

# Lunar dust: Formation, microphysics, and transport

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Lunar dust—the submillimeter fraction of the regolith—controls the optical, thermophysical, electrical, mechanical, and environmental behavior of the Moon’s surface. These properties set the performance envelopes of remote-sensing retrievals, regolith geotechnics, volatile cycles, and exploration systems, while also posing operational and biomedical risks. We synthesize Apollo sample analyses and *in situ* observations (Surveyor, Lunokhod, Apollo) with contemporary datasets from the Lunar Reconnaissance Orbiter (LRO) Diviner Lunar Radiometer, the Lunar Atmosphere and Dust Environment Explorer (LADEE)/Lunar Dust Experiment on LADEE exospheric dust measurements, and Chang’e-4 Lunar Penetrating Radar. We also incorporate 2024–2025 results: Chandrayaan-3 Chandra’s Surface Thermophysical Experiment thermophysics at the Vikram lander’s site, Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) plume-surface diagnostics from Intuitive Machines Mission 1, and Negative Ions at the Lunar Surface detections of a dayside near-surface  $H^-$  population on Chang’e-6. The review links (1) production and modification processes to (2) grain-scale physical/chemical/electrical/optical/mechanical properties, then to (3) mobilization pathways (meteoroid ejecta, electrostatic hopping, and rocket-plume entrainment), and finally to (4) region-specific design ranges across maria, highlands, pyroclastic units, magnetic swirls, and permanently shadowed regions (PSRs). We quantify temperature-illumination dependence across day/night and PSR-equator regimes through a two-channel  $k(T, \rho)$  model and charge-relaxation scaling. We provide closed-form expressions for adhesion-aware lift thresholds and for near-surface (0–3 m) dust transport at apex/hover heights as functions of sheath structure. The result is a design-ready set of relations, figures, and tables that propagate microphysics and composition into engineering parameters for upcoming landed and rover operations.

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## I. INTRODUCTION

Airless-body regolith evolves under micrometeoroid bombardment, solar-wind implantation, and thermal cycling. That evolution governs the microstructure and composition of the submillimeter fraction (“lunar dust”), which, in turn, sets thermal conductivity  $k$ , real permittivity  $\epsilon'$ , loss tangent  $\tan \delta$ , friction angle  $\phi$ , cohesion  $c$ , optical maturity, and charge exchange with the near-surface plasma. Microstructure and composition in turn determine thermophysical, electrical, optical, and mechanical properties that control dust behavior under changing illumination and plasma conditions. These properties determine when dust is liberated, where it accumulates, and how it ages. These same properties govern operational risks (e.g., fouling, abrasion, and charging) and scientific observables [e.g., reflectance, Christiansen Feature (CF) position, and dielectric]. Our intent is to connect the chain from production mechanisms to emergent properties to dynamical consequences and, finally, to engineering decisions.

The exploration-relevant uncertainties today are set by three recent developments: (1) centimeter-scale thermo-

physical structure resolved by Diviner inversions and now anchored *in situ* by Chandra’s Surface Thermophysical Experiment (ChaSTE) at high southern latitude; (2) direct near-surface constraints on sheath composition from Negative Ions at the Lunar Surface (NILS), which require negative ions to be included in daytime charging budgets; and (3) a generation of plume-surface diagnostics (SCALPSS-class stereo photogrammetry plus ejecta counters) necessary for bounding erosion rates, particle-size distributions (PSDs), and angular flux during landings. Together, these advances enable engineering-grade ranges that were not available at the time of earlier reviews.

This review is motivated by two gaps. First, landed/orbital constraints (ChaSTE, NILS, SCALPSS) have not been fused with Apollo-Diviner-LADEE-LPR (Apollo sample program-Diviner Lunar Radiometer-Lunar Atmosphere and Dust Environment Explorer-Lunar Penetrating Radar) into a quantitatively self-consistent reference that spans depth, latitude, and terrain. Second, the literature connecting grain-scale properties (particle-size distribution, angularity, agglutinate and nanophase metallic iron content, and composition) to design-relevant envelopes for mobilization pathways (meteoroid ejecta, electrostatic lofting, and rocket-plume entrainment) is scattered. Here, we close both gaps by (1) compiling region-specific ranges with uncertainty where available, and (2) providing equations with labeled parameters and default reference values, propagating microstructure to bulk properties, and integrating those into mobilization budgets.

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We (1) unify production and modification mechanisms into three microphysical levers that dominate downstream behavior (particle-size distribution and angularity, agglutinate fraction with nanophase  $\text{Fe}^0$ , and composition/oxidation state); (2) quantify how those levers map to specific surface area (SSA), vertical density structure, permittivity, thermal conductivity, and optical maturity; (3) derive lift thresholds including cohesion and show where preliberation is required; (4) integrate meteoroid ejecta, electrostatic mobilization, and rocket-plume entrainment across regions; and (5) tabulate region-specific reference values for use in design studies at the poles, over swirls, and at landing sites.

Our objectives are (1) to compile production and modification mechanisms with first-order scalings; (2) to provide ranges and recommended reference values for physical, chemical, dielectric, thermal, mechanical, and optical parameters by region; (3) to derive compact bridging relations that connect microstructure to  $k(T, \rho)$ ,  $\varepsilon'(\rho, \text{composition})$ , and electrostatic lift with adhesion; and (4) identify colocated measurements that most efficiently reduce design margins at the poles, magnetic swirls, pyroclastics, and landing sites.

To reach our objectives, we draw on Apollo geotechnics and petrography [1,2], Diviner thermophysics [3–5], LADEE/Lunar Dust Experiment on LADEE (LDEX) exospheric dust measurements [6], Chang’e-4 LPR dielectric profiles [7,8], syntheses of space-weathering and maturity [9–13], tribo/photo charging [14–17], composition and mineralogy [18–20], pyroclastics [21–23], plume-soil interaction [24–26], and health hazards [27–32]. Additional 2024–2025 results include Chandrayaan-3 ChaSTE *in situ* thermophysical measurements at the Vikram lander’s site (69.373° S, 32.319° E) (thermal conductivity at 80 mm depth and local packing density) [33], a consolidated review of plume-surface interaction (PSI) experiments and SCALPSS campaign status for Intuitive Machines Mission 1 (IM-1) and subsequent landings [34], and Chang’e-6 NILS detections of a dayside near-surface  $\text{H}^-$  layer [35,36]; we also include LADEE/LDEX meteoroid-stream responses that quantify event-driven dust variability [37].

Constraints derived here will make an engineering-grade synthesis feasible [38]: (1) centimeter-depth thermophysics anchored *in situ* by ChaSTE at high southern latitude; (2) daytime near-surface negative ions ( $\text{H}^-$ ) that modify sheath composition and charging; and (3) plume-surface diagnostics that bound erosion, PSD, and angular flux. We intend to fuse these with Apollo-Diviner-LADEE-LPR to produce a single, quantitative reference spanning depth, latitude, and terrain. Prior reviews treat subsets of this chain (thermophysics, dust charging, or PSI) in isolation; here, we provide a single, internally consistent map from sources  $\rightarrow$  properties  $\rightarrow$  transport  $\rightarrow$  subsystem impacts, with labeled equations and region-specific priors to enable immediate design use. Throughout, we treat the values compiled in Tables VII and VIII as engineering priors with explicit provenance (typically bracketing intersite variability and inversion/model systematics), not as specifications; wherever possible, designers should replace these priors with site- and hardware-specific measurements.

This paper is organized as follows. Section II synthesizes production and modification pathways and provides first-order scalings. Section III compiles grain-scale properties

TABLE I. Symbols used repeatedly throughout. Also, we use  $g_{\text{Moon}} = 1.62 \text{ m s}^{-2}$ ;  $a$  is grain radius.

| Symbol                      | Definition (units)                                                                                                                          |
|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| $\rho, \rho_s$              | Bulk, solid density ( $\text{kg m}^{-3}$ )                                                                                                  |
| $n$                         | Porosity = $1 - \rho/\rho_s$ (–)                                                                                                            |
| $k, \ell, A$                | Thermal conductivity parameters in Eq. (13); $k$ ( $\text{W m}^{-1} \text{K}^{-1}$ ), $\ell$ (–), $A$ ( $\text{W m}^{-1} \text{K}^{-1/4}$ ) |
| $E, \lambda$                | Near-surface electric field amplitude, $e$ -fold length ( $\text{V m}^{-1}$ , m)                                                            |
| $\Delta V_{\text{sh}}$      | Near-surface sheath potential drop<br>$\int_0^\infty E(z) dz \simeq E_0 \lambda$ (V)                                                        |
| $\phi_g$                    | Grain potential (V)                                                                                                                         |
| $W, R$                      | Work of adhesion, asperity radius ( $\text{J m}^{-2}$ , m)                                                                                  |
| $\Gamma$                    | Thermal inertia $\sqrt{k \rho c_p}$ ( $\text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2}$ )                                                     |
| $c_p$                       | Specific heat capacity ( $\text{J kg}^{-1} \text{K}^{-1}$ )                                                                                 |
| $\varepsilon', \tan \delta$ | Real permittivity, loss tangent (–)                                                                                                         |
| $\phi, c$                   | Friction angle, cohesion ( $^\circ$ , Pa)                                                                                                   |

(PSD, angularity/SSA, vertical density, and composition) that control contacts and observables. Sections IV and V connect that microstructure to geotechnical and thermophysical behavior via Mohr-Coulomb shear parameters, adhesion at asperities, and a two-channel  $k(T, \rho)$  model. Section VI develops dielectric mixing, charge relaxation, and sheath-field budgets, culminating in an adhesion-aware lift criterion and its scaling. Section VII summarizes optical and maturity diagnostics relevant to dust coatings and sorting. Section VIII integrates the mobilization pathways (meteoroid ejecta, electrostatic hopping in the first meters, and rocket-plume entrainment); it also quantifies near-surface (0–3 m) trajectories/hover heights versus sheath structure. Sections IX and X provide region-specific priors and global engineering ranges. Section XI discusses model relations useful in design; it also provides measurement priorities that most efficiently reduce design margins for upcoming polar and mid-latitude operations. In Sec. XII, we conclude and summarize our findings.

## II. FORMATION AND MODIFICATION MECHANISMS

The production and modification pathways establish the levers that control dust behavior: PSD and angularity, agglutinate fraction with nanophase metallic iron ( $\text{npFe}^0$ ), and composition/oxidation state (see Table I for notations). We quantify each process and provide scalings that are used downstream in Secs. IV–VI.

### A. Impact comminution and agglutination

Micrometeoroid impacts fragment rock and soil and produce glass-welded agglutinates embedding  $\text{npFe}^0$ , which dominate mature-soil optical behavior [1,12]. The  $<1 \text{ mm}$  soil fraction is well described by a lognormal PSD,  $\ln D \sim \mathcal{N}(\mu, \sigma^2)$ , with median  $D_{50} \approx 40\text{--}130 \text{ }\mu\text{m}$  and  $\sigma \approx 0.8\text{--}1.2$  by count [2]. Agglutinate fraction and  $I_{\text{s/FeO}}$  increase with exposure [9].

Measured Brunauer-Emmett-Teller (BET) SSA spans  $0.02\text{--}0.78 \text{ m}^2 \text{ g}^{-1}$ , with a widely used reference near

$0.5 \text{ m}^2 \text{ g}^{-1}$  (spherical-equivalent diameter 3–4  $\mu\text{m}$ ). A compact vertical density parametrization that matches Apollo cores and Diviner inversions is

$$\rho(z) = \rho_\infty - (\rho_\infty - \rho_0) e^{-z/z_c}, \quad (1)$$

with reference values  $\rho_0 \approx 1.4 \text{ g cm}^{-3}$  at the surface,  $\rho_\infty \approx 1.85 \text{ g cm}^{-3}$  at depth, and  $z_c = 0.15\text{--}0.30 \text{ m}$ .

### B. Space weathering

Solar wind and microimpacts generate nanophase metallic iron (npFe<sup>0</sup>) in 10–200 nm rims and within agglutinitic glass, lowering albedo, steepening spectral slopes, and suppressing mafic band depths (BDs) [10,12]. A first-order attenuation of a BD with cumulative solar-wind exposure is

$$\text{BD} \approx \text{BD}_0 \exp(-\alpha \phi_{\text{sw}}), \quad 0.1 \lesssim \alpha \lesssim 0.5, \quad (2)$$

where  $\phi_{\text{sw}}$  is a dimensionless solar-wind “dose” variable proportional to the cumulative solar-wind fluence at the surface. We write

$$\phi_{\text{sw}}(t) \equiv \frac{\Phi_{\text{sw}}(t)}{\Phi_{\text{ref}}}, \quad \Phi_{\text{sw}}(t) = \int_0^t F_{\text{sw}}(t') dt', \quad (3)$$

where  $F_{\text{sw}}$  is the solar-wind ion flux (dominated by protons) in particles  $\text{cm}^{-2} \text{ s}^{-1}$ , and  $\Phi_{\text{sw}}$  is the cumulative proton fluence in particles  $\text{cm}^{-2}$ .  $\Phi_{\text{ref}}$  is a characteristic fluence scale, chosen here as  $\Phi_{\text{ref}} \sim 10^{23} \text{ cm}^{-2}$ , comparable to the space-weathering doses inferred for mature lunar soils at 1 A.U. For design use, a representative proton flux  $F_{\text{sw}} \simeq 10^8 \text{ cm}^{-2} \text{ s}^{-1}$  gives  $\Phi_{\text{sw}} \sim 3 \times 10^{22}$  to  $3 \times 10^{23} \text{ cm}^{-2}$  over  $10^7$  to  $10^8$  yr of exposure, corresponding to  $\phi_{\text{sw}} \sim 0.3\text{--}3$ . In this parametrization both  $\alpha$  and  $\phi_{\text{sw}}$  are dimensionless, and the product  $\alpha \phi_{\text{sw}}$  is a dimensionless space-weathering “dose” variable for use in photometric/maturity correction. The Diviner CF shifts with both composition and weathering state [11,13] and is used in Sec. VI to cross-calibrate composition versus maturity.

### C. Thermal fatigue

Thermoelastic stresses scale as  $\sigma_{\text{th}} \sim E \alpha_T \Delta T / (1 - \nu)$ . With  $E = 50\text{--}100 \text{ GPa}$ ,  $\alpha_T = 5\text{--}10 \times 10^{-6} \text{ K}^{-1}$ ,  $\Delta T = 200\text{--}300 \text{ K}$ ,  $\nu \approx 0.25$ , stresses of order 10–100 MPa arise, consistent with laboratory cycling that produces crack advance and fines [42]. Diviner rock-abundance decay versus age indicates ongoing breakdown on Myr to 100 Myr timescales [3].

### D. Volcanic pyroclastics

Fire-fountain eruptions produced glass beads and shards (Apollo 15 green; Apollo 17 orange/black). Representative compositions: FeO 16–25 wt%, TiO<sub>2</sub> 9–16 wt% for high-Ti glasses [21–23]. These glasses generate fines with distinct mid-IR emissivity and CF positions.

