INDICATIVE *BASIC* ISSUES
ABOUT
LUNAR DUST IN THE LUNAR ENVIRONMENT
A WHITE PAPER
for the
NATIONAL ACADEMIES
PLANETARY SCIENCES DECADAL SURVEY

by

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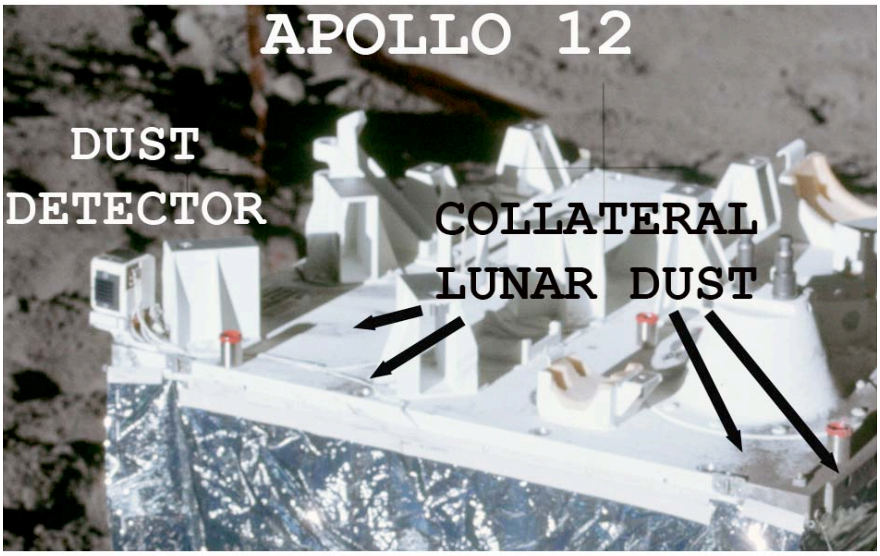

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INDICATIVE *BASIC* ISSUES ABOUT LUNAR DUST IN THE LUNAR ENVIRONMENT

SUMMARY:

"*Basic*" issues of lunar dust - including recent discoveries - so fundamental they affect a wide range of lunar research and exploration beyond their immediately obvious scientific disciplines, must be recognised as priorities instead of being often overlooked in scientific, engineering and operational aspects of lunar dust, itself the Number 1 environmental problem on the Moon.

Examples include (i) adhesive and cohesive forces on dust on sensitive surfaces as well as in plasmas; (ii) transport of charged dust due to local and global environments; (iii) nano-dust; (iv) collateral dust; (v) differentiation between composition of surface lunar dust and collateral dust on elevated surfaces which may be carried into a habitat. The unexpected and/or unknown realities of such basic issues can be overlooked in focussed analyses without the consequences to expectations being fully appreciated. Such factors are vital for full successes with future robotic and human missions to the Moon and Mars.

Four Recommendations with high or very high priorities are given together with the minimum perceived Outcome from each should it be implemented.

1. LUNAR DUST

In 2009, while images of ***levitated*** lunar dust fascinate scientists, memories of ***clinging*** dust worry and bewilder engineers and astronauts. "*Dust is the Number one environmental problem on the moon.*" And it is not coincidence that the Mars Human Precursor Science Steering Group (MHPSSG) identified dust as the number one operational and human issue for future Martian exploration as well.

Arguably, as a consequence, just as geology was the primary and dominant energising science before and during the Apollo era, lunar dust is becoming the principal and charismatic energising science for future lunar missions themselves and for applications of lunar findings to distant Mars.

2. LUNAR SOIL IN THE LUNAR ENVIRONMENT

The lunar soil is both scientifically interesting - formed by processes alien to the Earth's surface - and potentially hazardous. The mineral composition is, for the most part, similar to the Earth's crust, but the particle size distribution, shapes, and chemistry are alien (Heikan, 1991). The regolith is formed by space weathering, after billions of years of impacts of meteoroids of all sizes in an environment of intense, unfiltered solar radiation. This leads to an abundance of particle sizes down to 10 nm (Greenberg, 2009, Liu, 2008) and diverse shapes. Bombardment by hydrogen from the solar wind makes the chemistry reducing.

But many of the basic properties of the regolith, particularly the finest fraction, remain unknown. The particle size distribution of the sub-micron fraction of the native regolith has only recently been probed. There is little doubt but that sampling tools and the sample bags have clinging to them a dust sample heavily biased towards the finest particles. Particle shape distributions may be similarly biased. The surface of samples removed from the 10^{-12} Torr vacuum and the constant bombardment of solar and galactic radiation will necessarily be altered from their native state. Those most energetic surface states will be the ones least represented in the laboratory. Characterization of these states and the comparison of their abundance with those of dust on other airless bodies such as the moons of Mars, asteroids, and rocky moons of outer planets could tell much about the interaction of particles on airless bodies with solar radiation.

