Plasma-surface interactions: Implications for (spacecraft) surface charging and electrodynamic dust shields

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Abstract
Moon-plasma interactions were observed by orbital and surface experiments during the Apollo Program. Photons and charged particles charge the lunar surface and form thin Debye-scale plasma sheaths above both sunlit and shadowed hemispheres. Moreover, average thermal velocity of electrons causing a Debye sheath to form around the spacecraft. Photoelectron and plasma sheaths directly overlying the surface absorb dust grains lofted which charge negatively with subsequent charged dust streams attract and make contact with the positive surfaces of the landed spacecraft. As carriers of charges, dust particles become either attracted or repulsed to the charged spacecraft. Low density of the ambient plasma and high secondary emissions also contribute to high rates of surface charging on the spacraft. Accumulation of electrical charge on spacecraft and spacecraft components results from spacecraft interactions with space plasmas, energetic particle streams, and solar photons typically driven by free electrons and photons. Various effects attributed to spacecraft charging Have been reported as responsible for a number of operating anomalies including Operational anomalies component failures, spurious commands, physical spacecraft surface damage, and degradation of spacecraft surface material thermal and electric properties. Research in plasma-surface interactions show promising results for developing novel dust mitigating strategies for the safety management of spacecraft charging. This paper aims to investigate strategies that mitigate the role lunar dust plays as a carrier of charges in plasma-surface interactions resulting in spacecraft charging.
Keywords: plasma-surface interactions, plasma sheath, (spacecraft) surface charging

Background

Scientific study of the lunar plasma environment dates back to the early days of space exploration. Luna 2 made the first space measurements relevant to lunar plasma in 1959 [1], providing magnetometer evidence that the Moon, unlike the Earth, lacked a strong dipolar magnetic field. Years later in 1967, Explorer and Apollo missions provided data that form the foundation of the lunar plasma science [2]. These missions revealed the Moon to have a weak surface boundary exosphere [3]. Simultaneous Ogo 5, Vela 5, and Apollo 12 spectrometer data of ion density and velocity taken when the Ogo and Vela satellites were in the solar wind and the Apollo spectrometer was on the lunar day side, also showed that proton velocity was smaller and the proton density larger at the Apollo site than in the free stream solar wind. His observation suggested proton deceleration at the site by an electric field established via the plasma-remanent magnetic field interaction. Simultaneous plasma and magnetic field data, from the spectrometer and lunar surface magnetometer at the Apollo 12 location, further showed compression of the local remanent field by large solar wind and magnetosheath plasma dynamic pressures [4]. Moon-plasma interactions were later observed by orbital and surface experiments [Apollo Program]. More recent lunar missions including Geotail, Wind, Lunar Prospector, Nozomi, Kaguya, Chang'E, and Chandrayaan have further contributed to the study of lunar plasma-Moon interactions.
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I. Introduction

The Moon's plasma environment generates radiation directly to the Moon's surface, penetrating at different depths due to the absence of a protective atmosphere. Moreover, emission of a large amount of energetic vacuum UV light generates free radicals on the particulate surface [5], exposed to a plasma stream composed of charged ions and electrons, the flux of which tends to be higher than protons. Direct exposure to UV solar radiation causes the lunar surface to eject electrons due to the photoelectric effect. From measurements of the flux of photoelectrons emitted from the surface combined with measurements of their kinetic energy, the photoelectron density above the surface has been calculated to be ~100 cm^{-3}. Compared with a solar wind density of 10^{-3} cm^{-3}, it can be seen that photoelectron emission dominates over electron implantation. The loss of electrons from the surface leads the lunar day side to develop a positive charge with a potential of 1 to 5 V [6]. For over the last sixteen years, new measurements have expanded the understanding of Moon–plasma interactions and helped demonstrate their kinetic nature. Photons and charged particles charge the lunar surface, forming thin Debye-scale plasma sheaths above both sunlit and shadowed hemispheres. These impacts also produce photoelectrons and secondary electrons from the surface, as well as ions from both the surface and exosphere, all of which in turn feed back into the plasma environment [7]. Photoelectron and plasma sheaths directly overlying the surface absorb dust grains lofted shich charge negatively then pulled back to the positive surfaces of the landed spacecraft and regolith. Particles with a velocity high enough to pass through the photoelectron sheath experience their own photoemission and charge positively. Colwell et al. (2009) estimated that only particles < 0.5 µm become sufficiently light enough to levitate [8]. When lunar dust enters the plasma sheath, the ion drag force and neutral drag force caused by the plasma are negligibly smaller than the electrostatic force [9]. Oth[illegible] parti[illegible]imply follow a ballistic trajectory and return to the surface.