*From sources to properties.* The production pathways discussed above in Sec. II, set three levers that dominate the downstream physics: (1) particle-size distribution and angularity (impact comminution, thermal fatigue), (2) glassy agglutinate content with npFe<sup>0</sup> (space weathering), and (3) composition and oxidation state (basaltic versus anorthositic, pyroclastic glasses). Sections III–V quantify how these levers

map to specific surface area, vertical density structure, dielectric response, and spectral behavior that the rest of the paper builds upon.

## III. PHYSICAL AND CHEMICAL PROPERTIES

Given the pathways in Sec. II, we compile grain-scale properties that set contact mechanics, transport, and remote-sensing response: PSD, SSA, vertical density structure, and bulk chemistry/mineralogy.

### A. Particle-size distribution, shape, surface area

Mature soils exhibit a broad, well-graded PSD with median diameter  $D_{50} \approx 40\text{--}130 \mu\text{m}$  and abundant sub-20  $\mu\text{m}$  fines by count [2]. Irregular, angular grains raise SSA and promote interlocking at contacts. Measured BET SSA spans  $0.02\text{--}0.78 \text{ m}^2 \text{ g}^{-1}$ , with a widely used reference value near  $0.5 \text{ m}^2 \text{ g}^{-1}$  (spherical-equivalent diameter 3–4  $\mu\text{m}$ ) [1,2,43].

### B. Density, porosity, and vertical structure

A compact representation of bulk density  $\rho(z)$  from Eq. (1) is

$$\rho(z) = \rho_\infty - (\rho_\infty - \rho_0) e^{-z/z_c},$$

with  $\rho_0 = 1.4 \text{ g cm}^{-3}$ ,  $\rho_\infty = 1.85 \text{ g cm}^{-3}$ , and  $z_c = 0.15\text{--}0.30 \text{ m}$ . Near-surface porosity is typically 40%–50%. Regolith thickness: maria 3–5 m; highlands 10–20 m [1]. These structures are consistent with Diviner vertical  $k$  inversions [4].

### C. Mineralogy and chemistry

Maria are basaltic (FeO 15–22 wt%, TiO<sub>2</sub> 1–13 wt%); highlands are anorthositic (plagioclase rich, low FeO) [10,18,20]. Space weathering adds npFe<sup>0</sup> and amorphous rims that dominate optical maturity metrics.

From microstructure to mechanics. Given the PSD, angularity, and SSA, the Mohr-Coulomb parameters and contact physics follow: Higher angularity and packing density raise  $\phi$  and elevate  $c$  through interlocking; increased fines raise adhesion and increase the work required to detach grains from contacts in vacuum. These relations motivate the geotechnical formulations collected in Sec. IV.

## IV. MECHANICAL PROPERTIES AND CONTACT PHYSICS

### A. Shear strength

Under drained, vacuum conditions the peak shear strength of the lunar regolith on a plane at effective normal stress  $\sigma$  is described by the Mohr-Coulomb criterion

$$\tau(\sigma, z) = c(z) + \sigma \tan \phi(z), \quad (4)$$

where  $\tau$  is shear stress at failure (Pa),  $c$  is the apparent cohesion (Pa) arising from interlocking, adhesion, and any vacuum cementation,  $\sigma$  is the *effective* normal stress on the failure plane (Pa) (pore pressure  $u = 0$  in vacuum, so  $\sigma = \sigma_n$ ), and  $\phi$  is the friction angle (deg), which increases with relative

density and confinement. Apollo/Lunokhod and analog testing indicate  $\phi = 30^\circ$ – $50^\circ$  at the surface, approaching  $\sim 55^\circ$  with depth/relative density, and  $c = 0.1$ – $1$  kPa at the surface, increasing to  $>3$  kPa by  $0.5$ – $1$  m depth [1,44,45]. These trends are consistent with angular grains and broad PSDs that raise interlocking and contact density with depth.

To relate strength to depth, we again use the bulk-density profile of Eq. (1), which gives the vertical overburden (effective) stress:

$$\sigma_v(z) = \int_0^z \rho(\zeta) g_{\text{Moon}} d\zeta = g_{\text{Moon}}[\rho_\infty z - (\rho_\infty - \rho_0)z_c(1 - e^{-z/z_c})]. \quad (5)$$

*Permanently shadowed region (PSR) frost-cement contingency.* If a volumetric ice fraction  $f_{\text{ice}}$  is present within the near-surface pore space (PSR floors/rims), apparent cohesion and (possibly) friction angle are modified. For design, carry a parametric contingency:

$$c_{\text{PSR}}(z) \equiv c(z) + \Delta c_{\text{ice}}, \quad \phi_{\text{PSR}}(z) \equiv \phi(z) + \Delta \phi_{\text{ice}}, \quad (6)$$

with increments scaled to  $f_{\text{ice}}$ ,

$$\Delta c_{\text{ice}} = \alpha_c \frac{f_{\text{ice}}}{1 - n(z)} \sigma_{\text{ice}}(T), \quad \Delta \phi_{\text{ice}} = \alpha_\phi f_{\text{ice}}, \quad (7)$$

where  $n(z)$  is porosity from Eq. (1),  $\sigma_{\text{ice}}(T)$  is the unconfined compressive strength of ice at temperature  $T$ , and  $\alpha_c, \alpha_\phi$  are dimensionless design coefficients to be bracketed in sensitivity studies (e.g.,  $\alpha_c \in [0.1, 1]$ ,  $\alpha_\phi \in [0^\circ, 4^\circ]$ ). Use local  $T$  from Sec. V and update trafficability envelopes in Sec. IV C and Table IX accordingly.

As an illustrative design calculation (maria prior:  $\rho_0 = 1.4$  g cm $^{-3}$ ,  $\rho_\infty = 1.85$  g cm $^{-3}$ , and  $z_c = 0.20$  m), at  $z = 0.30$  m, the overburden is  $\sigma_v \simeq 7.9 \times 10^2$  Pa. With  $\phi = 40^\circ$  and  $c = 0.5$  kPa, this yields

$$\tau \approx c + \sigma_v \tan \phi \simeq 0.5 \text{ kPa} + (0.79 \text{ kPa}) \tan 40^\circ \simeq 1.16 \text{ kPa},$$

consistent with Apollo geotechnical ranges and the increase of  $(\phi, c)$  with density at depth [1,45].

### B. Adhesion and detachment thresholds

At a single asperity of radius  $R$ , the Johnson-Kendall-Roberts (JKR) estimate [46] for pull-off force for a sphere on a flat is

$$F_{\text{adh}} \approx \frac{3}{2} \pi W R. \quad (8)$$

With  $W \approx 0.05$ – $0.2$  J m $^{-2}$  and  $R \approx 1$ – $10$   $\mu\text{m}$ , Eq. (8) results in  $F_{\text{adh}} \approx 0.24$ – $9.42$   $\mu\text{N}$  for the stated ranges (for  $W = 0.1$  J m $^{-2}$ ,  $R = 5$   $\mu\text{m}$ ,  $F_{\text{adh}} = 2.36$   $\mu\text{N}$ ). For a  $1$   $\mu\text{m}$  grain with density  $\rho_p = 3100$  kg m $^{-3}$ , the gravitational force [gravitational acceleration on the Moon ( $g_{\text{Moon}}$ )]  $mg_{\text{Moon}} \approx 2.10 \times 10^{-14}$  N (8 orders of magnitude below the adhesion force for the parameters used here). Consequently, preliberation by vibration, microimpacts, or gas shear is typically required before electrostatic acceleration can act [47,48]; Sec. VI B quantifies the field strengths needed when  $F_{\text{adh}}$  is included.

*JKR versus DMT regime.* In the Derjaguin-Muller-Toporov (DMT) limit [49,50] appropriate to stiffer

materials and smaller contact radii, the pull-off force is  $F_{\text{adh}}^{\text{DMT}} = 2\pi W R$  [compare to Eq. (8)]. The appropriate contact model can be gauged by the Tabor parameter  $\mu = (RW^2/E^*z_0^3)^{1/3}$ , with reduced modulus  $E^*$  and intermolecular cutoff  $z_0 \sim 0.3$ – $0.4$  nm. For lunarlike values  $R \sim 1$ – $10$   $\mu\text{m}$ ,  $W \sim 0.1$  J m $^{-2}$ , and  $E^* \sim 50$ – $100$  GPa,  $\mu \gtrsim 1$ – $10$ , placing contacts in the JKR regime. If  $\mu \lesssim 1$ , the DMT limit applies, with  $F_{\text{adh}} \approx 2\pi W R$ . Given that  $F_{\text{adh}} \gg mg_{\text{Moon}}$  across the micron range, both models lead to the same design implication: Preliberation (vibration, microimpacts, or gas shear) is required before sheath acceleration is effective. We adopt JKR here and propagate  $(W, R)$  explicitly into the lift requirement via Eq. (26).

### C. Trafficability and wheel-soil interaction (design bridge)

For a driven wheel (radius  $R_w$ , width  $b$ ) carrying normal load  $W$ , the contact normal stress is  $\sigma \simeq W/(b\ell_c)$  with contact length  $\ell_c \sim \sqrt{2R_w z}$  for sinkage  $z \ll R_w$ . The available shear stress at the interface follows Mohr-Coulomb criterion (see Sec. IV A):

$$\tau_{\text{max}} = c + \sigma \tan \phi, \quad (9)$$

with cohesion  $c$  and friction angle  $\phi$  taken from Sec. IV and Table VII. A first-order upper bound on tractive force for one wheel is then

$$T_{\text{max}} \simeq \tau_{\text{max}} b \ell_c, \quad \Rightarrow \quad T_{\text{max}} \simeq \left( c + \frac{W}{b \ell_c} \tan \phi \right) b \ell_c, \quad (10)$$

which elevates with increasing  $\phi$  and  $c$  (depth/relative density), consistent with Apollo geotechnics and modern syntheses (Sec. IV). The corresponding rolling resistance force can be estimated as

$$F_{\text{rr}} \simeq k_{\text{rr}} W, \quad k_{\text{rr}} \approx \frac{z}{R_w}, \quad (11)$$

so denser near-surface structure [Eq. (1) and higher  $\phi$  reduce sinkage  $z$  and  $k_{\text{rr}}$ .

*a. Pressure-sinkage scaling.* For pressure  $p$  under a plate of width  $b$ , the classical pressure-sinkage form

$$p(z) \approx \left( \frac{k_c}{b} + k_\phi \right) z^n \quad (12)$$

is a convenient parametrization;  $(k_c, k_\phi, n)$  are site specific and should be calibrated with preflight terrain analogs using the density profile of Eq. (1) [51]. Combining Eqs. (9)–(12) with regional priors in Table VII gives a compact mobility envelope *without* invoking additional constitutive assumptions.

*b. Design use.* Given  $W, R_w, b$ , and site priors  $(\rho(z), \phi, c)$ , Eqs. (10) and (11) bound gradeability and power at slip. PSR rims and cold slopes tend to exhibit higher relative density near the surface (Sec. V), hence reduced  $z$  and  $k_{\text{rr}}$ ; pyroclastics and immature swirl lanes can deviate systematically (Tables VII and VIII).

## V. THERMOPHYSICAL PROPERTIES

Thermophysics mediates between structure and environment. The effective thermal conductivity of lunar regolith (or dust),  $k(T, \rho)$ , is a function of temperature  $T$  and bulk

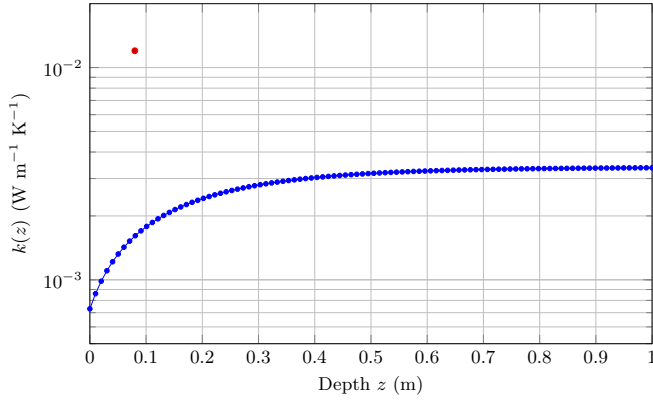


FIG. 1. Illustrative conductivity-depth profile  $k(z)$  anchored to Diviner day/night trends and the ChaSTE *in situ* point at  $z \approx 0.08$  m ( $k \approx 1.2 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$ ) [4,5,33] closes the long-standing gap between Diviner surface inversions and near-subsurface  $k(z)$ . The elevated  $k$  at 8 cm is consistent with higher density and local disturbance from landing, emphasizing centimeter-scale structure in  $k(T, \rho)$ .

density  $\rho$ . Depth-dependent  $k(T, \rho)$  determines the diurnal temperature wave and, through it, photoemission and charge relaxation times relevant to Sec. VI.

#### A. Conductivity and thermal inertia

A contact-plus-radiative representation captures both solid-network and pore-radiative pathways:

$$k(T, \rho) = k_{\text{cond}}(\rho) + A T^3, \quad k_{\text{cond}}(\rho) = k_{\text{cond},0} \left( \frac{\rho}{\rho_s} \right)^\ell, \quad (13)$$

with  $\ell \approx 2-3$ , solid density  $\rho_s$ , and radiative coefficient  $A$  ( $\text{W m}^{-1} \text{ K}^{-4}$ ) that scales with porosity and pore-size statistics. The radiative coefficient  $A$  is quantified in Sec. XIC. Diviner retrievals constrain  $k$  near the surface to  $\sim 7.4 \times 10^{-4} \text{ W m}^{-1} \text{ K}^{-1}$ , increasing to  $\sim 3.4 \times 10^{-3} \text{ W m}^{-1} \text{ K}^{-1}$  by  $\sim 1$  m depth, while ChaSTE measured  $k \approx (1.15-1.24) \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$  at  $z = 0.08$  m at  $69.373^\circ \text{ S}$ , consistent with local densification and the depth dependence in Eq. (13). Thermal inertia  $\Gamma = \sqrt{k \rho c_p}$ , with  $c_p$  being specific heat capacity in ( $\text{J kg}^{-1} \text{ K}^{-1}$ ), thermal inertia  $\Gamma$  is typically  $40-70 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$  for fines, increasing with rock abundance and latitude [3]. PSRs reach  $25-40 \text{ K}$  [5].

*In-situ* measurements by the Chandrayaan-3 ChaSTE probe at the Vikram site ( $69.373^\circ \text{ S}$ ,  $32.319^\circ \text{ E}$ ) report  $k = (1.15-1.24) \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$  at a depth of 80 mm and indicate a local packing density  $\rho \approx 1.94 \times 10^3 \text{ kg m}^{-3}$  [33]. The relatively high  $k$  compared to near-surface Diviner inversions is consistent with (i) density increase with depth, (ii) local compaction and fines redistribution associated with touchdown, and (iii) the explicit  $k(T, \rho)$  dependence in the two-channel (contact + radiative) model used here. These ChaSTE values provide an anchor for calibrating  $k(T, \rho)$  at centimeter depths in polar design studies [33]. See Fig. 1 for an illustrative  $k(z)$  profile anchored by Diviner near the surface and by the ChaSTE point at  $z \approx 0.08$  m.

