IMPACT OF LUNAR DUST ON THE EXPLORATION INITIATIVE. T. J. Stubbs, R. R. Vondrak and W. M. Farrell, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA, tstubbs@lepvax.gsfc.nasa.gov.

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]. An important step in dealing with dust-related problems is to understand how dust grains behave in the lunar environment.

Past Experiences. All astronauts who walked on the Moon reported difficulties with lunar dust. 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].

Highest Future Priority. Dust has also been highlighted as a priority by the Mars Exploration Program Assessment Group (MEPAG): "1A. Characterize both aeolian dust and particulates that would be kicked up from the martian regolith by surface operations of a human mission with fidelity sufficient to establish credible engineering simulation labs and/or software codes on Earth."

We shall briefly describe the properties of lunar dust and its impact on the Apollo astronauts, and then summarize three main problems areas for understanding its behavior: Dust Adhesion and Abrasion, Surface Electric Fields and Dust Transport. These issues are all inter-related and must be well understood in order to minimize the impact of dust on lunar surface exploration.

Properties of Lunar Dust: Lunar dust was found to be similar to fine-grained slag or terrestrial volcanic ash [3].

Grain Size. With an average grain radius of ≈70 μm, most dust is too fine to see with the human eye. 10 – 20% of dust has a radius <20 μm [3].

Grain Shape. Dust grain shapes are highly variable and can range from spherical to extremely angular. Although, in general, grains are somewhat elongated [3].

Grain Conductivity. Lunar dust has low conductivity, and so can hold charge. However, conductivity can increase with: surface temperature; Infra-red (IR) light by ~10; and Ultra-violet (UV) light by $\sim 10^6$ [3].

Dust Impact on Astronauts

Reduced Visibility. Exterior to the Lunar Module (LM) dust was kicked-up during landings which significantly reduced visibility [2]. Interior to the LM, 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].

Respiratory. 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.

Dust Adhesion and Abrasion

Dust on Spacesuits. Alan Bean also noted that "… dust tends to rub deeper into the garment than to brush off" [2]. Dust adhered to spacesuits both mechanically and electrostatically. Mechanical adhesion was due to the barbed shapes of the dust grains, which allowed them to work into the fabric. Electrostatic adhesion was caused by charging of objects by the solar wind plasma and photo-ionization (see below). The abrasive effect of adhered dust can wear through the fabric of a spacesuit, drastically reducing its useful lifetime.

Dust on Lunar Surface Apparatus. Problems were experienced during Lunar Roving Vehicle (LRV) excursions, with much dust being kicked-up and covering exposed area [1,3], leading to increased friction at mechanical surfaces. The resulting abrasive effect of dust increased wear and tear, which 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 heavier than anticipated [3]. In fact, the strength of dust adhesion to metallic (aluminum) surfaces was $\approx 2 - 3 \times 10^3$ dynes/cm^2, and to painted surfaces was $\sim 10^4$ dynes/cm^2 [3]. Note: 1 dyne/cm^2 = 0.1 Pa.

Surface Electric Fields

Lunar Surface Charging. Probe equations can be used to determine incident current densities on the Moon, and assuming that in equilibrium the net current to the surface is zero, the lunar surface potential can be found [4]. Using this approach it can be shown that the lunar dayside charges positive, as photoelectron currents dominate; and the lunar nightside charges negative, since plasma electron currents dominate. It is also possible for the transition from positive to negative surface potential to occur dayside of terminator.

Inclusion of Wake Physics. A wake or "void" forms downstream of the Moon when it is immersed in the solar wind flow [5]. This complicated interaction creates large electric potentials in the wake which leads to the formation of ion beams [6], and large electric fields at the terminators [5], amongst other phenomena.

Lunar Dust Transport

In-situ Evidence for Transport of Charged Dust. Data from the Apollo 17 Lunar Ejecta and Micrometeoroids (LEAM) experiment was dominated by low energy impacts from electrostatically charged dust [7]. The peaks in the counts registered occurred around the terminators.

Evidence for Dust Above the Lunar Surface. Horizon glow (HG) from forward scattered sunlight was observed above the terminator by both surface landers and astronauts [e.g., 8,9]. It was suggested that near-surface HG (<1 m) was caused by scattering from levitating dust grains with radii of ~5–6 µm. This was due to electrostatic charging of the lunar surface and dust grains by the solar wind plasma and photo-ionization by solar UV and X-rays [4], which caused the dust to be repelled from the like-charged surface [e.g., 8,9,10]. HG was ~10^7 too bright to be explained by micro-meteoroid-generated ejecta [9,10].

There was also evidence for 0.1 µm-scale lunar dust present sporadically at much higher-altitudes (~ 10^2 km) [11]. 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 [12]. Also, observations of these gases in the lunar exosphere have been too dim to be seen by the unaided human eye [12].

We suggest that dust observed at high-altitudes is "lofted" by a dynamic dust grain fountain, as opposed to static levitation mechanism used to explain heavier grains nearer the surface. In the dynamic "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., 13].

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Lunar Exploration Issues	→ Connection →	Space Science Expertise
Dust Adhesion	Determining how charged particulates in a plasma interact with a surface.	Surface physics Plasma surface interactions, e.g. sputtering
Surface Electric Fields	Understanding how large objects charge in a plasma and under ultraviolet/X-ray light.	Spacecraft charging Probe physics Wake physics
Dust Transport	Understanding how particulates immersed in a plasma interact with it. Knowing how the dust and plasma are modified by this interaction.	Dusty plasma physics Planetary Rings