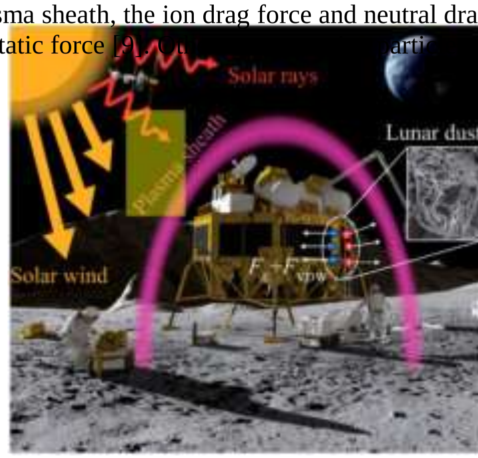

Fig. 1. A diagram illustrating the phenomenon of charged dust particles being attracted or repulsed to the charged spacecraft on the lunar surface [10].

As depicted in Fig. 1, dominated by the photoelectron effect induced by solar ultraviolet and x-ray radiation, the spacecraft and lunar regolith on lunar dayside typically charge positive [11]. As a result, a photoelectron sheath forms above the surface. On the lunar night side, the spacecraft and regolith usually are negatively charged due to plasma electrons [12]. Average thermal velocity of electrons is higher compared to ions, causing a Debye sheath to form around the vehicle. Besides the exposure to solar wind, the lunar plasma wake and plasma in the magnetotail lobes along with the plasma sheet electrically charge the spacecraft and regolith [13]. The lunar surface potentials in these various lunar environments are summarized as follows.

	Solar illumination (SZA: 180° to 0°) [48]	Lunar plasma wake	Magnetotail lobe	Plasma sheet
Lunar surface potential	−100 to 20 V	−200 to 0 V	−150 to 0 V	−1,000 to 0 V

Table 1. Typical lunar surface potentials [14]

Due to immersion in the same charging environment, the spacecraft equipotentiates with the lunar surface. Oppositely charged with respect to the charged spacecraft, dust particles attract long-range electrostatic and short-range van der Waals forces, which cause them to migrate toward the spacecraft surface and ultimately adhere [15]. On the contrary, dust particles with the same polarity as the charged spacecraft, are acted upon by repulsive electrostatic forces. The screen effect of the plasma prevents charged dust particles located outside the edge of sheath, electrostatic interaction with the spacecraft. An electric field is produced between the spacecraft surface and the plasma. This electric field exerts a force on the charged dust resulting in a lower electrostatic force between charged plasma dust and spacecraft. The spacecraft usuallt has a dielectric coating of high thickness and low permittivity. Figure 2 illustrates the trajectory diagrams of particles with positive and negative charge with different initial velocity v_0. These particles originate from the edge of the plasma sheath. No interaction is assumed between charged dust particles with the surrounding plasma sheath.