Coupling to the electrical environment. The  $k(T, \rho)$  structure regulates the near-surface diurnal temperature wave and hence photoemission, conductivity of the pore network, and the time constants of charge relaxation. At high latitudes and in PSRs, low  $T$  and high porosity lengthen charge-relaxation times, biasing the electrical regime toward persistent charge patches and large  $|E|$  at boundaries. These couplings are taken up in Sec. VI.

*a. Recommended parameter ranges and sensitivities (design use).* To make Eq. (13) directly actionable in trades, we recommend carrying explicit ranges and first-order sensitivities:

Exponent:  $\ell = 2.0-3.0$  (dimensionless). Sensitivity:

$$\frac{\partial \ln k}{\partial \ln \rho} = \frac{k_{\text{cond}}}{k} \ell \quad \text{with} \quad k_{\text{cond}} = k_0 \left( \frac{\rho}{\rho_s} \right)^\ell. \quad (14)$$

*b. Radiative coefficient:*  $A = (3.6 \times 10^{-12} \text{ to } 3.6 \times 10^{-11}) \text{ W m}^{-1} \text{ K}^{-4}$  (consistent with the day/night asymmetry used later in Sec. XIC). Sensitivity:

$$\frac{\partial \ln k}{\partial \ln T} = \frac{3AT^3}{k}. \quad (15)$$

*c. Contact term scale  $k_0$ :* set by calibration to the Diviner and ChaSTE anchors already cited:

$$k(z \rightarrow 0) \approx 7.4 \times 10^{-4} \text{ W m}^{-1} \text{ K}^{-1}, \quad (16)$$

$$k(z \approx 1 \text{ m}) \approx 3.4 \times 10^{-3} \text{ W m}^{-1} \text{ K}^{-1}, \quad (17)$$

$$k(z = 0.08 \text{ m}) \approx (1.15-1.24) \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1} \times (69.373^\circ \text{ S}, 32.319^\circ \text{ E}). \quad (18)$$

For a given region (Table VII), choose  $\{\rho_0, \rho_\infty, z_c\}$ , then solve for  $(k_0, \ell, A)$  that best fit these anchors at the local temperature; carry the resulting posterior intervals into design margins.

#### B. Temperature-illumination scalings and regional contrasts

The diurnal temperature wave couples into both thermo-physical and electrical regimes. Define the thermal diffusivity  $\kappa = k/(\rho c)$  and the frequency  $\omega = 2\pi/P$  with  $P = 2.55 \times 10^6 \text{ s}$  (synodic day). The diurnal skin depth is

$$\delta \equiv \sqrt{\frac{2\kappa}{\omega}} = \sqrt{\frac{2k}{\rho c \omega}}, \quad (19)$$

which is typically  $\delta \approx 2-5 \text{ cm}$  for  $k \approx (0.7-3.4) \times 10^{-3} \text{ W m}^{-1} \text{ K}^{-1}$ ,  $\rho \approx (1.3-1.6) \times 10^3 \text{ kg m}^{-3}$ , and  $c_p \approx 600-800 \text{ J kg}^{-1} \text{ K}^{-1}$ , matching Diviner-derived ranges [52]. Within  $z \lesssim \delta$ ,  $k(T, \rho) = k_0(\rho/\rho_s)^\ell + AT^3$  [from Eq. (13)] produces a day-night asymmetry in  $\Gamma = \sqrt{k \rho c_p}$  and sets the temperature-phase lag.

The electrical repercussions follow from the conductivity of the pore/grain network,  $\sigma(T)$ , entering the charge-relaxation time  $\tau_{\text{relax}} \approx \varepsilon_0 \varepsilon' / \sigma$  (Sec. VIA). For representative values  $\varepsilon' \approx 3$  and  $\sigma \sim \{10^{-13}, 10^{-15}, 10^{-17}\} \text{ S m}^{-1}$ ,  $\tau_{\text{relax}} \approx \{2.7 \times 10^2, 2.7 \times 10^4, 2.7 \times 10^6\} \text{ s}$ , respectively; thus colder, more porous environments (night, high latitudes, PSRs) maintain charge patches and field gradients far longer than sunlit equatorial terrains.

The dielectric response exhibits modest densification- and composition-driven changes [Looyenga mixing; Eq. (23)], with  $\varepsilon'$  increasing  $\sim 10\%$ – $30\%$  as  $\rho$  rises from 1.4 to 1.9 g cm $^{-3}$  at fixed composition (CE-4 LPR trends) (see Sec. VI A). Loss tangent  $\tan \delta$  increases with ilmenite fraction and temperature over the near-surface range relevant to LPR bands, implying larger rf attenuation in warm, Fe/Ti-rich maria than in cooler, feldspathic highlands.

*Regional contrasts (design priors).* (1) Equator, sunlit: higher  $T \Rightarrow$  larger  $AT^3$  in  $k(T, \rho)$ , smaller  $\tau_{\text{relax}}$ , weaker/persistently smaller  $|E|$  in uniform illumination. (2) Terminator/shadow edges: sharp  $E(z)$  gradients over decimeters; fields  $10^2$  to  $10^3$  V m $^{-1}$  (Sec. VI B). (3) PSRs and high latitudes:  $T \simeq 25$ – $40$  K on PSR floors  $\Rightarrow$  long  $\tau_{\text{relax}}$ , favoring persistent charge segregation and large  $|E|$  at boundaries. (4) Near- versus far side: composition differs statistically (far side more feldspathic on average), biasing  $\varepsilon'$  lower and  $\tan \delta$  smaller; this should be combined with local rock abundance and packing state when interpreting LPR and thermal data (Tables VI and VII).

### C. Vertical structure of the upper 3 m (by region)

We extend the density profile in Eq. (1) to  $z \leq 3$  m and make the implied porosity, dielectric constant, thermal conductivity, and overburden stress explicit. This provides design-ready priors for maria, highlands, pyroclastics, swirls, and PSR environments consistent with Apollo cores, Diviner inversions, and CE-4 LPR in the *upper meters* [1,4,7,8].

*a. Density and porosity.* With Eq. (1), porosity follows from  $n(z) = 1 - \rho(z)/\rho_s$  using  $\rho_s$  from composition (typically  $\rho_s \sim 2.9$ – $3.2$  g cm $^{-3}$ ). For the canonical parameters  $\rho_0 = 1.4$  g cm $^{-3}$ ,  $\rho_\infty = 1.85$  g cm $^{-3}$ , and  $z_c = 0.15$ – $0.30$  m,  $n(z)$  decreases from  $\sim 0.5$ – $0.55$  at the surface to  $\sim 0.38$ – $0.42$  by  $z \simeq 1$  m and asymptotes slowly below  $z \simeq 2$  m (consistent with Apollo and Diviner). See Eq. (1) and Secs. III B and V A.

*b. Vertical effective stress.* The overburden to depth  $z$  is [see Eq. (5)]

$$\begin{aligned} \sigma_v(z) &= g_{\text{Moon}} \int_0^z \rho(z') dz' \\ &= g_{\text{Moon}} [\rho_\infty z - (\rho_\infty - \rho_0) z_c (1 - e^{-z/z_c})], \end{aligned} \quad (20)$$

which gives  $\sigma_v \approx 2.8$  kPa at 1 m and  $\approx 8.8$  kPa at 3 m for the canonical parameters. This stress scale is consistent with the observed increase of  $c$  with depth (Sec. IV A).

*c. Dielectric profile to 3 m.* Using Looyenga mixing Eq. (23) with voids treated as  $\varepsilon = 1$  and solid volume fraction  $1 - n(z)$ ,

$$\varepsilon^{1/3}(z) = (1 - n(z)) \varepsilon_s^{1/3} + n(z) \times 1, \quad (21)$$

where  $\varepsilon_s$  depends on composition (ilmenite-rich basalts versus anorthosites). Equation (21) combined with Eq. (20) reproduces the CE-4 LPR trend of increasing  $\varepsilon'$  with depth/densification in the *upper meters* and supports the regional ranges in Sec. VI A (see Refs. [7,8]).

*d. Thermal conductivity to 3 m.* With Eq. (13),

$$k(z, T) = k_0 \left( \frac{\rho(z)}{\rho_s} \right)^\ell + A T^3, \quad (22)$$

whose  $z$  dependence inherits Eq. (1). Calibrate  $\{k_0, \ell, A\}$  by matching Diviner night/day  $k$  in the upper decimeters and the ChaSTE point at  $z = 0.08$  m at  $69.373^\circ$  S (Sec. V A). This yields a self-consistent  $k(z)$  through 3 m for thermal design.

*e. Regional priors (0–3 m).* Adopt region-specific  $(\rho_0, \rho_\infty, z_c)$  consistent with Table VII: maria (1.40, 1.85, 0.15–0.22), highlands (1.30, 1.80, 0.20–0.30), pyroclastics (1.40, 1.85, 0.15–0.22), swirls (1.40, 1.85, 0.15–0.25), and PSR floors (1.35, 1.80, 0.20–0.30). Combine Eq. (21) with composition-specific  $\varepsilon_s$  (ilmenite fraction) to propagate into  $\varepsilon'(z)$ ; then use Eq. (22) for  $k(z, T)$ , anchoring to Diviner and ChaSTE. These profiles are directly compatible with the LPR  $\varepsilon'$  ranges and the “upper meters” thermophysics summarized in Secs. V and VI.

## VI. ELECTRICAL AND DIELECTRIC PROPERTIES

The electrical and dielectric state follows from composition, porosity, illumination, and plasma forcing. We gather permittivity ranges, sheath fields, and charging pathways, and update them with recent dayside  $H^-$  detections.

### A. Dielectric constant and loss tangent

Shallow regolith exhibits  $\varepsilon' \approx 2.5$ – $3.5$  with  $\tan \delta \approx 10^{-3}$  to  $10^{-2}$ ; both rise with density and ilmenite fraction [7,8]. For compositional mixing, we use the Looyenga relation for the effective dielectric constant [53],

$$\varepsilon_{\text{eff}}^{1/3} = \sum_i v_i \varepsilon_i^{1/3}, \quad (23)$$

where  $v_i$  and  $\varepsilon_i$  are the volume fraction and dielectric constant of component  $i$ . At fixed composition, densification from 1.4 to 1.9 g cm $^{-3}$  raises  $\varepsilon'$  by  $\approx 10\%$ – $30\%$ , consistent with LPR trends [7,8]. Unless otherwise specified, reported  $\varepsilon'$  and  $\tan \delta$  refer to the upper meters at decimeter-meter wavelengths (LPR bands, cf. Sec. V C) and near-surface temperature ranges.

*a. Temperature and frequency dependence.* Both  $\varepsilon'$  and  $\tan \delta$  vary with temperature, frequency, porosity, and composition. Laboratory UHF–super-high frequency (SHF) measurements of representative lunar end members at fixed porosity show that cooling from 20 to  $-60^\circ$  C ( $293 \rightarrow 213$  K) reduces  $\varepsilon'$  by  $\sim 6\%$ – $18\%$  (composition dependent) [54]. Over 213–293 K, an engineering-linearized sensitivity  $\alpha_\varepsilon \equiv -\frac{1}{\varepsilon'} \frac{\partial \varepsilon'}{\partial T} \sim (0.7\text{--}2.3) \times 10^{-3}$  K $^{-1}$  captures this range to first order; extrapolation below  $\sim 200$  K (PSRs) remains poorly constrained and should be treated as an additional systematic uncertainty.

*b. Charge-relaxation time.* The local charge-relaxation timescale is  $\tau_{\text{relax}} \simeq \varepsilon_0 \varepsilon' / \sigma$ , where  $\sigma$  is the effective conductivity of the pore/grain network. Low  $T$  and high porosity in polar and PSR environments imply small  $\sigma$  and hence large  $\tau_{\text{relax}}$ , biasing the sheath toward persistent patches and large field gradients along illumination boundaries. (For example, with  $\varepsilon' = 3$  and  $\sigma = 10^{-13}$ ,  $10^{-15}$ ,  $10^{-17}$  S m $^{-1}$ ,  $\tau_{\text{relax}} \approx 2.7 \times 10^2$ ,  $2.7 \times 10^4$ ,  $2.7 \times 10^6$  s, respectively, see Table II) This provides the link from  $k(T, \rho)$  [Eq. ((13) to the electrical regime (this section).

*c. Neutral exosphere.* The neutral exosphere (He, Ne, Ar, Na/K, H $_2$ /H) is collisionless at the surface with scale heights

TABLE II. Charge relaxation priors by thermal/porosity regime (illustrative). Values assume  $\varepsilon' \approx 3$  so that  $\tau_{\text{relax}} \approx \varepsilon_0 \varepsilon' / \sigma$ .

| Regime                          | $\sigma$ (S m <sup>-1</sup> ) | $\tau_{\text{relax}}$ (s) |
|---------------------------------|-------------------------------|---------------------------|
| Warm, Fe/Ti-rich maria (sunlit) | 10 <sup>-13</sup>             | 2.7 × 10 <sup>2</sup>     |
| Temperate highlands             | 10 <sup>-15</sup>             | 2.7 × 10 <sup>4</sup>     |
| Cold, porous PSR/high latitudes | 10 <sup>-17</sup>             | 2.7 × 10 <sup>6</sup>     |

~10<sup>2</sup> to 10<sup>3</sup> km and near-surface densities  $\ll 10^{10}$  m<sup>-3</sup>; it is dynamically decoupled from grain motion in the 0–3 m layer, but sources (sputtering, micrometeoroid impact vapor, desorption) covary with processes that set dust charging and npFe<sup>0</sup> production. We therefore treat the exosphere as boundary forcing for charging (Sec. VI B) and dust maintenance (Sec. VIII A).

*d. Design note.* Use Table II with the  $k(T, \rho)$  state from Sec. V to pick a  $\sigma$  consistent with  $T$  and porosity; propagate  $\tau_{\text{relax}}$  into the time window over which  $q$  can be treated quasi-constant in Eqs. (46) and (47).

### B. Charging, sheath fields, and lift including cohesion

Photoemission current density  $J_{\text{ph}} \approx eYF_{\gamma}$  balances plasma currents to set floating potentials. Near-surface electric fields  $E$  at terminators and in shadows reach 10<sup>2</sup> to 10<sup>3</sup> V m<sup>-1</sup> [14,15]. Neglecting cohesion, the largest grain radius that can be lifted by an electric field  $E$  at grain potential  $\phi_g$  is

$$a_{\text{max}}(E) = \left( \frac{3 \varepsilon_0 \phi_g E}{\rho_p g_{\text{Moon}}} \right)^{1/2}. \quad (24)$$

For  $\phi_g = 5$  V,  $E = 300$  V m<sup>-1</sup>,  $\rho_p = 3100$  kg m<sup>-3</sup>, and  $g_{\text{Moon}} = 1.62$  m s<sup>-2</sup>, Eq. (24) gives  $a_{\text{max}} \approx 2.8$   $\mu\text{m}$ .