Because there are such significant variations across the parent regolith, one expects consequential differences in lunar dust which largely originates locally from that parent. What such differences may be is not known. What operational consequences follow for robotic equipment or astronaut activity is consequently unknown.

Soil properties unknown or poorly understood can impact the safety of planned human missions. Apollo astronauts were unprepared for the severity of the problems that the dust caused (Gaier, 2005). Current and future research must prevent a repetition, as well as probe complex phenomena to illuminate science. Pragmatic attention to basic issues is essential to help achieve both goals.

3. NANO-DUST ON THE MOON – A UNIQUE LABORATORY

Apollo expeditions in 1969-72 were completed before understanding and technological skills developed in nanoparticles, with dimensions of order 0.001 µm. It is now timely and possible to examine both the physics and the chemistry of lunar dust at nano dimensions (*nano-dust*). New and unexpected processes will be revealed.

Knowledge of the physical characteristics of lunar surface nano-dust, based on lunar samples, is essential to give Ground Truth validity to such theoretical models as suggestions the lunar regolith is the source of ultrafine dust (circa 10 nm) which causes horizon glow when it levitates at sunrise to altitudes of tens of kilometers (Stubbs 2006).

Research into chemically reactive nano-particles currently examines potential toxicity to the health of human populations. Recognition is increasing of potential hazards to astronauts of long-term exposure to lunar dust, with different hazards for different particle sizes. New understanding of the physics and chemistry of lunar nano-particles will create synergies with terrestrial nanotechnology in medical and industrial applications.

Size distributions of lunar dust particles from various Apollo expeditions are reported to peak in the range 100 to 300 nm, with none apparently measured with radii of less than about 20 nm (Liu, 2008). Whether the absence of smaller particles is due to laboratory limitations or to absence of such ulltrafine dust particles in regolith dust appears presently uncertain. Core samples of lunar nano-dust layering would be a permanent calendar of events, much as ice-cores from the Arctic and Antarctic provide monitors of the Earth's atmosphere for the past million years. Lunar nano-dust could also be a valuable monitor of lunar characteristics and pollution of the moon, but collecting, packaging and analysing uncontaminated samples of nano-dust present extreme difficulties. The present lack of information about such nano-dust also represents a "missing link" between the "Lunar Dusty Exosphere" and Lunar Volatiles white papers put together by the NLSI's Dust & Atmosphere Focus Group.

RECOMMENDATION #1:

With very high priority, new experimental and theoretical programs should focus on lunar nanoparticles, their properties if they exist and reasons for their absence if they do not exist.

OUTCOMES #1: The minimum outcome will complete a gap in knowledge of primeval cosmic and lunar dust size and composition. The knowledge is vital to the height and composition of a lunar exosphere, to understanding processes of uniquely powerful and toxic nano-dust – including those with abundances of nanophase metallic iron (np-Fe^o) (Liu et al. 2008) – and medical applications on earth. The information will fill a “missing link” in descriptions of the lunar environment.

4. HUMAN HEALTH AND LUNAR DUST

Although no long-term effects of lunar dust exposure have been reported in any of the Apollo astronauts, they were on the lunar surface for no longer than about three days, and completed no more than three EVAs. With plans for stays as long as six months, and each astronaut participating in perhaps a hundred EVAs, the health risks of inhaling, ingesting, and contamination with lunar dust must be reassessed.

Although there are organizations, such as the NASA Lunar Airborne Dust Toxicology Advisory Group (LADTAG) studying this problem, they do not have access to lunar dust fresh from the lunar environment. At best they can use regolith samples that have remained in storage under nitrogen for forty years and activate it by crushing or exposure to a proton beam. A worrisome indicator is that using grinding to activate various dusts leads to the conclusion that freshly fractured lunar dust generates more destructive hydroxyl radical in solution than freshly ground quartz, which is known to be toxic (Wallace, 2008). But this is no guarantee that the material being used in the toxicology test has the same surface properties that a sample fresh from the lunar surface would have. For example, there have been no reports from the activated lunar dust samples of the “burnt gunpowder” smell of fresh lunar dust reported by the Apollo astronauts. **It is difficult to do credible toxicology studies when the toxin is not available.**

5. ADHESIVE AND COHESIVE FORCES AND LUNAR DUST

Lunar dust in the lunar environment is so troublesome for humans and equipment because of its very high cohesion and adhesion. Perhaps the largest contributing factor is the absence of an atmosphere, so that dust grains remain molecularly clean. Electrostatic interactions among particles and between particles and other surfaces must play a major role in the enhanced cohesion and adhesion, but there is little knowledge of the importance of other interactions such as mechanical interlocking and van der Waals forces.