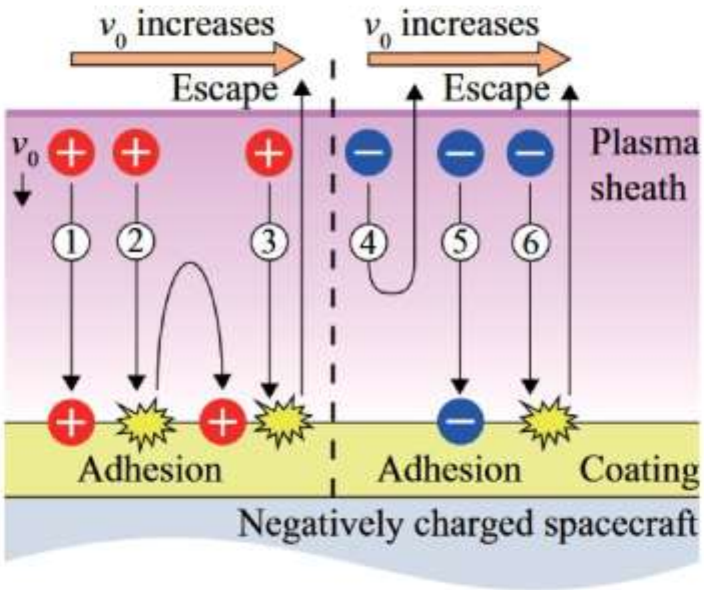

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Figure 2. Diagram illustrating adhesion and escape trajectories of positively and negatively charged particles interacted with negative spacecraft potential.

Positively charged particles of low initial velocity experience electrostatic attraction toward the surface for immediate contact and adhesion, following trajectory ①. However, in the event that the residual kinetic energy after the initial impact does not surpass the work performed by the electrostatic force, the particle remains incapable of overcoming the electrostatic pull of the spacecraft, resulting in its adherence to the surface after a finite number of collisions (trajectory ②). Only when the initial velocity v_0 increases to the critical escape velocity can the particle successfully overcome the attraction of the spacecraft and break free from the sheath (trajectory ③). The situation becomes complex for a negatively charged particle as it encounters long-range repulsion and short-range attraction while approaching the surface of the spacecraft. If the initial kinetic energy is insufficient to exceed the work done by the repulsive force, the particle will not come into contact with the spacecraft (trajectory ④). With a progressively higher initial velocity, once the velocity v_0 reaches the critical adhesion velocity, the particle has the capability to adhere to the surface of the spacecraft after the collision (trajectory ⑤). However, if the initial velocity v_0 surpasses the critical escape velocity, the remaining kinetic energy will exceed the work performed by the attractive force. As a result, the particle will success- fully escape, following trajectory ⑥. Adhesion to the surface occurs only when the initial velocity of a negatively charged particle is within the range of the critical adhesion and escape velocities [16]. Critical adhesion velocity refers to the velocity threshold at which a particle transitions from the escape state to the adhesion state. On the other hand, the critical escape velocity represents the velocity threshold at which the final state of a particle shifts from adhesion to escape. For positively charged particles, the spacecraft negative potentials are increased, leading to an amplified electrostatic force, subsequently raising the critical escape velocity. Similarly, in the case of negatively charged particles, an elevation in spacecraft negative potential results in an augmentation of critical adhesion and escape velocities. Due to a considerably lower average work done by the short-range electrostatic attractive force, the critical escape velocity is closely related to the critical adhesion velocity. Only if the speed of negatively charged dust exceeds the critical escape velocity can dust get rid of the electrostatic interaction with the positively charged spacecraft. The final adhesion or escape state of low-velocity charged dust is mainly determined by electrostatic interaction rather than contact interaction velocities [17].