Including adhesion [JKR form at a single asperity of radius  $R$  with work of adhesion  $W$ ; see Eq. (8),

$$qE \gtrsim mg_{\text{Moon}} + F_{\text{adh}}, \quad F_{\text{adh}} \approx \frac{3}{2} \pi WR, \quad q = 4\pi \varepsilon_0 a \phi_g, \quad (25)$$

so that the field required to separate a grain of radius  $a$  is

$$\begin{aligned} E_{\text{req}}(a) &\gtrsim \frac{\frac{4}{3} \pi a^3 \rho_p g_{\text{Moon}} + \frac{3}{2} \pi WR}{4\pi \varepsilon_0 a \phi_g} \\ &= \left( \frac{\rho_p g_{\text{Moon}}}{3\varepsilon_0 \phi_g} \right) a^2 + \left( \frac{3WR}{8\varepsilon_0 \phi_g} \right) \frac{1}{a} \\ &\Rightarrow E_{\text{req}}(a) \gtrsim C_{\text{no}} a^2 + C_{\text{adh}} \frac{1}{a}. \end{aligned} \quad (26)$$

With  $W = 0.1$  J m<sup>-2</sup> and  $R = 5$   $\mu\text{m}$ ,  $F_{\text{adh}} = \frac{3}{2} \pi WR \simeq 2.36$   $\mu\text{N}$ , which exceeds the weight of a 1  $\mu\text{m}$  grain by  $\sim 1.1 \times 10^8$  (see Fig. 2). This explains why preliberation (vibration, microimpacts, or gas shear) is commonly required prior to sheath acceleration.

Even if rare transients were to push near-surface fields toward 10<sup>4</sup> to 10<sup>5</sup> V m<sup>-1</sup> in special geometries, Eq. (26) still implies  $E_{\text{req}} \gg 10^7$  V m<sup>-1</sup> for micron-scale grains under the reference ( $W, R$ ), so preliberation remains necessary even then.

For representative values  $W = 0.1$  J m<sup>-2</sup>,  $R = 5 \times 10^{-6}$  m,  $\rho_p = 3.1 \times 10^3$  kg m<sup>-3</sup>,  $g_{\text{Moon}} = 1.62$  m s<sup>-2</sup>,  $\varepsilon_0 = 8.854 \times 10^{-12}$  F m<sup>-1</sup>, and  $\phi_g = 5$  V, from Eq. (26), we have [55]

$$\begin{aligned} C_{\text{no}} &= \frac{\rho_p g_{\text{Moon}}}{3\varepsilon_0 \phi_g} = 3.781 \times 10^{13} \text{ m}^{-2} \quad \text{and} \\ C_{\text{adh}} &= \frac{3WR}{8\varepsilon_0 \phi_g} = 4.236 \times 10^3 \text{ (SI, } a \text{ in m)}. \end{aligned} \quad (27)$$

As a result, Eq. (26) yields fields far exceeding realistic sheath values unless grains are preloosened by vibration, microimpacts, thermal cycling, or gas shear. For example,  $a = 1$   $\mu\text{m}$  gives  $E_{\text{req}} \sim 4.2 \times 10^9$  V m<sup>-1</sup>, dominated by  $F_{\text{adh}}$ ; at  $a = 5$   $\mu\text{m}$ , the requirement is still  $E_{\text{req}} \sim 1.0 \times 10^9$  V m<sup>-1</sup>. This quantifies why electrostatic mobilization of adhered grains requires preliberation even when  $E \sim 10^2$  to  $10^3$  V m<sup>-1</sup> near terminators and shadow edges (see Table III for numerical examples and Fig. 2 for the plotted behavior).

*a. Design-relevant optimum of the adhesion-gravity trade.* Because  $E_{\text{req}}(a) = C_{\text{no}} a^2 + C_{\text{adh}}/a$  [Eq. (26)], the minimum

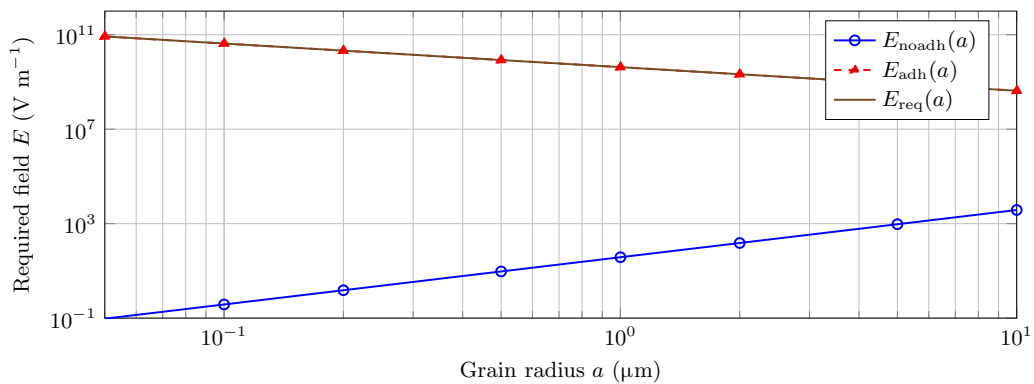


FIG. 2. Electric field required to lift a grain of radius  $a$  when the charge is limited by  $q \approx 4\pi \varepsilon_0 a \phi_g$ . Curves show the no-adhesion term  $E_{\text{noadh}}(a)$ , the adhesion term  $E_{\text{adh}}(a)$  for  $W = 0.1$  J m<sup>-2</sup>, and  $R = 5$   $\mu\text{m}$  using the JKR pull off  $F_{\text{adh}} = \frac{3}{2} \pi WR$ , and their sum  $E_{\text{req}}(a)$ . Small red triangles mark  $E_{\text{adh}}(a)$  at the same abscissae where open circles mark  $E_{\text{noadh}}(a)$ . Across the micron range, adhesion dominates and  $E_{\text{req}}$  far exceeds typical sheath values (10<sup>2</sup> to 10<sup>3</sup> V m<sup>-1</sup>) unless grains are preloosened. Also, adhesion is made explicit via  $C_{\text{adh}}$ , turning electrostatic lift into a preliberation criterion rather than a field-only condition.

TABLE III. Illustrative adhesion-aware lift thresholds from Eq. (26) with  $\rho_p = 3100 \text{ kg m}^{-3}$ ,  $g_{\text{Moon}} = 1.62 \text{ m s}^{-2}$ ,  $\phi_g = 5 \text{ V}$ ,  $W = 0.1 \text{ J m}^{-2}$ ,  $R = 5 \text{ }\mu\text{m}$ , and  $F_{\text{adh}} = \frac{3}{2}\pi WR$ . Values highlight the dominance of adhesion over gravity for micron-scale grains.

| Radius $a$        | $mg_{\text{Moon}}$ (N) | $F_{\text{adh}}$ (N)  | $E_{\text{req}}$ ( $\text{V m}^{-1}$ ) |
|-------------------|------------------------|-----------------------|----------------------------------------|
| 0.1 $\mu\text{m}$ | $2.10 \times 10^{-17}$ | $2.36 \times 10^{-6}$ | $\sim 4.24 \times 10^{10}$             |
| 1.0 $\mu\text{m}$ | $2.10 \times 10^{-14}$ | $2.36 \times 10^{-6}$ | $\sim 4.24 \times 10^9$                |
| 5.0 $\mu\text{m}$ | $2.63 \times 10^{-12}$ | $2.36 \times 10^{-6}$ | $\sim 8.47 \times 10^8$                |

field occurs at

$$a_* = \left( \frac{C_{\text{adh}}}{2C_{\text{no}}} \right)^{1/3}, \quad E_{\text{req, min}} = E_{\text{req}}(a_*) = \frac{3}{2^{2/3}} C_{\text{no}}^{1/3} C_{\text{adh}}^{2/3}. \quad (28)$$

For the reference values used in Fig. 2 ( $\phi_g = 5 \text{ V}$ ,  $\rho_p = 3100 \text{ kg m}^{-3}$ ,  $W = 0.1 \text{ J m}^{-2}$ , and  $R = 5 \text{ }\mu\text{m}$ ), this gives  $a_* \simeq 3.8 \times 10^{-4} \text{ m}$  and  $E_{\text{req, min}} \simeq 1.7 \times 10^7 \text{ V m}^{-1}$ , i.e., even the most “lift-favorable” size under these adhesion assumptions still requires fields far above the  $10^2$  to  $10^3 \text{ V m}^{-1}$  envelope in Table III; therefore, bed-mediated detachment and/or mechanical preliberation remain necessary for micron-scale grains.

*b. Bed-mediated detachment: microcavity charge pumping and the patched-charge model (PCM).* Equations (25) and (26) treat a grain as an isolated sphere and therefore provide a *lower bound* on the external field needed to lift an already-detached (or very weakly adhered) particle. In contrast, a series of laboratory experiments has demonstrated that dust resting in a porous, insulating *bed* can be self-ejected under UV and/or plasma exposure due to charge pumping in microcavities between grains [56–58]. In the PCM picture, photoelectrons (and/or secondary electrons) emitted into microcavities are preferentially reabsorbed by surrounding grains, producing large *negative* grain charges and strong interparticle repulsion even under overall dayside illumination [56].

A simple order-of-magnitude detachment criterion for two like-charged grains is obtained by comparing Coulomb repulsion to the adhesive pull-off force. Approximating the repulsive interaction at a characteristic separation  $d$ ,

$$F_{\text{rep}} \sim \frac{q_p^2}{4\pi\epsilon_0 d^2} \gtrsim F_{\text{adh}}, \quad (29)$$

yields a required patch/particle charge

$$q_{p, \text{req}} \gtrsim d \sqrt{4\pi\epsilon_0 F_{\text{adh}}} = \pi d \sqrt{6\epsilon_0 WR}, \quad (30)$$

where  $F_{\text{adh}}$  is given by Eq. (8). For the reference values  $W = 0.1 \text{ J m}^{-2}$  and  $R = 5 \text{ }\mu\text{m}$  (so  $F_{\text{adh}} \simeq 2.36 \text{ }\mu\text{N}$ ), Eq. (30) gives

$$\frac{q_{p, \text{req}}}{e} \approx 1.0 \times 10^3 \left( \frac{d}{10 \text{ nm}} \right) \left[ \left( \frac{W}{0.1 \text{ J m}^{-2}} \right) \left( \frac{R}{5 \text{ }\mu\text{m}} \right) \right]^{1/2}, \quad (31)$$

showing that nanometer-scale microcavity separations can, in principle, enable electrostatic detachment at charge levels far below what would be required if the interaction acted only over grain-scale distances.

Consistent with this mechanism, lofted grains have been reported to carry unusually large *negative* charges (up to  $10^5$  to  $10^6$  electrons for  $\sim 20\text{-}\mu\text{m}$ -radius grains) and to exhibit peak lofting rates of order  $\sim 5 \text{ cm}^{-2} \text{ s}^{-1}$  in representative 1 A.U. conditions [57,58]. Therefore, Eq. (26) should be interpreted as the external-field requirement for lifting an *isolated adhered grain*; bed-scale microcavity charging can provide an additional detachment pathway that bypasses the need for purely mechanical preliberation in some regimes.

### C. Triboelectric charging

Contact/frictional charging among insulating fines and with rover or suit materials is efficient in vacuum; net charge depends on work-function offset, contact area, and history [16,17]. Tribocharge increases adhesion and modifies separation thresholds.

*Vehicle charging and electrostatic discharge (ESD) posture (design note).* Given  $\tau_{\text{relax}} \simeq \epsilon_0 \epsilon' / \sigma$  (Sec. VI), cold, porous PSR and high-latitude soils exhibit long relaxation times, admitting quasistatic patch potentials on vehicle and local soil. Near shadow/illumination boundaries, fields ( $E_0 \sim 10^2$ ) to ( $10^3 \text{ V m}^{-1}$ ) can persist over ( $\lambda \sim$ ) a few tens of centimeters, consistent with the adhesion-aware lift thresholds (Fig. 2). Design implications: (1) Reference chassis/booms to a single ground and avoid floating appendages in strong gradients; (2) pair electrostatic dust mitigation with *mechanical preliberation* where relevant, and account for bed-mediated electrostatic ejection via microcavity charge pumping (patched-charge model) as an additional detachment pathway under UV/plasma exposure [56–58]; and (3) treat dayside  $\text{H}^-$  (Sec. VI) as a modifier to sheath composition, particularly for daylight traverses over anomaly boundaries.

### D. Near-surface negative ion layer (dayside)

Chang’e-6 NILS detected a dayside near-surface  $\text{H}^-$  population over the far side, with  $(2.5_{-0.8}^{+1.2})$  percent of incident solar-wind protons charge exchanged and backscattered as  $\text{H}^-$ ; a local number density  $\sim 1.8 \times 10^{-1} \text{ cm}^{-3}$  and a scale height of order 10 km were inferred, limited by rapid photo detachment [36]. The presence of negative ions modifies photoelectron sheath structure, grain-charging time constants, and therefore the spatiotemporal envelope in which Eq. (26) can be satisfied. Practical modeling should include electrons, positive ions, and  $\text{H}^-$  with photodetachment to assess daylight lofting near boundaries and over magnetic anomalies.

*a. Link to optical maturity.* The same processes that drive charge balance (photoelectron production, implantation, micrometeoroid impact vaporization) also control the rate at which  $\text{npFe}^0$  accumulates. Consequently, optical maturity metrics and CF shifts provide an independent clock on the surface exposure that, in principle, can be fused with charging models to predict where and when electrostatic mobilization is favored. Section VII summarizes the relevant spectral diagnostics.

*b. Neutral exosphere context.* The neutral lunar exosphere is collisionless on meter scales; neutral number densities and mean free paths imply that drag over the  $\lesssim 2\text{--}3 \text{ s}$  timescales of submeter hops is negligible compared to electrostatic and

gravitational forces considered here. Consequently, the dynamical budgets in Eqs. (24)–(26) and (47) are governed by the charged component (photoelectrons, ions, and the dayside near surface  $H^-$  detected by NILS) rather than by neutral drag.

*c. Measured properties and loss-limited scale height.* NILS reports  $H^-$  energies in the  $\sim 50$ – $400$  eV range and interprets the vertical distribution as loss limited by photo detachment, with a characteristic lifetime  $\tau_{pd} \sim 70$  ms and a scale height of order  $H_{H^-} \sim 10$  km [36]. A simple consistency check follows from ballistic transport with photodetachment loss:

$$H_{H^-} \sim \langle v_z \rangle \tau_{pd} \approx \frac{v_{H^-}}{2} \tau_{pd}, \quad (32)$$

where  $v_{H^-} = \sqrt{2E_{H^-}/m_H}$ . For  $E_{H^-} \sim 239$  eV and  $\tau_{pd} \sim 70$  ms,  $v_{H^-} \tau_{pd} \sim 15$  km, consistent with the inferred  $\sim 10$  km scale height [36].