Basic construction techniques, such as digging and trenching, in this highly compacted surface in reduced gravity will have to be better understood if effective construction equipment is to be designed and built. The soil cohesion is so high and the gravity field so low that the loose soil does not easily flow through funnel. This greatly impacts many construction activities and the operation of chemical reactors that will be used to generate oxygen from the soil.

6. DUST TRANSPORT AND ELECTRICAL ENVIRONMENT.

Near-surface dust in the active lunar exosphere forms a highly complex and self-interacting system of ions, electrons, electric fields, and dispersed charged dust particles

[Stern,1999]. It is subject to many large-scale variable forces common to other bodies of the inner Solar system such as variable solar wind plasma and photo-electron emissions forced by sunlight. It also is subject uniquely by the passing of the earth magnetic field wake. This dusty plasma is itself of great active interest in the physics literature in itself and in its contrasts with conventional plasmas [Shukla, 2001].

Basic issues related to lunar and other inner-planetary missions include:

- Dusty plasma interaction with conductive and non-conductive surfaces should lead to non-trivial surface charging processes, particularly near terminators;
- Electrostatic repulsions could lead to lofting. A gradation of grain-size distributions, with compositions richer in smaller sized dust at higher heights, results from the electrical forces (area proportional) and gravitational forces (volume proportional). Consequently, dust properties, size, and shape parameters differ on elevated surfaces (eg suits) from their nominal lunar surface values;
- Gradients in solar wind plasma could lead to vertical and horizontal transport [Stubbs, 2006], of primary concern near the terminator region;
- The charging time constants of nanometer vs. micrometer size particles could be vastly different, eg hours for the former and minutes for the latter [Pines et al, 2009].

Consequently the net sum of all adhesive forces is not simply an “electrostatic force” but a complex function of multiple parameters, including the nature of the surface itself.

Charged-dust behaviour should dominate most observed dust-related phenomena *outside* the habitat. Hence carried dust inside the habitat should also be different than its nominal surface counterpart. The details of such differences, associated partly with solar wind, makes high fidelity experiments on charged dust behaviour difficult on earth.

RECOMMENDATION #2: Very high priority should be placed on understanding the relationship between surface and adhered lunar dust, with synergistic theoretical support to connect all relevant physical forces associated with charging, lofting, transport, and adhesion/cohesion of lunar dust.

OUTCOME #2: Strong theoretical and experimental basis for predicting surface adhered type, size distribution, charge and surface forces directly from measured and/or estimated lunar surface dust parameters; Predictability of behaviour in challenging lunar regions (e.g., polar) and during global events; Basis for rational engineering estimates and technology for dust management.

7. COLLATERAL DUST

Collateral dust and soil, splashed on lunar hardware from human actions such as rocket exhausts and activities by astronauts, caused many difficulties during Apollo. Two recent studies from revisiting Apollo 12 measurements and photos provide unexpected basic information and focus on collateral dust not generically studied previously (O’Brien 2009, Gaier and O’Brien, 2009).

Properties of collateral dust may well differ from the surrounding regolith dust. For example, it may be more highly charged if it is elevated by a process that increases its tribocharging (i.e., a rover wheel) or because the particles in flight are more thoroughly in contact with the solar wind. Conversely, the elevated dust is more thoroughly exposed to the solar ultraviolet radiation, and the resulting photoelectric effect may act to discharge it.

If collateral dust is in a different charge state than the surrounding dust this may affect the design of dust mitigation measures that utilize particle charge. Producing collateral dust intentionally may be useful for beneficiation if different minerals or different particle sizes charge to different degrees while elevated. But the interactions between elevated dust and the complex lunar environment are not well enough understood at this point to take operational advantage of this possibility.

8. SYNERGIES OF SCIENCE AND ENGINEERING

In space research, synergies of science and engineering are essential for outstanding, consistent and effective success. In human expeditions effective synergies between the cultures of science and engineering are most stressed, because their purposes are now quite different because of the added priorities for human safety. A particular problem with Apollo ALSEPs was inflexibility. Schedule constraints frustrated optimizing instruments quickly in response to discoveries and unexpected phenomena on earlier missions.

A strong recommendation exists for future missions to include Suitcase Science Package (like ALSEPs) and less sophisticated monitoring Landed dust-gas packages to be deployed on the lunar surface. That concept is supported. However, it will be cost-effective, sustainable and most rewarding scientifically only if the Suitcase Science Packages are flexible in both the science and the engineering.