Problem
One of the primary concerns for a human and robotic operation on the surface of the Moon is spacecraft charging, which involves electrical charge build up on the lunar surface regolith, habitats, vehicles, or space suits. Spacecraft charging is the balance of currents between the space environment and spacecraft. It is largely dependent on the energy and density of the plasma, photoemission, and secondary emissions. Surface-plasma interactions increase with certain material properties such as dielectrics or mechanical designs like extended booms. The low density of the ambient plasma at the Moon and high secondary emissions also contribute to high rates of surface charging. The

dayside surface plasma includes a population of photoelectrons which increases the plasma density. In general, an object in full sunlight will charge to a low positive electric potential ~5 to10 V [18]. This is due to photoemission dominating over plasma currents [19]. Accumulation of electrical charge on spacecraft and spacecraft components results from spacecraft interactions with space plasmas, energetic particle streams, and solar photons typically driven by free electrons and photons. The flux and kinetic energy of high-energy charged particles, local space plasma density and temperature, spacecraft motion relative to the local space plasma and magnetic field, as well as spacecraft systems operating voltages and currents , all affect the spacecraft charging current balance. Various effects attributed over 25 years to spacecraft charging are responsible for a number of operating anomalies and should be of concern to engineers planning, designing, and operating space missions [20]. These effects include

- Operational anomalies (i.e. , telemetry glitches, logic upsets, component failures, spurious commands) caused by the coupling of arc-discharged-induced transients into spacecraft electronics.
- Physical spacecraft surface damage (i.e., mirrored thermal control surfaces) as a result of arc-discharging
- Degradation of spacecraft surface material thermal and electric properties due to increased surface contamination.

Purpose

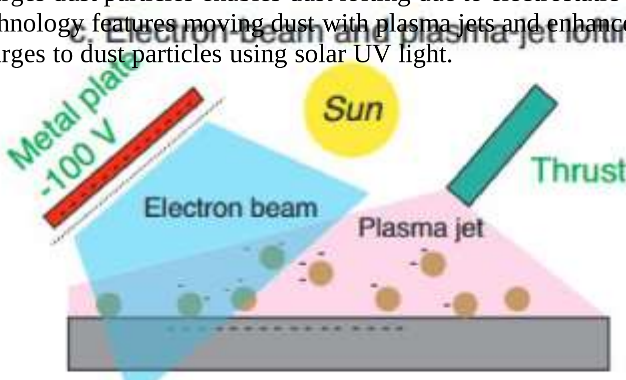
Apart that triboelectric charging occurs through photoemission induced by UV irradiation and ionisation of a small quantity of particles, emitted photoelectrons readily collect on nearby dust grains, resulting in individual grains carrying a net positive or negative charge [21]. This paper aims to investigate strategies that mitigate the role lunar dust plays as a carrier of charges in plasma-surface interactions resulting in spacecraft charging.

II. Methods

A literature research survey was conducted to review various aspects of plasma-surface interactions with subsequent charging of dust particles. The survey further reviewed relevant experiments that highlighted such plasma-dust / surface interactions and instrumental approaches for mitigation of dust-induced surface charging. A historical perspective was provided when available.

III, Results and Discussion

Kawamoto and Hashime (2018) developed a system that uses a four-phase rectangular voltage and also showed that the cleaning process is improved by application of ultrasonic vibrations [22]. This approach, allowing both positively and negatively charged dust particles to be cleared without changing the configuration of the system, has been tested using the lunar dust brought back by Apollo 11. The Lunar Dust Science Definition Team is organized by the Jet Propulsion Lab/California Institute of Technology through NASA's Biological and Physical Sciences Division to develop and assess dust remediation techniques concepts: electrostatic dust shield; surface electrostatically collecting dust, later called attractive surface; and electron beam -plasma jet inducing electrostatic dust lofting from a surface. This paper will focus on the Electron-beam and plasma jets induced lofting technique which combines an electron beam and a plasma jet to enhance the dust removal process. This technique actively charges dust particles enables dust lofting due to electrostatic forces and plasma jets [23]. Uniqueness of this technology features moving dust with plasma jets and enhanced performance with active supply of electrostatic charges to dust particles using solar UV light.