*d. Electronegativity and its impact on the sheath length scale.* A convenient nondimensional measure of the negative-ion importance is the electronegativity

$$\alpha(z) \equiv \frac{n_{H^-}(z)}{n_e(z)}. \quad (33)$$

In a linearized (small-amplitude) multispecies limit, the shielding scale entering exponential closures like in Eq. (45) is controlled by the generalized Debye length,

$$\lambda_D^{-2} \approx \frac{e^2}{\epsilon_0 k_B} \left( \frac{n_e}{T_e} + \frac{n_i}{T_i} + \frac{n_{H^-}}{T_{H^-}} \right), \quad (34)$$

so that, all else equal, increasing  $n_{H^-}$  (or decreasing  $T_{H^-}$ ) decreases  $\lambda_D$  and steepens near-surface potential gradients. In the near-surface photoelectron layer,  $n_e$  can be large, so  $\alpha \ll 1$  may imply only a small perturbation to  $\lambda$  very close to the surface; however, because  $n_e(z)$  typically falls rapidly with altitude while loss limited  $n_{H^-}(z)$  can persist over kilometer scales (Sec. VID, c and d),  $\alpha(z)$  may increase with height, enabling negative space charge to reshape  $\phi(z)$  outside the first meters (potential humps/wells), which can in turn modify dust trajectories that extend above the near-surface region [59–61].

*e. Minimal sheath model with an electronegative component.* To first order, the near-surface potential must satisfy Poisson's equation with electrons, positive ions, and negative ions,

$$\epsilon_0 \frac{d^2 \phi}{dz^2} = -e(n_i(z) - n_e(z) - n_{H^-}(z)), \quad (35)$$

with  $n_{H^-}(z)$  constrained by Eq. (32) in the loss-limited regime. Even if  $n_{H^-}$  is small compared to the peak photoelectron density close to the surface, it can contribute negative space charge over kilometer scales and thereby alter the effective  $\lambda$  and/or introduce nonmonotonic potential structure (e.g., shallow potential wells/humps) relevant for dust trajectories that extend above the first meters.

*f. Implications for dust charging and mobilization.* Dust charging enters lift and transport scalings through the capacitance-limited charge  $q(a) = 4\pi\epsilon_0 a \phi_g$  [Eq. (25)] and the near-surface sheath model  $E(z) = E_0 \exp(-z/\lambda)$ , with  $\Delta V_{sh} \simeq E_0 \lambda$  given by Eq. (45). The floating potential  $\phi_g$  is determined by current balance. With  $H^-$  present, the net

collected current includes an additional negative-ion term,

$$I_{tot}(\phi_g) = I_e(\phi_g) + I_i(\phi_g) + I_{ph}(\phi_g) + I_{H^-}(\phi_g) + I_{sc}(\phi_g) = 0, \quad (36)$$

so that both the equilibrium  $\phi_g$  and the charging time constant  $\tau_{ch} \sim C/(\partial I_{tot}/\partial \phi_g)$  (with  $C \simeq 4\pi\epsilon_0 a$ ) are modified relative to the electron + ion + photoelectron case. Since Eq. (26) scales as  $E_{req} \propto 1/\phi_g$  for fixed  $(W, R)$ , any  $H^-$ -driven shift in  $\phi_g$  maps directly into the detachment threshold, and any modification to  $E(z)$  [through Eq. (35)] maps into  $\Delta V_{sh}$  and thus into  $h_{ball}$  and  $h_*$  [Eqs. (46) and (47)]. In practice, incorporating  $H^-$  requires (1) enforcing Eq. (36) for  $\phi_g$  and  $\phi_{surface}$ , (2) updating the field priors  $(E_0, \lambda)$  in Eq. (45), and (3) propagating the updated  $q(a)$  into Eqs. (26), (46), and (47).

### E. Surface-bounded neutral exosphere and coupling to dust

The Moon hosts a surface-bounded, collisionless neutral exosphere sourced by photon-stimulated desorption, solar-wind sputtering, micrometeoroid impact vaporization (MIV), and, for  $^{40}\text{Ar}$ , radiogenic outgassing [62,63]. Dominant species include He, Ne, Ar,  $\text{H}_2/\text{H}$ , and alkalis (Na, K) [64–67]. In a ballistic exosphere, the density scale height

$$H = \frac{k_B T_s}{m g_{Moon}} \quad (37)$$

is set by a characteristic source (kinetic) temperature  $T_s$  and molecular mass  $m$ . Representative values:  $H_{\text{He}} \sim 100$ – $400$  km for  $T_s = 100$ – $400$  K;  $H_{\text{Ar}} \sim 10$ – $30$  km for  $T_s = 100$ – $300$  K; Na/K have  $H \sim 100$ – $200$  km owing to hot PSD/MIV source distributions [62,63,65–67]. If a vertical column  $N$  is known, a near-surface density estimate follows as  $n_0 \simeq N/H$ .

*a. Variability and day-night/far-near differences.* LADEE/Neutral Mass Spectrometer (NMS) observed strong temporal and local-time variability, with He tracking solar-wind flux and nightside enhancements, while  $^{40}\text{Ar}$  varies with longitude/local time consistent with a radiogenic source and cold trapping/release [65,67]. Lunar Reconnaissance Orbiter (LRO)/Lyman Alpha Mapping Project (LAMP) detections of He corroborate nightside columns of order  $10^{11}$  to  $10^{12}$   $\text{cm}^{-2}$  [64]. Because the neutral mean free path is  $\gg$  meters under all conditions, neutral drag is negligible for 0–3 m dust dynamics (Sec. VIIC); the exosphere influences dust primarily by production (PSD/sputtering/MIV that generate fines or alter coatings) and by providing independent tracers of surface processes that also control maturity and charging.

*b. Coupling to dust/charging.* PSD/sputtering efficiencies scale with UV/EUV and ion fluxes that also set photoemission and sheath structure, so neutral columns (He, Na, K) can serve as environmental proxies for the likelihood of electrostatic mobilization in strongly forced geometries (terminators, shadow edges, PSR rims). In PSRs, low  $T$  and long charge-relaxation times (Sec. VI) favor persistent fields; any local neutral release (e.g., MIV) is quickly ballistic and does not screen  $E(z)$  in the first meters.

*c. Design use.* Use Eq. (37) with species mass and a site-specific  $T_s$  to project  $N \rightarrow n_0$  (or vice versa); interpret neutral variability in concert with  $E(z)$  (Sec. VIB) and the 0–3 m dust envelope (Sec. VIIC) to bound generation and transport.

### F. Context for dust-neutral exosphere design

As we discussed, the Moon hosts a surface-bounded, collisionless neutral exosphere with species-dependent source and loss: noble gases (He, Ar, Ne) from solar-wind implantation and radiogenic outgassing; alkalis (Na, K) from micrometeoroid impact vaporization and photon-stimulated desorption [62,65]. Typical nightside number densities are  $n_{\text{He}} \sim 10^3$  to  $10^5 \text{ cm}^{-3}$  and  $n_{\text{Ar}}(^{40}\text{Ar}) \sim 10^3$  to  $10^4 \text{ cm}^{-3}$ , with scale heights  $H = kT/(mg_{\text{Moon}})$  ranging from tens of kilometers (alkalis) to  $\gtrsim 100 \text{ km}$  (He) for  $T \sim 100\text{--}400 \text{ K}$  [62,65]. Gas-grain drag is negligible for micron scales in vacuum, so the exosphere does not alter the kinematics of the 0–3 m dust hops derived here [Eqs. (46) and (47)]. However, the exosphere modulates surface charging and photoemission context (through day/night  $T$  and UV illumination), and it supplies Na/K that can form transient films on cold optical/thermal surfaces. For rover design, exosphere relevance enters via (1) day/night fouling rates (thin film deposition) and (2) context for photoemission yields used in sheath models.

## VII. OPTICAL AND MATURITY DIAGNOSTICS

Lunar reflectance is non-Lambertian with a strong opposition surge. For particulate surfaces, the Hapke bidirectional reflectance formalism [68] provides a compact, dust-relevant parametrization. For incidence  $i$ , emission  $e$ , and phase angle  $g$  (with  $\mu_0 = \cos i$ ,  $\mu = \cos e$ ), the radiance factor is

$$r(i, e, g) = \frac{w}{4} \frac{\mu_0}{\mu_0 + \mu} [(1 + B(g))P(g) + H(\mu_0)H(\mu) - 1] S(\bar{\theta}), \quad (38)$$

where  $w$  is the single-scattering albedo,  $P(g)$  a particle phase function (often a one- or two-term Henyey-Greenstein),  $B(g) = B_{\text{SH}}(g) + B_{\text{CB}}(g)$  the opposition term (shadow hiding + coherent backscatter),  $H$  are the Chandrasekhar  $H$  functions for multiple scattering, and  $S(\bar{\theta})$  accounts for macroscopic roughness with mean slope  $\bar{\theta}$ . Equation (38) may be used to link grain-scale properties (PSD, shape,  $\text{npFe}^0$ , SSA) to observables.

### A. Dust-controlled photometric behavior

Angular, fine grains (high SSA) lower  $w$  at visible wavelengths by increasing internal path length and absorption and enhance backscatter through larger  $B_0$  [the  $g \rightarrow 0$  limit of  $B(g)$ ]. In the small- $w$  limit, the reflectance sensitivity to  $w$  is approximately linear:

$$\left. \frac{\partial r}{\partial w} \right|_{w \ll 1} \approx \frac{1}{4} \frac{\mu_0}{\mu_0 + \mu} [(1 + B)P + H(\mu_0)H(\mu) - 1] S(\bar{\theta}). \quad (39)$$

Thus, modest changes in  $w$  from space weathering or dust coatings induce nearly proportional changes in  $r$  once geometry is fixed. Mature maria have lower  $w$  and stronger backscatter; highlands are brighter. Diviner CF plus near infrared (NIR) band depths provide compositional and maturity constraints [11,19]. Typical normal albedo ranges ( $0.55 \mu\text{m}$ ) are  $\sim 6\%\text{--}10\%$  for maria and  $\sim 12\%\text{--}18\%$  for highlands.

*Opposition terms as microtexture proxies.* Shadow-hiding and coherent-backscatter parameters ( $B_0$ ,  $h$ ) covary with microtexture: higher fines/SSA  $\Rightarrow$  larger  $B_0$  and smaller  $h$ . Tracking ( $B_0$ ,  $h$ ) in repeat imaging (constant  $i$ ,  $e$ ) offers a noncontact indicator of near-surface textural change (e.g., plume dusting or sorting). Note that here,  $h$  denotes the angular half-width (in radians) of the opposition surge in Hapke's opposition functions in Eq. (38):  $B_{\text{SH}}(g) = B_{0,\text{SH}}[1 + (h_{\text{SH}}^{-1} \tan(g/2))]^{-1}$  and  $B_{\text{CB}}(g) = B_{0,\text{CB}}[1 + (h_{\text{CB}}^{-1} \tan(g/2))]^{-2}$ . Smaller  $h$  implies a narrower, steeper surge near  $g \rightarrow 0^\circ$ , diagnostic of finer, higher-SSA microtexture. Thus,  $h$  is the shorthand for these width parameters ( $h_{\text{SH}}$  and/or  $h_{\text{CB}}$ ). Finer, more porous/rough microtexture (higher SSA) typically yields larger amplitude  $B_0$  and smaller  $h$  (a steeper, narrower opposition spike). On the Moon, indicative values are  $h_{\text{SH}} \sim 0.02\text{--}0.08 \text{ rad}$  ( $\approx 1^\circ\text{--}5^\circ$ ) and  $h_{\text{CB}} \sim 0.01\text{--}0.05 \text{ rad}$ , varying with maturity and texture.

### B. Space weathering, $\text{npFe}^0$ , and maturity metrics

Solar-wind implantation and microimpacts generate  $\text{npFe}^0$  in 10–200 nm rims and in agglutinitic glass, decreasing  $w$ , reddening continua, and suppressing mafic bands [10,12]. A first-order attenuation of a BD with solar-wind fluence  $\phi_{\text{sw}}$  was introduced in Sec. II and captures the maturation trend used for photometric/maturity correction [69]. The ferromagnetic resonance index  $I_s/\text{FeO}$  and Diviner CF position covary with  $\text{npFe}^0$  abundance and composition [9,11,13], enabling cross calibration of maturity between visible and near infrared (VNIR) and thermal infrared (TIR).

### C. Christiansen Feature in the thermal IR

The Diviner Christiansen Feature (CF; peak in emissivity where refractive index  $\approx 1$ ) shifts with polymerization (felsic versus mafic), Fe/Ti content, and weathering state. To first order, the apparent CF position  $\nu_{\text{CF}}^{\text{app}}$  inferred from radiance spectra depends on both composition and the thermal state via the Planck weighting:

$$L_\nu(\nu, T) = \epsilon_\nu(\nu) B_\nu(T), \quad \nu_{\text{CF}}^{\text{app}} = \arg \max_\nu \epsilon_\nu(\nu) B_\nu(T). \quad (40)$$

Consequently, diurnal/seasonal  $T$  variations [set by  $k(T, \rho)$ ; Sec. V] introduce small, geometry-dependent CF biases unless temperature is comodeled. Combining CF with VNIR band depths separates basaltic (maria) from anorthositic (highlands) terrains and can be mapped against LPR inferred  $\varepsilon'$  to constrain composition and density jointly [11,19].

### D. From dust to photometric correction (operational recipe)

For site-to-site or time-series comparisons (e.g., monitoring dust deposition near landers), normalize bidirectional reflectance factor (BRF) to a standard geometry ( $i_0$ ,  $e_0$ ,  $g_0$ ) by the Hapke ratio:

$$R_{\text{norm}}(\lambda) = R_{\text{meas}}(\lambda) \frac{r(i_0, e_0, g_0; \Theta)}{r(i, e, g; \Theta)}, \quad \Theta \equiv \{w(\lambda), P, B, \bar{\theta}\}. \quad (41)$$

Using Eq. (41) with a fixed  $\Theta$  isolates geometry; allowing only ( $B_0$ ,  $h$ ) (and optionally  $w$ ) to vary [with  $B(g) = B_{\text{SH}}(g) +$

$B_{CB}(g)$  as in Eq. (38)] is an effective way to detect dust textural changes without conflating composition. Because  $\text{npFe}^0$  modifies both  $w(\lambda)$  and CF, joint VNIR + TIR normalization [Eq. (40) + Eq. (41)] mitigates maturity/composition crosstalk [11].

