetic anomalies tell us about what happens at other places on the Moon or other airless bodies?

Dust Mitigation

- *How can we leverage dust mitigation efforts to learn about the regolith, the Moon, or exploration?*
- *What techniques/technologies are needed to reduce/mitigate lunar dust impacts on the astronauts, their equipment, habitats, and spacecraft?*
- Which simulants should be used for testing dust mitigation technologies/techniques?

Dust and Human Interactions

- *How does the lunar regolith behave (dynamically, electrostatically, etc.) during human-induced interactions?*
- *What are the particle size distribution, mineralogy/chemical composition and possible toxicity of lunar dust, especially for the particles < 50 μm?*
- *Would you travel to the Moon if your good health could not be guaranteed?*

System Design/Trafficability

- *How do we design science systems and procedures to collect and return regolith grains with their outer surfaces in as pristine a state as possible?*
- *In evaluating factors such as surface adhesion and chemical activities relative to engineering systems, how much does surface pristinity affect the fidelity of engineering tests ("what makes lunar grains stick?")?*

3. Discussion

Several broad topics were identified during the workshop discussions, breakout sessions, and outbrief. These topics categorize outstanding issues that must be addressed in order to optimize scientific and technical return from upcoming lunar surface missions. Broadly, these topics can be organized to address two key questions related to upcoming lunar exploration strategies:

- ***What are the immediate questions regarding dust and regolith that need to be answered/addressed prior to landing with human systems?***
- ***What are the first science/exploration objectives with respect to dust & regolith that should be addressed with the Artemis III landing?***

Below we summarize the discussion relating to those questions.

3.1. What are the immediate questions regarding dust and regolith that should be answered/addressed?

3.1.1. Physical properties

Despite in-situ data collected by the Surveyor, Luna, and Apollo missions, and observations from orbital spacecraft, many outstanding questions still exist regarding the physical properties of lunar regolith, especially for the unexplored polar regions. One key question that has emerged is ***what are the geotechnical properties of the lunar surface (especially in the polar regions), and what precursor measurements are needed to inform human exploration in these regions.***

Specifically, it is crucial to determine where it is safe to send a rover to drive, the best approaches for digging trenches for science or mining, how steep trench walls can be, and what the bearing capacity of the regolith is for the purpose of building structures and excavating. Questions remain regarding how long it takes the soil to be loosened and then re-compacted after a trafficability event such as a rover traverse. Recent analyses of boulder tracks within PSRs could potentially be used to help inform this question, and data from the Chang'E-4 missions also provides more recent context.

Many open questions also remain about which, if any, regolith properties will be different in the polar regions. For example, *will the lack of thermal cycling lead to differences in porosity and compaction in polar regolith compared to regolith in equatorial regions? Will the space weathering environment be different? Are agglutinates different in the polar regions? Is the mean grain size different in the polar regions? How much ice do you have to have before physical properties begin changing?* Without the extreme temperature cycles that the equatorial and mid-latitude regions experience, the regolith in the polar regions is likely to be less compact and more porous. Temperature may affect the size of nanophase iron particles, thereby causing space weathering processes to be different in the polar regions due to the cooler temperatures.

Current remote sensing data sets measure properties such as surface roughness, porosity, density, and mineral identification. However, these measurements are restricted to the upper few mm of the surface and have footprints larger than the size of typical human/rover interactions. Instruments on board a lander would give higher spatial resolution information that can better answer some of the questions stated above. Polarization data from the upcoming Korean Lunar Pathfinder Orbiter (KPLO) mission may answer some of the questions regarding grain size distributions and porosity in the polar regions, and data from LRO is being used to produce grain size maps and answer other questions regarding surface properties of lunar regolith. However, landers with dedicated instruments designed to measure grain size, porosity, compaction, etc. are necessary to fully answer these questions. Precursor robotic missions will gather the necessary data to better inform trafficability and sampling strategies.

Since the Surveyor missions, lunar surface observations have hinted at the existence of processes that cause natural electrostatic dust lofting; however, these processes were not directly observed during Apollo, and it is challenging to produce all of the aspects of lofting in the natural environment with numerical simulations. Recent laboratory experiments have made additional progress in understanding and developing a model for how these lofting processes might occur. Outstanding questions remain about the size distribution of naturally lofted dust, the height of lofting, and the magnitude of the effect. There may be preferential locations for observing this phenomenon, as the conditions for charged dust lofting depend on factors such as topography, lighting, and plasma conditions. Some models indicate that these effects could be exacerbated in polar regions, where the plasma conditions (due to interactions with the solar wind and illumination) vary from those at equatorial locations. In situ measurements of the plasma and dust dynamics are needed to resolve these questions, and to determine the magnitude of the problem, including assessing how seriously it must be addressed.