Electron beams

Flanagan and Goree (2006) generated a 70-eV electron beam in a setup where a hot tungsten filament was used in conjunction with an applied 70 V bias with respect to ground walls. The resulting thermal electrons were characterized by two Maxwellian populations, one colder with temperature cold ~0.3-4 eV and one hotter with temperature 3-16 eV [24]. The density varied between 2.4×106 cm^{-3} and 2.5×108 cm^{-3}. A 4.5 cm diameter glass sphere was coated with JSC-1 lunar dust stimulant from a size distribution of less than 20 µm. The coated sample was then exposed to the thermal plasma or the electron beam or both. Three key findings were observed by Flanagan and Goree [25]. First, measurable dust release could only be obtained when the sample was exposed to both the thermal plasma and the electron beam. Second, significant dust release occurred only for plasma densities above 2.4 × 106 cm^{-3}, suggesting a density threshold for strong dust mobilization. Last, the release time-dependence followed an exponential decay with a release rate between 4 s and 25 s, with faster release rates associated with higher plasma densities.

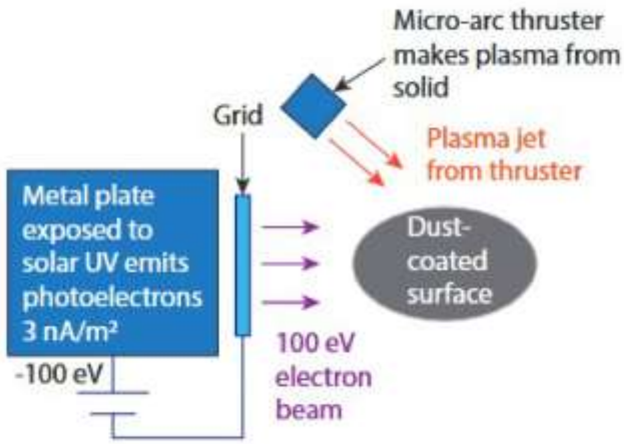


Figure 3: Sketch of proposed dust remediation scheme. This scheme is inspired by [26], who applied plasma and electron beams to enhance particle release. An electron beam created from accelerated photoelectrons was aimed at the region to be cleaned. This region is also sprayed with low density plasma coming from a continuous operating vacuum arc thruster.

Plasma jets

Ticos et al. (2017) reported a technique for using plasma jets to clean surfaces, which they called the plasma broom technique. The reported plasma broom produced a pulsed discharge (pulse length of ~ 1 µs). The setup by Ticos et al. [57] was based on a coaxial plasma gun with the gap filled by CO_2 gas with pressure of 670 Pa and an applied voltage between 1 kV and 2 kV [27]. This plasma jet technique was applied to the cleanup of solar panels coated by a thick layer of JSC-1 martian simulant dust. During the operation of this technique, plasma densities were extremely high, of the order of 1021 m^{-3}, and the dust particles were expelled from the surface simply by drag forces. Ticos et al. (2017] demonstrated a high cleaning efficiency of > 97% after only a few shots at 2 kV voltage, and an energy consumption of about 250 J per pulse) [28].

A plasma micro-thruster is used to generate a continuous plasma jet with a focus on thrust, efficiency, and longevity [29]. This type of thruster is intended for small satellites such as low-power CubeSats. Both the vacuum arc thruster and the Polytetrafluoroethylene (PTFE known as Teflon) thruster are small, light-weight and intended for quasi-continuous operation [30]. An alternative approach uses both electron beams and plasma jets without the need for a hot filament providing electrons and a gas supply for the plasma mass. Electron beams are sourced by naturally provided photoelectrons (solar UV), and plasma jets come from another source. The plasma density for this device may be as high as 1021 m^{-3}, while that in the lunar environment only may only reach 106 m^{-3} with large uncertainties,