### E. Optical consequences for dust transport and system performance

*Diagnostics of near-surface dust:* Phase-angle dependence near  $g \rightarrow 0$  is acutely sensitive to surficial fines; a measurable increase in  $(B_0, r_0)$  at fixed composition flags fresh coatings or fine sorting by electrostatic hopping (Sec. VIII). LADEE's lack of a dense, persistent 0.1  $\mu\text{m}$  high-altitude layer is consistent with *localized*, meter-scale hopping that does not build an optically thick haze aloft.

*Engineering impacts:* Dust coatings lower  $w$ , increase backscatter ( $B_0 \uparrow$ ), and reduce thermal IR contrast (via  $\epsilon_v \rightarrow 1$  near CF), degrading albedo-based power/thermal margins and instrument radiometry. These effects are detectable with coregistered VNIR/TIR observations using Eqs. (38)–(40). Terrain differences (maria versus highlands; near side versus far side) expressed in Fe/Ti and maturity (Tables VII and VIII) translate to systematic albedo, spectral slope, and CF contrasts, which should be treated as priors in contamination/discoloration assessments.

To isolate dust-texture changes from composition and geometry, we recommend (1) fixing  $\bar{\theta}$  and using a reduced phase function to track  $(B_0, h)$  at small phase angles, and (2) normalizing TIR spectra about the CF [Eq. (40)], while using coregistered VNIR band depths. This joint VNIR + TIR normalization mitigates maturity/composition crosstalk and is sensitive to surficial fine coatings expected from near-surface hopping (Sec. VIII).

*a. Dust coatings on engineered surfaces (power, thermal, rf).* For a surface with solar absorptance  $\alpha_s$  and thermal emissivity  $\epsilon_s$ , partially covered by a dust film of area fraction  $f_d$  (with  $\alpha_d, \epsilon_d$  appropriate to local composition/maturity; Sec. VII), a first-order areal mixing gives

$$\alpha_{\text{eff}} \approx (1 - f_d)\alpha_s + f_d\alpha_d, \quad \epsilon_{\text{eff}} \approx (1 - f_d)\epsilon_s + f_d\epsilon_d. \quad (42)$$

Radiator capacity scales as  $Q \propto \epsilon_{\text{eff}} \sigma A (T^4 - T_{\text{sink}}^4)$ ; thus even modest  $f_d$  reduces margin if  $\epsilon_d < \epsilon_s$ . For solar arrays at low Sun angles, the effective transmittance/reflectance change can be linearized as  $\Delta P/P \simeq -\kappa f_d$  with  $\kappa \sim \mathcal{O}(1)$ , tuned to array coatings.

A thin dust layer of thickness  $t$  on an rf window (wavelength  $\lambda$ ) and complex permittivity  $\epsilon'(1 - j \tan \delta)$  yields one-way power attenuation:

$$L_{\text{dB}} \approx 8.686 \alpha t, \quad \alpha \simeq k_0 \text{Im}\{\sqrt{\epsilon'(1 - j \tan \delta)}\}, \quad k_0 = \frac{2\pi}{\lambda}, \quad (43)$$

with  $\epsilon'$  and  $\tan \delta$  from Sec. VI (and Table VII) at the relevant temperature. Engineering impacts cited above (albedo reduction, backscatter increase, CF shift) explain observed degradations in radiometry and power (cf. Sec. VIIC for near-surface dust densities).

*b. Thin dust films on optics.* For a gray dust film of areal coverage  $f_d$ , the effective normal reflectance  $R_{\text{eff}}$  of a coated surface with clean reflectance  $R_0$  and dust single-scattering albedo  $w$  obeys, to first order in  $f_d$ ,

$$R_{\text{eff}} \simeq R_0(1 - f_d) + \frac{w}{\pi} f_d, \quad (44)$$

so that a few percent coverage ( $f_d \sim 0.05$ ) on a dark substrate (e.g., solar cells) reduces  $R_{\text{eff}}$  roughly linearly with  $f_d$  while increasing backscatter (larger  $B_0$ , smaller  $h$ ).

*c. Thermal IR contrast under dust coatings.* A porous dust overburden of thickness  $t$  and conductivity  $k$  on a radiator with emissivity  $\epsilon_r$  adds an areal thermal resistance  $R_{\text{th}} = t/k$ , shifting the effective radiative temperature by  $\Delta T \simeq q R_{\text{th}}$  at heat flux  $q$ ; for  $t = 100 \mu\text{m}$  and  $k = 10^{-3} \text{ W m}^{-1} \text{ K}^{-1}$  (Table VIII),  $R_{\text{th}} \approx 100 \text{ K m}^2 \text{ W}^{-1}$ , which is non-negligible for  $q \gtrsim 10 \text{ W m}^{-2}$ .

## VIII. MOBILIZATION AND TRANSPORT

Dust transport operates through three distinct channels with weak coupling except during transients: (1) meteoroid ejecta maintain a persistent, dawn-enhanced exospheric population and mix the upper centimeters on Myr timescales; (2) electrostatic hopping is intermittent and localized near strong  $E$ -field gradients at illumination and plasma transitions; and (3) rocket plumes drive brief, intense events with the highest grain velocities  $v_{\text{ejecta}} \sim 10^2$  to  $10^3 \text{ m s}^{-1}$ .

In this Section, we will quantify each channel; the integrated risk picture maps (PSD,  $\rho, n, \epsilon', k$ ) into flux, spectrum, and angular distributions at a site.

### A. Meteoroid-generated dust cloud

LADEE/LDEX resolved a permanent, asymmetric dust cloud with dawn enhancement; characteristic detected radii  $a \gtrsim 0.3\text{--}0.7 \mu\text{m}$  and speeds of order  $10^2 \text{ m s}^{-1}$ ; instantaneous mass  $\sim 10^2 \text{ kg}$  [6]. Impact gardening mixes the upper centimeters on Myr timescales. Stream encounters produce large, time-dependent enhancements; during the 2013 Geminids, LDEX measured over  $10\times$  the number of dense ejecta plumes relative to nonshower periods, constraining source variability and ballistic fluxes [37].

### B. Electrostatic lofting near the surface

Terminator and shadow transitions impose sharp horizontal and vertical electric-field gradients. Under these conditions, submicron grains can execute short hops from centimeters to meters. Apollo-era *in situ* dust sensors provide additional but still debated constraints: The Apollo 17 Lunar Ejecta and Meteorites (LEAM) experiment reported an unexpected enhancement of low-altitude dust impacts near the terminator, though later analyses suggested possible thermal/mechanical artifacts; nevertheless the LEAM timing and directionality remain a useful bound on any terminator-linked near-surface dust component [70,71]. Surveyor's horizon glow [72] is consistent with forward scattering by near-surface grains, while LADEE placed strict upper limits on any dense, sustained, high-altitude 0.1  $\mu\text{m}$  layers [6,14,15]. The net picture is

TABLE IV. Recommended near-surface field envelopes by terrain/geometry.  $E_0$  is a characteristic near-surface amplitude;  $\lambda$  is an  $e$ -folding scale [use with Eqs. (46) and (47)].

| Setting                   | $E_0$ (V m <sup>-1</sup> )         | $\lambda$ (m) | Notes                                                          |
|---------------------------|------------------------------------|---------------|----------------------------------------------------------------|
| Terminator/shadow edge    | 10 <sup>2</sup> to 10 <sup>3</sup> | 0.03–0.30     | Strong gradients over decimeters; patchy in space/time.        |
| PSR rims/cold traps       | 10 <sup>2</sup> to 10 <sup>3</sup> | 0.03–0.30     | Similar $E_0$ ; longer $\tau_{\text{relax}}$ sustains patches. |
| Magnetic swirl boundaries | 10 <sup>2</sup> to 10 <sup>3</sup> | 0.03–0.30     | Modified photoemission/charging; site-specific $E(z)$ .        |
| Sunlit interiors          | $\leq 10^2$                        | $\leq 0.05$   | Weak vertical gradients; intermittent hopping only.            |

intermittent, localized mobilization governed by sheath dynamics rather than a persistent, optically thick layer.

### C. Near-surface dust (0–3 m above the surface)

We quantify trajectories of *preliberated* grains in the first meters above the surface, where  $E(z)$  varies on decimeter

scales and the adhesion threshold (Fig. 2) can prevent injection into the sheath [cf. Eq. (26)]. We parametrize the near-surface sheath by its potential drop:

$$\Delta V_{\text{sh}} \equiv \int_0^\infty E(z) dz, \quad \text{with} \quad E(z) = E_0 \exp\left(-\frac{z}{\lambda}\right) \Rightarrow \Delta V_{\text{sh}} \simeq E_0 \lambda, \quad (45)$$

with  $E_0$  a near-surface amplitude and  $\lambda$  the  $e$ -folding scale ( $\sim 3$ – $30$  cm near illuminated terminators and shadow edges; Table IV). The terrain-specific envelope implied by Eqs. (46) and (47) is summarized in Table V using the field priors of Table IV (Sec. VIB) and the detachment threshold in Fig. 2.

In vacuum, the field does work  $q \Delta V_{\text{sh}}$  on a grain of charge  $q = 4\pi\epsilon_0 a \phi_g$ . Neglecting drag and assuming  $q$  remains approximately constant during a short hop (charge-relaxation times  $\tau_{\text{relax}}$  in cold, porous soils are typically  $\gg$  hop times; see Sec. VIA), the ballistic apex height is

$$h_{\text{ball}}(a) \simeq \frac{q \Delta V_{\text{sh}}}{m g_{\text{Moon}}} = \frac{3 \epsilon_0 \phi_g}{a^2 \rho_p g_{\text{Moon}}} \Delta V_{\text{sh}}, \quad (46)$$

where  $m = \frac{4}{3}\pi a^3 \rho_p$ . For an exponential sheath,  $E(z) = E_0 e^{-z/\lambda}$ , the static “hover” height  $h_*$  (where the upward electrostatic force equals weight) solves  $q E(h_*) = m g_{\text{Moon}}$ :

$$h_*(a) \simeq \lambda \ln\left(\frac{q E_0}{m g_{\text{Moon}}}\right) = \lambda \ln\left(\frac{3 \epsilon_0 \phi_g E_0}{a^2 \rho_p g_{\text{Moon}}}\right), \quad (47)$$

valid when  $q E_0 > m g_{\text{Moon}}$ . Equation (46) applies once adhesion is already overcome [cf. Eq. (26)]; the field needed for detachment is given by Eq. (26), which is dominated by the  $F_{\text{adh}}$  term across the micron range (Fig. 2). The terrain-specific envelope implied by Eqs. (46) and (47) is summarized in Table V. In fact, these heights apply once detachment is achieved [adhesion-aware requirement in Eq. (26) and Fig. 2]; detachment may be provided by mechanical preliberation

TABLE V. Expected apex/hover heights for *preliberated* grains in the first 0–3 m from Eqs. (46) and (47) using  $E_0, \lambda$  from Table IV and baseline  $\phi_g = 5$  V,  $\rho_p = 3.1 \times 10^3$  kg/m<sup>3</sup>, adhesion satisfied per Eq. (26). Field envelopes  $E_0$  and  $e$ -folds  $\lambda$  follow Sec. VIB; hover heights  $h_*$  use Eq. (47) with  $\phi_g = 5$  V,  $\rho_p = 3.1 \times 10^3$  kg m<sup>-3</sup>. Where ranges are given,  $E_0 = 300$  V m<sup>-1</sup>,  $\lambda = 0.03$ – $0.30$  m are assumed for the  $h_*$  examples. These ranges operationalize adhesion-aware transport in the near-surface meter-scale regime.

| Terrain/setting                         | Field envelope (Sec. VIB)                                                       | Example $h_*$ (preliberated) <sup>a</sup>                                       | Notes/constraints                                                                                 |
|-----------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Terminator and sharp shadow edges       | $E_0 \sim 10^2$ to $10^3$ V m <sup>-1</sup> ;<br>$\lambda \sim 0.03$ – $0.30$ m | $a = 1.0$ $\mu\text{m}$ : 0.06–0.62 m;<br>$a = 0.5$ $\mu\text{m}$ : 0.10–1.04 m | Patchy, time-variable $E(z)$ ; short hops/hovers within 0–3 m, Eqs. (46) and (47), Fig. 2.        |
| PSR rims/cold traps                     | Similar $E_0$ ; longer $\tau_{\text{relax}}$                                    | Similar $h_*$ ; longer-lived charge patches                                     | Low $T$ and high porosity increase $\tau_{\text{relax}}$ (Sec. VIA); persistent gradients likely. |
| Magnetic swirl boundaries               | Lateral $E$ gradients; modified photoemission                                   | Comparable $h_*$ when $E_0$ is in the same band                                 | Reduced weathering and altered charging; grain sorting possible; use site $E(z)$ where available. |
| Sunlit interiors (away from boundaries) | $E_0$ smaller, $\lambda$ short                                                  | $h_* \lesssim$ few cm to dm                                                     | Weak vertical gradients; intermittent hopping only.                                               |
| Meteoroid ejecta (all terrains)         | –                                                                               | Broad ballistic arcs; many cm-m cross the 0–3 m layer                           | Maintains exosphere; stream spikes (Sec. VIII A); independent of $E(z)$ .                         |

<sup>a</sup>Computed from Eq. (47) with  $\phi_g = 5$  V,  $\rho_p = 3.1 \times 10^3$  kg m<sup>-3</sup>;  $E_0, \lambda$  from Sec. VIB.

and/or by bed-mediated microcavity charge pumping in the patched-charge model [56–58].

*a. Including finite launch velocity from bed-mediated ejection.* Equation (46) assumes negligible initial vertical kinetic energy at detachment. If a grain is ejected from the bed with an initial vertical speed  $v_0$  (as observed in microcavity/PCM laboratory experiments [56,73]), the apex height generalizes to

$$h_{\text{ball}}(a) \simeq \frac{q \Delta V_{\text{sh}} + \frac{1}{2} m v_0^2}{m g_{\text{Moon}}} = \frac{q \Delta V_{\text{sh}}}{m g_{\text{Moon}}} + \frac{v_0^2}{2 g_{\text{Moon}}}. \quad (48)$$

For example,  $v_0 \sim 0.6 \text{ m s}^{-1}$  corresponds to  $h \sim v_0^2/(2g_{\text{Moon}}) \approx 0.11 \text{ m}$ , consistent with centimeter-scale lofting observed in vacuum-chamber conditions [56].

*b. Representative (terminator/shadow-edge) envelope:* Using  $E_0 = 10^2$  to  $10^3 \text{ V m}^{-1}$  and  $\lambda = 0.03$ – $0.30 \text{ m}$  (Sec. VIB),  $\phi_g = 5 \text{ V}$ ,  $\rho_p = 3.1 \times 10^3 \text{ kg m}^{-3}$ :

(1)  $a = 1.0 \text{ }\mu\text{m}$ :  $h_* \approx 0.06$ – $0.62 \text{ m}$  for  $\lambda = 0.03$ – $0.30 \text{ m}$  at  $E_0 = 300 \text{ V m}^{-1}$ ; extending to  $\sim 2 \text{ m}$  for  $\lambda = 1 \text{ m}$  (upper bound used in design trades).

