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Introduction: The Moon is continually bombarded by on the order of $10^6$ kg/y of interplanetary dust particles (IDP) that are micrometeoroids of cometary and asteroidal origin. Most of these projectiles range from 10 nm to about 1 mm in size and impact the Moon with speeds in the characteristic range of 10 to 72 km/s. At Earth, the passage through the atmosphere ablates most of these particles turning them into “shooting stars”. However, they directly reach the surface of the Moon, generate secondary ejecta particles and leave a crater record on the surface from which the micrometeoroid size distribution has been deciphered [1]. Most of the ejecta particles have initial speeds below the escape speed from the Moon (2.4 km/s) and following ballistic orbits return to the surface, blanketing the lunar crust with a highly pulverized and impact gardened regolith with $\gg 1$ m thickness. Micron and sub-micron sized secondary particles that are ejected at speeds up to the escape speed form a highly variable, but permanently present, dust cloud around the Moon. Such tenuous clouds have been observed by the Galileo spacecraft around all lunar-sized Galilean satellites at Jupiter [2]. Our understanding of the lunar dust exosphere before NASA’s Lunar Atmosphere and Dust Environment Explorer mission [3] has been summarized elsewhere [4], hence here we focus on the results of that mission greatly enhancing our understanding of the high-altitude ($\gg 1$ km) lunar dust environment. These findings provide a unique opportunity to map the composition of the lunar surface from orbit [5] and identify regions that are rich in volatiles, providing opportunities for future in situ resource utilization (ISRU).

Near the lunar surface ($\ll 1$ km) the exposure to UV radiation and the solar wind plasma flow have been suggested to explain a number of unusual observations indicate processes related to dust charging and subsequent electrostatic mobilization of lunar dust. Images taken by the television cameras on Surveyors 5, 6, and 7 showed a distinct glow just above the lunar horizon referred to as horizon glow (HG). This light was interpreted to be forward-scattered sunlight from a cloud of dust particles above the surface near the terminator. A photometer onboard the Lunokhod-2 rover also reported excess brightness, most likely due to HG. From the lunar orbit during sunrise the Apollo astronauts reported bright streamers high above the lunar surface, which were interpreted as dust phenomena. The Lunar Ejecta and Meteorites (LEAM) Experiment was deployed on the lunar surface by the Apollo 17 astronauts in order to characterize the lunar dust environment. Instead of the expected low impact rate from interplanetary and interstellar dust, LEAM registered hundreds of signals associated with the passage of the terminator, which swamped most signatures of primary impactors of interplanetary origin [6]. Currently no theoretical model explains fully the formation of a dust cloud just above the lunar surface, but the observations discussed above all indicate the role of charging, subsequent mobilization and transport of lunar fines [4]. Here we summarize the results of recent laboratory experiments indicating that the interaction of dust on the lunar surface with solar UV and plasma is more complex than previously thought, and can possibly offer an answer to many questions that remained open since the Apollo era [7, 8].