		Pulsed plasma thruster	Vacuum arc thruster	
		Value	Value	Units
Operation	Mass	6.60*	0.15**	[kg]
	Pulse length	~ 20	> 250	[μs]
	Power	~ 100	0.1 − 20	W
	Repetition rate	1	1	[Hz]
Propellant		Teflon	Aluminum**	[-]
Plasma	Ionization	10 − 40	100	[%]
	Electron density	10^{16}	10^{14}	[cm^{-3}]
	Exhaust velocity	10 − 50	20 − 40	[km/s]

Table 2: Categorization of microthrusters. We referred to Burton and Turchi (1998) for the pulsed plasma thruster and Kolbeck and Anders for the vacuum arc thruster. ∗Values for the LES-8/9 PPT thruster, given in Table 2 in Burton [31. ∗∗Values based on the thruster planned for the Illinois Observing Nanosatellite (ION), a 2U CubeSat from the University of Illinois at Urbana-Champaign [32].

UV-irradiated electrodynamic dust shield

The electrostatic force's ability to induce dust uplift has been studied in relation to various adhesive forces and gravity, both experimentally and through modeling in different environments and applications [33]. Apart that triboelectric charging occurs through photoemission induced by UV irradiation and ionisation of a small quantity of particles in the vacuum chamber, emitted photoelectrons readily collect on nearby grains, resulting in individual grains carrying a net positive or negative charge. This allows the electrostatic field to act on the grains. It is worth noting the possibility for strong differential charging (i.e. significant potential differences between grains) to develop, which can generate sufficient force to uplift dust particles alone [34], or at the very least, facilitate uplift. Brief exposure to UV radiation is commonly used to neutralise samples in a vacuum chamber [35]. While the sum of all charges in the chamber is near-zero regardless of the UV treatment, Kim et al., (2017) observed the tenuous plasma created from a brief period of UV exposure has time to deplete and partially neutralise oppositely charged particles [36]. However, with layers of granular, poorly conducting particles, it is unclear to what extent the dust would be neutralised. Without a charging mechanism, dust grains would otherwise not be affected by electrostatic forces.

Wang et al (2024) demonstrated the impact of UV irradiation on the efficiency of EDS in conditions resembling the lunar surface [37]. Continuous exposure to UV, which leads to the continuous creation of photoelectrons and the formation of local weak plasma, enhances dust removal efficiency (DRE) of the EDS system across various combinations of dust species and surface coating materials when compared to scenarios without UV radiation. Notably, the initial charge state of the particles does not seem to significantly affect the final cleanliness of the surface when exposed to an external charging mechanism. Even minimal variation in removal efficiency was observed in the UV cases, compared to the generally large spread in removal efficiency for the no-UV cases. On smooth surfaces such as glass and Kapton, dust particles were efficiently removed across all simulants. The exception was larger particles (80–100 m and agglutinates) on Beta cloth, where multiple-point contacts on the fiber material likely caused particles to adhere. Other factors such as temperature and pressure can potentially affect the system's dust removal efficiency, which remain important parameters for future tests. Dielectrophoretic forces may have contributed to particle mobilisation, but analysis of the charge state of the particles and the EDS electric field lines was needed to confirm this. Uniqueness of this technology features moving dust with plasma jets and enhanced performance with active supply of electrostatic charges to dust particles using solar UV light [38].

Figure 4 shows the response of lunar dust stimulants LHS-1 and LMS-1 under the different UV irradiation exposures with activated EDS. Approximately 200 mg of dust was used in each test; for each size range (25–50 µm and 80–100 µm), the experiment was repeated at least three times. Across all simulant types, the DRE (dust reduction efficiency) was significantly higher for dusty surfaces exposed to continuous UV irradiation. The results were consistent with recent results from Schaible et al. (2023) that UV enhances charging of dust grains on an uncoated 2-phase EDS surface, requiring less voltage to achieve the same level of cleanliness as in the absence of UV [39]. The transient-UV cases and no-UV cases exhibited little to no discernible pattern: the large data spread in the no-UV case was likely due to variations in the initial charge states of the dust layer caused by uncontrolled surface conditions and tribocharging. For the UV case, since photoelectric charging dominates, the effect of initial charging conditions prior to UV irradiation was insignificant. In the case of transient-UV, most of the particles were assumed to be neutralised by UV. The DRE of 200 mg of LHS-1 in the 80–100 µm size range was examined under