(2)  $a = 0.5 \text{ }\mu\text{m}$ :  $h_* \approx 0.10$ – $1.04 \text{ m}$  (same envelope).

(3)  $a = 0.1 \text{ }\mu\text{m}$ :  $h_*$  readily exceeds meters if  $q$  is maintained. However, LADEE/LDEX placed strict upper limits on any dense, sustained, high-altitude  $0.1 \text{ }\mu\text{m}$  layers, so persistent populations above  $\mathcal{O}(10) \text{ m}$  are unlikely except during transients (meteoroid streams) or strong local anomalies (Secs. VIIC and VIIC).

For  $a = 1 \text{ }\mu\text{m}$ ,  $E_0 = 300 \text{ V m}^{-1}$ , and  $\lambda = 0.10 \text{ m} \Rightarrow \Delta V_{\text{sh}} = 30 \text{ V}$ . Then,  $h_{\text{ball}} \approx 0.79 \text{ m}$  and a symmetric hop has  $t_{\text{flight}} \approx 2\sqrt{2h_{\text{ball}}/g_{\text{Moon}}} \sim 2 \text{ s}$ , well below typical  $\tau_{\text{relax}}$  values inferred for cold, porous soils (Sec. VIA), so treating  $q$  as quasiconstant during a hop is appropriate. Field envelopes and adhesion thresholds used here are those compiled in Sec. VIB; see Eqs. (46) and (47) and Fig. 2. Table V summarizes expected heights by terrain, using site-resolved  $E(z)$  where available.

#### D. Rocket-plume entrainment

Gas dynamic pressure and wall shear accelerate fines; empirical scalings suggest  $\dot{m}_e \propto q^n$  with  $n \approx 2$ – $3$  [25]. Apollo 12 dusted Surveyor III at  $\sim 155 \text{ m}$ , implying mm-sub-mm ejecta at several hundred  $\text{m s}^{-1}$  [24]. Artemis landers require plume-surface monitors to bound flux, PSD, and angular distributions [26].

Here, we use  $q$  as the surface energy flux density from the impinging jet at the soil, and  $\tau_w$  as the wall shear stress. Empirical fits in PSI testing may be written as  $\dot{m}_e \propto q^n$  with  $n \approx 2$ – $3$ , or alternatively  $\dot{m}_e \propto \tau_w^m$  with  $m \approx 1$ – $2$ , with calibration constants determined per engine and soil state.

Recent rebenchmarking indicates that total eroded mass during Apollo landings was  $\sim 4$ – $10\times$  larger than earlier estimates, which expands the downrange dust-loading envelope and sandblasting hazard [74]. Risk parametrization should therefore be expressed in terms of  $(q, \partial q/\partial r, \theta_{\text{plume}})$  and local soil state (PSD,  $\rho, n$ ), with validation against SCALPSS-class stereo and ejecta-count data on upcoming Commercial Lunar Payload Services (CLPS) and Artemis flights.

Contemporary PSI instrumentation is maturing: SCALPSS stereo photogrammetry flew on IM-1 (2024) and is planned for additional CLPS and Artemis landings; despite anomalies

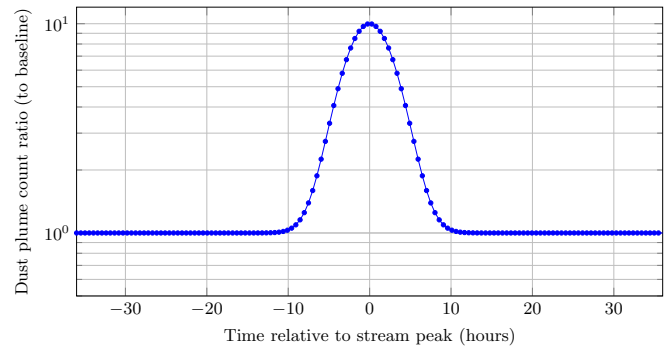


FIG. 3. Schematic of meteoroid-stream forcing (e.g., Geminids [37]) and the resulting transient enhancements in near-surface dust flux. The persistent background is maintained by sporadics; stream spikes modulate injection independent of  $E(z)$  (cf. Sec. VIIC). Stream forcing sets event-driven upper bounds on exospheric dust.

on IM-1, the campaign yielded engineering lessons and partial data products [34]. Payloads (e.g., EJECTA, DERT, PIE) will constrain ejecta flux, velocity, and PSD *in situ* to validate PSI models.

Taken together, the updated erosion-rate calibration, event geometry, and SCALPSS-class measurements imply that PSI risk envelopes should be parameterized in terms of  $(q, \partial q/\partial r, \theta_{\text{plume}})$ , local soil state (PSD,  $\rho, n$ ), and landing geometry, with verification against stereo and ejecta-counter data on future CLPS and Artemis flights.

*Operational impacts and mitigations:* Angular fines and elevated specific surface area enhance abrasion, fouling of seals and radiators, and optical scattering. Adhesion forces  $F_{\text{adh}} \approx \frac{3}{2}\pi WR$  (JKR, with  $W \sim 0.1 \text{ J m}^{-2}$ ,  $R \sim 5 \text{ }\mu\text{m}$ ) typically exceed lunar gravity for micron-scale grains:  $F_{\text{adh}} \approx 2.36 \text{ }\mu\text{N}$  versus  $mg_{\text{Moon}} \approx 2.10 \times 10^{-14} \text{ N}$  for  $a = 1 \text{ }\mu\text{m}$ . Consequently, preliberation by vibration, micro-impacts, or gas shear is usually required before sheath acceleration is effective. To reduce risk, (1) minimize dust-entraining geometries near high energy fluxes, (2) use abrasion-tolerant coatings and sacrificial layers on high-flux surfaces, (3) design dust-tolerant seals and connectors, (4) provide localized mechanical agitation prior to electrostatic removal, and (5) colocate plume/dust monitoring with  $E$ -field probes during landings to bound  $\dot{m}_e$ , PSD, and angular distributions for future designs.

#### E. Mechanisms, observables, and measurements

The three mobilization channels leave distinct, jointly observable signatures. Table VI crosswalks mechanisms to observables and heritage constraints. Meteoroid ejecta maintain a persistent, asymmetric dust cloud with stream-driven enhancements (Fig. 3); electrostatic hopping is intermittent and localized near strong sheath gradients at illumination or plasma boundaries; rocket-plume entrainment produces brief, intense episodes with the highest  $v_{\text{ejecta}}$  and the greatest engineering consequences. Coregistered electric fields, grain charge, PSD, and flux near terminators, PSR rims, and landing sites resolve model degeneracies and tighten design ranges by directly linking source, transport, and redeposition.

TABLE VI. Crosswalk from production/modification mechanisms to primary observables/key constraints used in this review.

| Mechanism                             | Primary observables                                                                                                                                  | Key missions/instruments                                                         |
|---------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Impact comminution, agglutination     | PSD shape; agglutinate fraction; maturity indices (Is/FeO)                                                                                           | Apollo samples (imaging, sieving) [1,2,9]                                        |
| Space weathering (npFe <sup>0</sup> ) | Albedo reduction; CF shift; suppression of mafic band depths                                                                                         | LRO/Diviner CF; M <sup>3</sup> (Moon Mineralogy Mapper on Chandrayaan-1) [11,19] |
| Thermal fatigue                       | Boulder-size decay; fines production versus age                                                                                                      | Diviner rock abundance versus crater age [3]                                     |
| Pyroclastic fragmentation             | Glass-rich spectra; CF diagnostics                                                                                                                   | Diviner mapping of pyroclastic mantling deposits [21]                            |
| Near-surface charging                 | Sheath electric field; lofting thresholds; negative ions                                                                                             | Surveyor horizon glow; LADEE constraints; CE-6 NILS H <sup>-</sup> [14,15,36]    |
| Exospheric maintenance                | Dust flux versus local time and meteoroid streams                                                                                                    | LADEE/LDEX cloud and stream responses [6,37]                                     |
| Plume-surface entrainment (PSI)       | $v_{\text{ejecta}} \sim 10^2 \text{ to } 10^3 \text{ m s}^{-1}$ ; $\dot{m}_e \propto q^n$ , $n \approx 2-3$ ; erosion scales with engine energy flux | Surveyor III coating; Apollo; SCALPSS and PSI payloads [24–26,34]                |

## IX. REGIONAL REFERENCE VALUES (DESIGN RANGES)

### A. Regional narratives

Maria, highlands, swirls, pyroclastics, and polar PSRs are end members in a continuum. Maria typically combine higher FeO and variable TiO<sub>2</sub> with lower albedo and, locally, higher rock abundance; their dielectric response tends to be higher with ilmenite content and compaction. Highlands are plagioclase rich with lower FeO, brighter albedo, thicker regolith, and a dielectric response dominated by lower-density silicates. Swirls sit atop magnetic anomalies that partially shield solar wind, reducing space weathering rates and producing optically immature lanes; electrostatic grain sorting may further separate fines. Pyroclastics include glass-rich mantling units with distinct CF positions and mid-IR signatures. PSR floors push toward extreme  $T$ , slow charge relaxation, and potential frost cements; rims and near-PSR slopes mix cold-regime charging with occasional direct illumination and enhanced horizontal  $E$  fields. The row added for Vikram lander's site highlights how *in situ* thermophysics at high southern latitude modifies expectations for  $k$  and  $\rho$  at centimeter depths. Use these as priors and propagate to thermal and electrical behavior with Eqs. (1) and (13) and the Looyenga mixing in Eq. (23).

### B. Design takeaways by region

Maria: higher FeO/TiO<sub>2</sub> and compaction bias toward higher  $\varepsilon'$  and  $k$ , increasing rf losses and thermal conduction. Highlands: Lower FeO and thicker regolith reduce  $\varepsilon'$ , with lower near surface  $k$ . Swirls: Reduced space weathering maintains high albedo and may alter charge balance along anomaly boundaries. Pyroclastics: Glass-rich fines shift CF and may reduce grain strength. PSR floors: Extreme  $T$  and long charge-relaxation times increase the likelihood of persistent fields; frost cements alter mechanics. Vikram site: *In situ* ChaSTE shows  $k$  at 80 mm, which is several times the Diviner near-surface reference, emphasizing centimeter-scale structure.

*Design callout for polar traverses.* For cold, porous soils near PSR rims, long  $\tau_{\text{relax}}$  (Sec. VIA) increases the likelihood of persistent charge patches. Combined with high-SSA,

angular fines, this elevates *adhesion* and *abrasion* risks to radiators, optics, seals, and electrical connectors. Trafficability envelopes should therefore use the upper end ( $\phi$ ,  $c$ ) in Table VII with frost-cement contingencies (PSR floors row in Table VII; frost-cement contingency [Eqs. (6) and (7)] and dust-mitigation strategies should assume that electrostatic removal is ineffective unless mechanical preliberation is provided (Fig. 2 and Table III). Operationally, minimize prolonged loitering at strong illumination/plasma boundaries during high meteoroid-flux windows (Sec. VIII A), when both ejecta and charging transients are maximized.

## X. ENGINEERING REFERENCE RANGES (GLOBAL)

Table VII summarizes regional reference regolith values, while Table VIII provides representative lunar dust/regolith properties. To use these ranges in design, we recommend the following approach:

- (1) Select a regional prior from Table VII (maria, highlands, pyroclastics, swirls, PSR) and latitude.
- (2) Initialize  $\rho(z)$  with  $\rho_0$ ,  $\rho_\infty$ , and  $z_c$ ; propagate  $k(T, \rho)$  to obtain  $\Gamma$  and the diurnal  $T(z, t)$ .
- (3) Use composition and densification to set  $\varepsilon'$  and  $\tan \delta$  (Looyenga mixing).
- (4) Evaluate adhesion and Mohr-Coulomb parameters ( $\phi$ ,  $c$ ) for detachment thresholds and trafficability.
- (5) For plume events, parametrize erosion and  $v_{\text{ejecta}}$  by ( $q$ ,  $\partial q/\partial r$ ,  $\theta_{\text{plume}}$ ) and local soil state (PSD,  $\rho$ ,  $n$ ), and verify against SCALPSS-class stereo and ejecta-counter data where available.

## XI. MODEL RELATIONS USEFUL IN DESIGN

The equations below formalize three scale-bridges used throughout. First, microstructure and composition set  $\varepsilon'$  and  $\tan \delta$  via compositional mixing and densification. Second, the thermophysical profile  $k(T, \rho)$  sets the diurnal  $T$  wave and thereby the photoelectron current and charge-relaxation time, which together determine whether  $qE$  can overcome  $mg_{\text{Moon}} + F_{\text{adh}}$ . Third, heliophysical forcing (meteoroid streams, solar-wind variability) sets the stochastic envelope for ejecta production and sheath variability, where

TABLE VII. Regional reference values (upper meters unless noted). Use as design references and adjust with site-resolved data. Dielectric values are referenced to LPR frequencies (decimeter-meter wavelengths) and near-surface temperatures. *Provenance and uncertainty.* The ranges in Table VII are intended as engineering priors that bracket both geographic variability and inversion/model systematics. PSD medians are anchored by returned-sample distributions but are sensitive to comminution state and electrostatic lofting; treat as  $\sim \times 2$  uncertainty in median radius at fixed location. Bulk densities/porosities are based on Apollo core tubes and Diviner thermophysical inversions; use  $\pm 0.1$ – $0.2 \text{ g cm}^{-3}$  as a typical site-level uncertainty. Dielectric parameters are referenced to decimeter-meter wavelengths (LPR scale) and dry soils; systematic errors from radar inversion and temperature dependence can reach  $\mathcal{O}(10\%)$  in  $\epsilon'$  and factors of  $\sim 2$  in  $\tan \delta$  for low-loss materials. Cooling from  $293 \rightarrow 213 \text{ K}$  reduces  $\epsilon'$  by  $\sim 6\%$ – $18\%$  for common end members at fixed porosity [54]; below  $\sim 200 \text{ K}$  data remain sparse and should be treated as an additional systematic in PSRs.