3.1.2. Interaction effects

Understanding rocket exhaust interactions with the lunar surface is crucial to safely land, protect landing hardware and assets already in place, and conduct scientific investigations. The need is especially true for Artemis, which will require multiple landings at the same site and will involve landing larger total masses than was done for Apollo. Many additional questions exist regarding landing spacecraft in the polar regions, such as *"Will differences in regolith porosity/compaction due to volatiles and colder temperatures cause variations in how much rocket exhaust interacts with the surface?"* Polar regions with more volatiles and more porous surfaces could experience different surface alterations than non-polar regions.

For the Artemis program, the landers will be much larger than those used in Apollo, so plume effects will be much larger. The larger CLPS landers' plumes will cause interactions in very different physical regimes than previously observed (*e.g.* lower Knudsen number, possible turbulence transitions around the impingement point, higher stagnation pressure on the lunar surface, etc.), and it is unknown whether there will be localized effects such as crater formation under the nozzle because accurate modeling of these regimes is still limited. The HLS landers will also have engine configurations different from the Apollo single-engine configuration; multi-engine configurations could redirect plume-lofted dust back up at the spacecraft, potentially leading to damage to the spacecraft. This leads to the question, "*How will this difference in spacecraft design affect the blowing of dust during landing?"* More information and modeling is needed to accurately predict the extent of surface disturbance that will occur, especially by landers much larger than those of Apollo.

Finally, these disturbances will have significant implications for science and data collection in the surrounding regions. Scouring and removal of material from the surface will have the effect of modifying the natural stratification, but also revealing previous-buried surfaces. Any sampling/collecting in the region immediately surrounding landers must take this into account. An estimate of the affected area is necessary to know to what distance rovers/humans will need to go to sample pristine surfaces.

The very fine-grained (dust to sand-sized) materials that compose the regolith in the area surrounding the Apollo Lunar Modules were shown to be blown at velocities up to 3 km/s, so a fraction of that material can exceed escape velocity of the Moon. Any dust lofted to these altitudes can cross through the regions of orbital assets, including the proposed orbit of the Gateway. Impact velocities can be estimated based on the orbital speeds of the spacecraft. The LDEX instrument on the LADEE spacecraft provides estimates of naturally lofted dust populations. Additional orbital dust detectors would be of use to understand this extended lofting.

3.1.3. Collecting regolith samples

Before returning to the surface of the Moon, we must investigate sampling strategies that will allow us to understand and study regolith properties. For example, the submicron grains are important for understanding respiration issues for astronauts, so learning more about the behavior of these grains is important for astronaut health. Studying the presence of nanophase iron on particles will also help us understand more about space weathering in the polar regions. Thus, *how do we design systems and procedures to collect and return grains with their outer surfaces in a pristine state?*

Additionally, improved ways of collecting regolith samples must be considered. These could include automated coring devices, deeper core samples, more trench sampling, etc. Sampling techniques such as tape-like materials could prove useful for sampling the uppermost layer of regolith, especially to determine grain size distributions and fine-scale surface changes induced by rocket exhaust effects. See the LSSW Tools and Instruments and the LSSW: Samples and Volatiles reports for more details on sampling strategies.

3.1.4. Dust charging, and the need for exclusion and/or mitigation

A common question for those designing surface systems, technologies, scientific instruments, and human systems is "*to what extent do we need to worry about dust exclusion and dust mitigation?"* It is known from the Apollo missions that dust can cause issues by sticking on spacesuit material, degrading suit seals, being introduced into habitats, etc., and dust accumulation on surfaces such as radiators and solar panels can cause significant thermal and power issues. However, many of these observations are anecdotal - there is little technical information on these behaviors.

Dust grain charging can occur naturally or due to interactions with dynamical systems. Systems on the surface of the Moon are exposed to the natural plasma and illumination conditions - this is true for landers, rovers, humans, and dust. Dynamical interactions between these objects can lead to a buildup of charge, which must be understood in order to avoid deleterious electrical discharge effects. This applies to objects such as drills, rover wheels, and even potentially humans shuffling on the surface. The conditions during the Apollo missions (strong daylight) were right to mitigate these effects, but they may be exacerbated if systems are operating in both light and dark regions, and in the changing plasma conditions at the lunar poles.

Dust exclusion applies when reducing the chances of allowing dust to interact with systems at all, such as with dust covers on optics, or by keeping suits out of habitats. Dust mitigation techniques acknowledge that surfaces will be exposed to natural and disturbed lunar dust, and seek passive and/or active ways to mitigate dust adhesion to surfaces, collection on surfaces, or intrusion into mechanisms. These may be able to take advantage of the natural electric fields that are present based on plasma/illumination conditions. There are a range of passive (surface coatings, surface modification techniques) and active (the Electrodynamic Dust Shield (EDS), other electrodynamic techniques) technologies currently under investigation. Techniques such as brushing, which was tested prior to Apollo but had issues when used on the lunar surface, are also continued to be studied.