UV exposure durations of 5, 10, 15, and 30 min. The results showed that the initial UV irradiation duration before EDS activation did not significantly affect the final DRE outcome. No apparent correlation between exposure duration and DRE was observed, suggesting that an equilibrium charging state is reached within a few minutes, if not seconds. It is also possible that any charge neutralisation would be instantaneous.

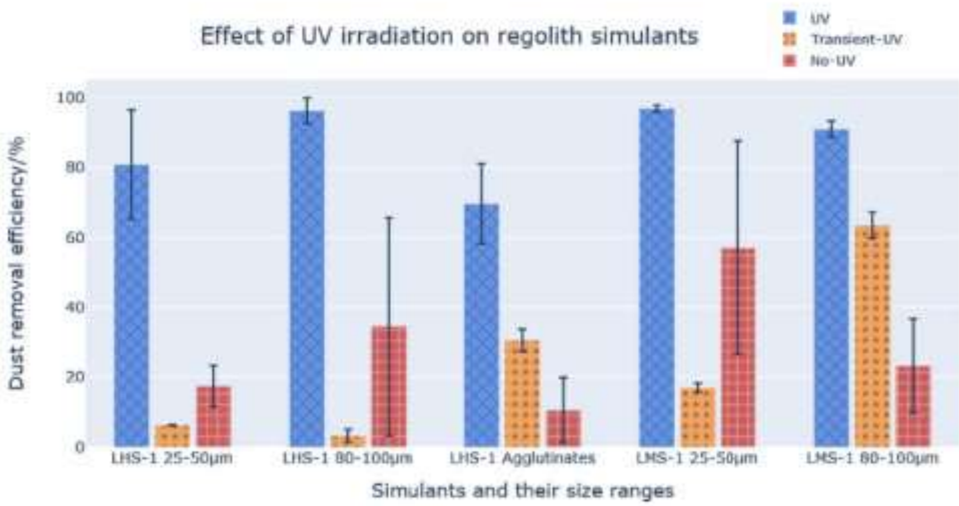


Figure 4. DREs (by mass) of different species of simulants on a glass coating, with UV-irradiated simulants shown in blue, compared to transient UV exposure in orange, and no UV exposure in red.

IV. Conclusion

Moon-plasma interactions were observed by orbital and surface experiments during the Apollo Program. Photons and charged particles charge the lunar surface and form thin Debye-scale plasma sheaths above both sunlit and shadowed hemispheres. Moreover, average thermal velocity of electrons causing a Debye sheath to form around the spacecraft. Photoelectron and plasma sheaths directly overlying the surface absorb dust grains lofted which charge negatively with subsequent charged dust streams attract and make contact with the positive surfaces of the landed spacecraft. As carriers of charges, dust particles become either attracted or repulsed to the charged spacecraft. Low density of the ambient plasma and high secondary emissions also contribute to high rates of surface charging on the spacraft. Accumulation of electrical charge on spacecraft and spacecraft components results from spacecraft interactions with space plasmas, energetic particle streams, and solar photons typically driven by free electrons and photons. Various effects attributed to spacecraft charging Have been reported as responsible for a number of operating anomalies including Operational anomalies component failures, spurious commands, physical spacecraft surface damage, and degradation of spacecraft surface material thermal and electric properties. Research in plasma-surface interactions show promising results for developing novel dust mitigating strategies for the safety management of spacecraft charging. This paper aims to investigate strategies that mitigate the role lunar dust plays as a carrier of charges in plasma-surface interactions resulting in spacecraft charging.

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