RECOMMENDATION #3: With high priority, a working group of space engineers and scientists should analyse lessons from the Apollo era, plus updated developments, to develop protocols to foster synergies between the two cultures.

OUTCOMES #3: Minimum outcome will include optimised efficient flexibility in Suitcase Science Packages on the moon and in any other landings on a celestial body, particularly those deployed on human expeditions.

9. WIDE-RANGING CONSEQUENCES OF NEW APOLLO FINDINGS OF "BASICS"

Discoveries with the minimalist Apollo 12 Dust Detector Experiment (DDE) provide 3 examples where popular and long-standing understandings of several "basics" of lunar dust now require unexpected reconsideration (O'Brien 2009). Each revision is significant to science, engineering and lunar operations (Table 1).

TABLE 1 – CONSEQUENCES OF 3 "BASICS" DISCOVERIES IN 2009 (O'Brien 2009)

DISCOVERY #1	The strength of adhesive forces of lunar dust varies as solar elevation angle changes, being more sticky as solar illumination of a surface increases.

CONSEQUENCES #1	(a) Dust adhesion can differ on horizontal and vertical surfaces.
	(b) Dust adhesion during the middle of the lunar day may be far stronger than with the early morning Apollo missions.
	(c) Preferences for lunar settlement in polar regions require review with regard to differential local variations in dust adhesion.
DISCOVERY #2	Rocket exhaust gases of Apollo 11 caused expected dust contamination and overheating of instruments deployed 17 meters from the Lunar Module (LM), but with Apollo 12 caused unexpected and un-modelled cleansing of collateral dust when the instruments were deployed at 130m.
CONSEQUENCES #2	(a) For either near or far deployment distance, astronaut photos of dust on lunar experiments from any Apollo mission cannot be relied upon as a true record of their condition after astronauts departed.
	(b) Future lunar missions must transmit to Earth photos taken after all rockets have left.
DISCOVERY #3	Apollo 12 LM descent apparently winnowed potentially mobile dust away from the site.
CONSEQUENCE #3	Successive rocket landings and take-offs at a future lunar station may not cause successive equal additive layers of contamination by dust, as is commonly assumed. Astronaut activities near the Lunar Module may refresh surface dust, but Apollo 12 findings cast doubt on the extent of such refreshment.

10. REVISITING “BASIC” DISCOVERIES FROM APOLLO ERA

Apollo experiments appreciably increased knowledge and understanding of many lunar properties and phenomena. However, other Apollo measurements have not yet been fully analysed. Two basic features of lunar dust, cohesive and adhesive forces, were examined by the Apollo 14 Thermal Degradation Samples Experiment (Gold 1971) and the Apollo 12 Dust Detector Experiment (O’Brien 2009) respectively, the only studies and measurements of these forces on the moon. Neither data set has been fully analysed, the first because records have not been found, the second because records were revisited only in recent years.

SCEM has already recommended the desired solution, in the first of its five highest integrated science implementation priorities:

Utilize information from Apollo and post-Apollo missions or upcoming lunar science missions (U.S., as well as international) to the fullest extent. This is a low-cost/high-return element of the lunar science program (National Research Council, 2007).

NASA instituted the Lunar Advanced Science and Exploration Program (LASER) in 2007 to meet such needs. Significant Apollo records should be found and/or fully analysed as soon as practicable. Searches should continue to find, retrieve, translate and make available significant historic Apollo data, and make them available to the global community through the NASA National Space Science Data Center (NSSDC).

RECOMMENDATION 4: Programs such as LASER should continue to be given very high priority support recommended by SCEM.

OUTCOMES #4: Recent peer-reviewed discoveries from revisited Apollo 12 data, although not funded by LASER, are proof of the importance of updated intensive analyses of significant Apollo data (O'Brien 2009).

11. CONCLUDING COMMENTS

The indicative "basics" in this white paper are examples of fundamental properties of lunar environments that are still little known, little explored and even unexpected by theories and models in 2009, 40 years after Apollo 11.

Recommendations about such "basics" include measures that do not all deal directly with lunar science itself, but with the vitally important measures as to how such science should be explored:

- **with innovation, such as focus on nano-dust (Recommendation 1)**
- **thoroughly and comprehensively, integrating theory and experiments (Recommendation 2)**
- **with optimised, synergistic human skills and expertise of scientists and engineers (Recommendation 3).**
- **efficiently, at low-cost where practicable, by use of existing but otherwise not previously accessible, Apollo and post-Apollo measurements (Recommendation 4)**

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