Key to the design of these technologies, and predicting their performance, will be improved characterization of surface and lofted dust populations, including predictions of upper limits for dust loading, distribution of particle sizes, and distribution of particle charge as a function of location on the surface, time of day (which influences the natural sunlight and plasma environment). Simulants can be used for testing technologies; both fundamental and applied experiments can help determine the roles that properties of lunar dust such as size, shape, and composition play on dust adhesion in order to improve mitigation techniques.

Before significant constraints are known, teams designing instruments and technologies can work backwards to determine the loading and dust interactions that can be handled by the system, and then design deployment techniques to keep dust interactions below upper limits. This could include dust covers, deployment at a predetermined time after landing (when the dust has settled), deployment on raised platforms, such that the instrument is less likely to have dust kicked up on it, and more. Looking at technologies from Apollo, Mars surface missions, and current asteroid sampling missions, as well as assets deployed in extreme environments on Earth, can give insight into such techniques. These designs can then be further improved with operational experience on the lunar surface.

3.2. What are the first science/exploration objectives with respect to Dust & Regolith that should be addressed with the Artemis III landing?

3.2.1. Characterize the fine-scale polar regolith

Outstanding questions remain regarding the existence and nature of the fine-scale surface structure of the lunar regolith, especially in the polar regions. One such feature is the fairy-castle structure, which refers to the stacking of grains when particles are small enough that adhesive forces overcome gravitational forces, allowing a particle to be supported by one contact rather than three. This stacking configuration creates a very cohesive and highly porous structure that resembles towers (hence the term fairy castle, coined by Hapke and van Horn, 1963). However, this fairy-castle structure has not been observed in-situ, and is difficult to replicate in terrestrial labs.

Resolving questions related to the existence and nature of fairy castle structures will directly aid in our understanding of the porosity and roughness of lunar regolith. Fairy-castle structures have implications for space weathering and understanding the deposition of nanophase iron on particles. Understanding the nature of fairy castles at the polar regions will also help us better understand optical remote sensing data. For example, remote observations of the optical properties (e.g., backscattering characteristics) of the surface regolith can be used to infer surface porosity and roughness, and having direct measurements from the surface will help us better interpret this remote data. The destruction of fairy-castle structures has been proposed as a cause for the brightness seen around spacecraft landing sites, since destroying this structure reduces porosity and increases the reflectance of the surface. Hence, understanding how fine-scale structures of the regolith affects our remote sensing data will greatly improve our understanding of the lunar regolith.

The creation and destruction of fairy-castle structures is believed to be related to electrostatic variations on the lunar surface, especially during the day-night cycle. Observing these structures across different times of the lunar day/night can also inform our understanding of electrostatic processes on the Moon. Direct sampling of the fairy castle structure is difficult, because it will be destroyed as soon as it is touched. Dedicated techniques for imaging/observing the surface gently can and should be developed for the Artemis III landing. Additionally, a very slow moving rover such as Moonba may be more successful in imaging these structures..

3.2.2. Characterizing lander effects on the natural surface

Prior to surface operations, it is critical that lander companies take steps to characterize the lander exhaust plume ***chemistry***. This includes characterization of the exhaust products - chemical species and amounts, as well as an understanding of the plume profile (temperature and pressure). This can be used to improve models of the surface interactions, but will also be crucial so that researchers taking scientific measurements on the lunar surface can account for these byproducts in their analysis.

Small landers can be used as test beds for understanding plume-surface interactions (PSI). A number of instruments have already been selected to study plume effects during CLPS missions, and there should be instrumentation on every lander to build up a database. Artemis missions, with a far greater scale, should similarly include instrumentation to study PSI.This may be done with the landers themselves or with pre-deployed instrumentation.

All lander missions should characterize the observable changes to the landing sites pre- and post-landing. This can be done with orbital observations, but it would be desirable to deploy landers or rovers prior to the Human landing, or to continue observations in between landings.

3.2.3. Characterize the natural dust and plasma environment

All landed surface systems will operate in the natural plasma and dust environment, but this natural system is also influenced by inputs due to emission from landers and human systems.

Early missions should deploy instruments to study the natural environment to characterize changes over the course of the mission, as well as long-term observations that allow for study during the changing conditions over the course of a lunar day and night. Active instruments may include plasma instrument suites and dust detectors, and passive or ancillary measurements maybe be done with cameras and witness plates. Technologies can be actively monitored to understand the electrical conditions, or dust loading on surfaces of systems such as solar panels and radiators.

3.2.4. Materials sample return

Instrumentation deployed on the surface is needed to catalog dust behavior in situ, but much can be learned by returning hardware and materials that have operated on the lunar surface, in addition to scientific samples. This includes spacesuits and tools that have been used to interact with the lunar dust, as well as passive systems that were deployed on the surface. If possible, returning samples with different exposure ages and degradation. Samples may be from the Artemis 1 mission, or from early landed missions at a nearby location.