The Lunar Dust Experiment (LDEX): LADEE was launched in September 2013, it reached Moon in about 30 days, continued with an instrument checkout period of about 40 days in the altitude of 220 - 260 km, followed by an approximately 150 days of science observations period in a typical altitude of 20 - 100 km. LADEE followed a near-equatorial retrograde orbit, with a characteristic orbital speed of 1.6 km/s. LDEX detected a total of approximately 140,000 dust hits (Figure 1) during about 80 days of cumulative observation time by the end of the mission in April 2014. LDEX was designed to explore the ejecta cloud generated by sporadic interplanetary dust impacts, including possible intermittent density enhancements during meteoroid showers, and to search for the putative regions with high densities of dust particles with radii $\ll 1\mu m$ lofted above the terminators [9]. LDEX was an impact ionization dust detector, which measures both the positive and negative charges of the plasma cloud generated when a dust particle strikes its target. The amplitude and shape of the waveforms (signal versus time) recorded from each impact are used to estimate the mass of the dust particles. The instrument had a total sensitive area of 0.01 m², gradually decreasing to zero for particles arriving from outside its dust field-of-view of $\pm 68^\circ$ off from the normal direction [10]. The measured fluxes indicate that the Moon is engulfed in a permanently present, but highly variable dust exosphere (Figure 2).
Compositional Mapping of the Lunar Surface: The dust particles comprising the lunar ejecta cloud are small samples from the surface and could be used to map the chemical composition of the Moon from orbit [5], and could be used to identify regions that could be most valuable for In Situ Resource Utilization (ISRU), a key element in establishing human habitats on the Moon. The expected availability of water, ice, and other volatiles, in Permanently Shadowed Regions (PSR) makes the lunar poles of prime interest. However, the relative strength of the various sources, sinks, and transport mechanisms of water into and out of PSRs remain largely unknown. At high latitudes, the lunar surface is exposed to the continual bombardment from the northern and southern toroidal meteoroids as well as intermittent, intense meteoroid showers [11]. Impact bombardment produces transiently large quantities of lunar dust ejecta, which serve to re-blanket and cover the surrounding terrain, and also produces impact vapor from the volatile distribution at the surface.

Water is thought to be continually delivered to the Moon through geological timescales by water-bearing comets and asteroids, and produced continuously in situ by the impacts of solar wind protons of oxygen-rich minerals exposed on the surface. IDPs are an unlikely source of water due to their long UV exposure in the inner solar system, but their high-speed impacts can mobilize secondary ejecta dust particles, atoms and molecules, some with high-enough speed to escape the Moon. Other surface processes that can lead to mobilization, transport and loss of water molecules and other volatiles include solar heating, photochemical processes, and solar wind sputtering. Since none of these are at work in PSRs, dust impacts remain the dominant process to dictate the evolution of volatiles in PSRs. The mobilized atoms and molecules can get trapped in PSRs, and the accumulation of water in these regions has been suggested since the early days of the space age [12, 13]. While there are several processes leading to the accumulation of volatiles in PSRs, the only recognized and possibly significant loss mechanism is due to IDP impacts. The competing effects of dust impacts are: a) ejecta production leading to loss out of a PSR; b) gardening and overturning the regolith; and c) the possible accumulation of impact ejecta, leading to the burial of the volatiles. The competition between the volatile influx and these dust impact induced processes determine the ability of a PSR to accumulate volatiles, as well as their accessibility for ISRU [14]. Hence, the measurement of the temporal and spatial variability of the dust influx, and the characteristics of the impact generated secondary dust particle plumes are critical to assess the availability of water in PSRs.

A polar-orbiting spacecraft (Figure 3) could directly sample the lunar ejecta, providing the critical link between IDP bombardment and the evolution of water ice in PSRs [5, 15].

Near-surface Dust Transport Observations: In addition to bombardment by interplanetary dust, the exposure of airless surfaces to ultraviolet radiation and solar wind

Figure 1: Impact rates observed by LDEX throughout the LADEE mission. The daily running average of impacts per minute of particles with radii $a > 0.3\,\mu m$ and $a > 0.7\,\mu m$ recorded by LDEX. Four of the several annual meteoroid showers generated elevated impact rates lasting several days. The labelled annual meteor showers are: the Northern Taurids (NTa); the Geminids (Gem); the Quadrantids (Qua); and the Omicron Centaurids (οCε) [9].

Figure 2: left: The average dust ejecta cloud density observed by LDEX for each calendar month LADEE was operational in 2014. Each color ring corresponds to the density every 20 km [16]. right: The modeled annually averaged lunar dust density distribution for particles with $a > 0.3\,\mu m$. These plots are in a reference frame where the Sun is on the left ( +x direction) and the apex motion of the Moon about the Sun is towards the top of the page (+y direction) [17].
plasma flow has been suggested to result in the lofting of small dust particles, owing to electrostatic charging and subsequent mobilization [18]. Electrostatic dust mobilization on the lunar surface has remained a controversial topic since the Apollo era. In situ [18, 19, 20, 6], as well as remote sensing observations [21, 22, 23, 24] have potentially indicated the efficient lofting of charged dust particles near the lunar terminators.

High altitude observations also indicated the existence of lofted dust at tens of km above the surface. The first high altitude, remote sensing optical observations were made during the Apollo 15-17 missions, which took a series of calibrated images to analyze the zodiacal light and the solar corona. Some of these images indicated an excess brightness that has been interpreted as forward scattered light from small grains with characteristic radii \( a \approx 0.1 \mu m \) lofted over the terminator regions of the Moon by electrostatic effects. The density of such a dust population was first calculated to be on the order of \( 10^4 \text{ m}^{-3} \) near the surface using Apollo data [21, 22]. Subsequent remote sensing surveys by Clementine [23] and LRO/LAMP [24] have significantly lowered the upper limit of the lofted dust density to \( \approx 1 \text{ m}^{-3} \) near the surface. LDEX was designed to be able to identify the anticipated high-density of small lofted particles [25] but found no evidence of electrostatically lofted grains in the altitude range of 3 - 250 km above the lunar terminator [26]. Contrary to the LDEX in situ and recent LRO/LAMP remote sensing observations [24], the most recent analysis of the Ultraviolet/Visible Spectrometer (UVS) onboard LADEE did observe a dense cloud of nanodust particles with radii in the range of 20 - 30 nm, driven from the surface by electrostatic charging and/or IDP impacts [27]. The accumulation, or ponding [28] of nanodust in PSRs can offer an explanation for their high FUV surface albedo reported by LRO/LAMP [29], and likely to alter their near-surface geotechnical properties possibly reducing the production of secondary ejecta particles generated by IDP impacts and the accessibility of potential resources for ISRU.

**Dust Transport Laboratory Experiments:** Laboratory experiments cannot reproduce the conditions on the lunar surface, but have been invaluable to shed light on the microphysical processes that contribute, or even control, the properties of the regolith. Recent laboratory experiments (Figure 4) recorded micron-sized dust particles jumping to several centimeters high with an initial speed of \( \approx 0.5 \text{ m/s} \) under ultraviolet illumination or ex-
Dust exposure to plasmas (Figure 5), resulting in an equivalent height of $\sim 0.1$ m on the lunar surface, that is comparable to the height of the so-called lunar horizon glow [7]. These experiments showed that the emission and re-absorption of photoelectron and/or secondary electron at the walls of micro-cavities formed between neighboring dust particles below the surface are responsible for generating unexpectedly large negative charges and intense particle-particle repulsive forces to mobilize and lift off dust particles [7, 8, 31]. The initial speed distribution of the particles (Figure 6) is on the order of 0.5 m/s and it is expected to be inversely proportional to the size of the particles with a large scatter due to the somewhat stochastic effects of particle-particle cohesion [30]. These experiments indicate that electrostatic dust transport could be a surprisingly fast and efficient process to lift off dust particles [7, 8, 31]. The initial speed distribution of the particles is presented in Figure 6.

Figure 6: The initial velocity distribution of lofted dust particles as function of the grain size. The modeling parameters are: $\gamma$ characterizes the geometry of the cavity and the dust grains, $\phi$ is the surface potential of negatively charged grains inside a micro-cavity, $\rho$ is the specific density of the dust particles, and $r$ is the radius of a lofted particle [30].

References


Figure 7: top: Schematic of EDA, and bottom: photo of its fully integrated functional module. The magnitude of a particle’s charge, $Q$, is measured by induced signals at the entry and exit of EDA, and the charge-to-mass ratio, $Q/m$, is estimated by bending the dust trajectory by applied electric fields. Hence the measurement can provide the speed, mass, and charge of mobilized dust on the lunar surface [33].


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