| Region                                                              | PSD<br>median ( $\mu\text{m}$ ) | Bulk density $\rho$ at<br>0 m/1 m ( $\text{g cm}^{-3}$ ) | $\epsilon'/\tan \delta$<br>(upper meters) | Notes                                                                                                          |
|---------------------------------------------------------------------|---------------------------------|----------------------------------------------------------|-------------------------------------------|----------------------------------------------------------------------------------------------------------------|
| Maria                                                               | 50–120                          | 1.4/1.85                                                 | 3.0 to 3.5/ $10^{-3}$ to $10^{-2}$        | Elevated FeO, $\text{TiO}_2$ ; low albedo; higher rock fraction [3,18].                                        |
| Highlands                                                           | 60–140                          | 1.3/1.80                                                 | 2.6 to 3.1/ $10^{-3}$ to $10^{-2}$        | Plagioclase rich; brighter; thicker regolith [18].                                                             |
| Pyroclastics                                                        | 40–100                          | 1.4/1.85                                                 | 3.1 to 3.6/ $10^{-3}$ to $10^{-2}$        | Glass-rich; distinct CF; Fe/Ti often high [21].                                                                |
| Swirls                                                              | 50–120                          | 1.4/1.85                                                 | 2.8 to 3.3/ $10^{-3}$ to $10^{-2}$        | Reduced weathering; optically immature lanes [75,76].                                                          |
| PSR floors                                                          | 60–150                          | 1.35/1.80                                                | 2.5 to 3.2/ $10^{-3}$ to $10^{-2}$        | 25–40 K; negative charging; possible frost cements [4,5].                                                      |
| Vikram site ( $69.373^\circ \text{ S}$ , $32.319^\circ \text{ E}$ ) | 40–120                          | 1.94/–                                                   | Not measured/not measured                 | ChaSTE at 80 mm:<br>$k \approx 1.2 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$ ;<br>local compaction [33]. |

TABLE VIII. Representative lunar dust/regolith properties; values depend on grain size, maturity, depth, composition, and region. *Interpretation of ranges.* Unless noted otherwise, values in Table VIII are order-of-magnitude envelopes combining intersite variability and measurement/model systematics. When propagating into the charge-relaxation relation  $\tau_{\text{relax}} \simeq \epsilon_0 \epsilon' / \sigma$  (Sec. VI A, Eqs. (46) and (47), and the rf-loss relation in Eq. (43), the dominant uncertainties are typically (1) depth- and temperature-dependent conductivity  $\sigma$  (hence  $\tau_{\text{relax}}$ ), and (2) frequency/temperature dependence of  $\epsilon'$  and  $\tan \delta$ . For cold soils,  $\tau_{\text{relax}}$  may vary by many orders of magnitude with small changes in pore-network connectivity; design trades should therefore treat  $\sigma$  (or  $\tau_{\text{relax}}$ ) as a log-uncertain parameter and bracket at least  $\pm 2$  decades around the nominal values.

| Property                               | Representative values                                                                                                                             | Notes/primary constraints                                                      |
|----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Particle-size distribution (PSD)       | Median $\sim 40$ – $130 \mu\text{m}$ ; fines $< 20 \mu\text{m}$ abundant                                                                          | Broad, well-graded PSD; agglutinates common, Apollo sieving and imaging [1,2]. |
| Specific surface area (SSA)            | $\sim 0.02$ – $0.78 \text{ m}^2 \text{ g}^{-1}$ ; typical $\sim 0.5 \text{ m}^2 \text{ g}^{-1}$                                                   | Irregularity $\sim 8\times$ versus spheres; BET; angular grains [1,43,77].     |
| Bulk density $\rho_{\text{bulk}}$      | From $1.3$ – $1.6 \text{ g cm}^{-3}$ (surface) to $\gtrsim 1.7$ – $1.9 \text{ g cm}^{-3}$ (1 m)                                                   | Exponential compaction with depth [1].                                         |
| Friction angle $\phi$ , cohesion $c$   | $\phi \sim 30^\circ$ – $50^\circ$ (to $\sim 55^\circ$ by 1 m); $c \sim 0.1$ – $1 \text{ kPa}$ (surface) to $> 3 \text{ kPa}$ (0.5–1 m)            | Apollo/Lunokhod/analogs geotechnics [1,45].                                    |
| Thermal conductivity $k$               | $\sim 7.4 \times 10^{-4}$ (surface) to $\sim 3.4 \times 10^{-3} \text{ W m}^{-1} \text{ K}^{-1}$ (1 m)                                            | Diviner inversions [4].                                                        |
| $k$ (80 mm, $69.373^\circ$ )           | $(1.15$ – $1.24) \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$                                                                                  | ChaSTE <i>in situ</i> [33].                                                    |
| PSR $T_{\text{surf}}$                  | $\sim 25$ – $40 \text{ K}$                                                                                                                        | Diviner [5].                                                                   |
| Dielectric $\epsilon'$ , $\tan \delta$ | $\epsilon' \sim 2.5$ – $3.5$ ; $\tan \delta \sim 10^{-3}$ to $10^{-2}$ (upper meters)                                                             | CE-4 LPR; ilmenite/density dependence [7,8].                                   |
| Maturity indices                       | $I_{\text{s/FeO}}$ ferromagnetic resonance (FMR), optical maturity (OM)/CF trends                                                                 | npFe <sup>0</sup> abundance vs exposure [9–11].                                |
| Near-IR hydration                      | Variable $2.8$ – $3.0 \mu\text{m}$ band; diurnal/latitudinal dependence                                                                           | $\text{M}^3$ , follow up [78,79].                                              |
| Exospheric dust                        | Persistent, meteoroid-sourced; dawn-enhanced; $a \gtrsim 0.3$ – $0.7 \mu\text{m}$ ; $v \sim 10^2 \text{ m s}^{-1}$                                | LADEE/LDEX [6].                                                                |
| Plume-surface entrainment (PSI)        | $v_{\text{ejecta}} \sim 10^2$ to $10^3 \text{ m s}^{-1}$ ; $\dot{m}_e \propto q^n$ , $n \approx 2$ – $3$ ; erosion scales with engine energy flux | Surveyor III, Apollo, modern PSI [24–26].                                      |

TABLE IX. Design mapping from dust/regolith properties to rover subsystems. Variables and equations refer to sections/labels in this paper; use regional priors from Table VII and global ranges in Table VIII.

| Subsystem                         | Dust/regolith property                                                   | Design equation/use (pointer)                                                                               |
|-----------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| Mobility (wheels)                 | $\phi, c, \rho(z), \text{PSD}, k(T, \rho)$                               | Traction/sinkage: Eqs. (9)–(11); density versus depth [Eq. (1)]; thermal state via $k(T, \rho)$ [Eq. (13)]. |
| Power/thermal (radiators, arrays) | $\alpha_d, \varepsilon_d, f_d$ ; near-surface dust density (0–3 m)       | Coating mix [Eq. (42)]; near-surface heights [Eqs. (46) and (47)] and Table V for dust exposure.            |
| Mechanisms and seals              | SSA, angularity, adhesion $F_{\text{adh}}$ , PSD                         | Adhesion threshold [Eq. (26)] and Fig. 2; Mohr-Coulomb parameters (Sec. IV) for intrusion loads.            |
| Optics/sensors                    | $w, B_0, h, \bar{\theta}$ , CF, maturity                                 | Photometric trends (Sec. VII); engineering impacts paragraph; use regional priors (Table VII).              |
| rf windows/antennas               | $\varepsilon', \tan \delta, t, f$                                        | Thin-film insertion loss (43); material selection Sec. VI.                                                  |
| Charging/ESD                      | $\varepsilon', \sigma(T, n), E_0, \lambda, H^-$                          | Relaxation $\tau_{\text{relax}}$ (Sec. VI); lift with adhesion [Eqs. (26) and (47)]; NILS update (Sec. VI). |
| PSI (landing environments)        | PSD, $\rho, n$ , plume $q, \partial q/\partial r, \theta_{\text{plume}}$ | Erosion/flux scalings (Sec. VIII D); use SCALPSS-class constraints for site priors.                         |

rock abundance and topography focus gas flow or  $E$  fields, transport becomes locally efficient. The model relations that follow supply the parameters needed to propagate these effects into design calculations. Table IX provides design mapping from dust/regolith properties to rover subsystems.

#### A. Electrostatic lift with adhesion

For a sphere on a flat in the JKR regime, the pull-off force is  $F_{\text{adh}} \simeq \frac{3}{2}\pi WR$ . With  $W = 0.1 \text{ J m}^{-2}$  and  $R = 5 \text{ }\mu\text{m}$ ,  $F_{\text{adh}} = 2.36 \text{ }\mu\text{N}$ . For a  $1 \text{ }\mu\text{m}$  grain ( $\rho_p = 3100 \text{ kg m}^{-3}$ ), the weight is  $mg_{\text{Moon}} = 2.10 \times 10^{-14} \text{ N}$ , so adhesion exceeds gravity by  $\sim 1.12 \times 10^8$ . This justifies the need for preliberation (vibration, microimpacts, gas shear) before sheath acceleration.

#### B. Dielectric mixing (Looyenga form)

With silicate matrix  $\varepsilon_s \approx 2.7$  and ilmenite  $\varepsilon_{\text{ilm}} \approx 80$  (rf), modest  $v_{\text{ilm}} = 0.02\text{--}0.05$  raises  $\varepsilon'$  by several tenths when combined with densification, consistent with LPR trends.

#### C. Radiative term in thermal conductivity

At  $T = 380 \text{ K}$ , the radiative term contributes  $AT^3 \approx (2 \times 10^{-4} \text{ to } 2 \times 10^{-3}) \text{ W m}^{-1} \text{ K}^{-1}$  for  $A \approx (3.6 \times 10^{-12} \text{ to } 3.6 \times 10^{-11}) \text{ W m}^{-1} \text{ K}^{-4}$ , matching Diviner day/night asymmetry.

#### D. Design implications and measurement priorities

The present synthesis reduces unknowns by connecting particle-scale structure and composition to bulk properties and, in turn, to mobilization channels. For mission design, the practical question is not whether dust moves, but when, where, and with what spectrum and flux. The measurements prioritized below close specific loops: They coregister  $E$  field, charge, PSD, and flux in the environments where the models are most sensitive (terminators, PSR boundaries, magnetic anomalies, and active landing sites).

Reducing design margins requires: (1) colocated measurements of near-surface  $E$  fields, grain charge, and PSD to close the lofting budget; (2) time-resolved dust flux versus meteor streams to quantify ejecta maintenance; (3) PSR microphysics at centimeter depths (dielectric, conductivity, frost fraction);

(4) anomaly traverses across swirls to decouple magnetic shielding from electrostatic sorting; (5) standardized *in situ* geotechnical profiling with depth; (6) plume-surface interaction monitors to bound  $\dot{m}_e$ , PSD, and angular distributions during landings. (7) Polar-site *in situ* thermophysics: replicate ChaSTE-style active heating at multiple depths to tie  $k(T, \rho)$  to Diviner retrievals at high latitudes [33]. (8) Near-surface plasma and dust charging: colocate  $E$  field probes with negative-ion and electron spectrometers to quantify sheath composition and charging/lofting budgets in daylight [35,36]. (9) PSI monitors: fly SCALPSS-class stereo cameras plus ejecta counters on CLPS and Artemis landers to bound  $\dot{m}_e$ , ejecta PSD, and angular distributions during landings [34].

*a. Dust mitigation and operations: physics-limited requirements.* Equations (26) and (27) highlight an important design implication: For  $a \lesssim 10 \text{ }\mu\text{m}$ , the adhesion term  $C_{\text{adh}}/a$  typically dominates gravity by many orders of magnitude. Using the nominal contact parameters in Table III ( $W = 0.1 \text{ J m}^{-2}$ ,  $R = 5 \text{ }\mu\text{m}$ ,  $\phi_g = 5 \text{ V}$ ), Eq. (26) gives  $E_{\text{adh}}(1 \text{ }\mu\text{m}) \approx 4 \times 10^9 \text{ V m}^{-1}$ , whereas the gravity-only term is  $E_{\text{no}}(1 \text{ }\mu\text{m}) \approx 40 \text{ V m}^{-1}$ . Therefore, the natural near-surface fields compiled in Table IV ( $E_0 \sim 10^2 \text{ to } 10^3 \text{ V m}^{-1}$ ) cannot detach strongly adhered micron-scale dust from engineering surfaces; electrostatics primarily controls transport *after* grains have been mechanically liberated (impacts/abrasion, plume scouring, vibration) or deposited in weak-contact configurations.

In terms of mitigation taxonomy [39,41], this motivates two complementary design levers:

(1) *Reduce adhesion and contact activation* (materials/coatings, surface texturing, minimizing dust trapping geometries, controlled vibration, and contamination-tolerant clearances). Because  $E_{\text{adh}} \propto WR/(\phi_g a)$  via Eq. (27), even modest reductions in effective  $W$  or asperity radius  $R$  translate directly into lower detachment thresholds.

(2) *Actively remove or redirect preliberated grains* [electrodynamic dust shields (EDSs), gas or mechanical blow off, electrostatic deflection, purge flows, filtration/airlocks]. For example, an EDS has now been demonstrated on the lunar surface with reported dust-removal fractions of 82% from a radiator surface and 97% from glass over multiple cleaning cycles [40], suggesting that repeated-cycle transport (rather

than single-shot electrostatic “lift off”) is a viable approach for optics/thermal-control surfaces subject to weakly bound deposits.

*b. Worked design example: terminator preliberated grain hop.* Using the terminator/shadow-edge envelope in Sec. VIII C with  $E_0 = 300 \text{ V m}^{-1}$  and  $\lambda = 0.10 \text{ m}$ , Eq. (45) gives  $\Delta V_{\text{sh}} \simeq E_0 \lambda \approx 30 \text{ V}$ . For a  $a = 1 \text{ }\mu\text{m}$  grain at  $\phi_g = 5 \text{ V}$ ,  $q = 4\pi\epsilon_0 a \phi_g \approx 5.6 \times 10^{-16} \text{ C}$  and  $m = \frac{4}{3}\pi a^3 \rho_p \approx 1.3 \times 10^{-14} \text{ kg}$  (with  $\rho_p = 3.1 \times 10^3 \text{ kg m}^{-3}$ ), so Eq. (46) yields a ballistic apex height  $h_{\text{ball}} \approx q\Delta V_{\text{sh}}/(mg_{\text{Moon}}) \approx 0.8 \text{ m}$  and a flight time  $t_{\text{flight}} \sim 2\sqrt{2h_{\text{ball}}/g_{\text{Moon}}} \approx 2 \text{ s}$ . Meanwhile, Eq. (47) gives an equilibrium hover height  $h_* \approx \lambda \ln(qE_0/(mg_{\text{Moon}})) \approx 0.21 \text{ m}$ . This example illustrates why (1) realistic sheath voltages can support cm-m motion of preliberated micron grains, but (2) the adhesion-limited detachment condition in Eq. (26) must be treated separately in contamination-control trades.

## XII. CONCLUSIONS

Lunar dust emerges from impact comminution, space weathering (npFe<sup>0</sup> in rims and agglutinates), thermal fatigue, and volcanic fragmentation. The resulting microphysics (PSD, angularity/SSA, agglutinate fraction, composition/oxidation) sets the bulk thermophysical, dielectric, mechanical, and optical response that governs mobilization under local illumination and plasma conditions. Our main conclusions are as follows:

(1) *Sources  $\rightarrow$  properties.* Three microphysical levers dominate: (1) PSD and angularity, (2) glassy agglutinates with npFe<sup>0</sup>, and (3) composition/oxidation state. These map to  $k(T, \rho)$ ,  $\epsilon'$ ,  $\tan \delta$ , shear strength  $(\phi, c)$ , and adhesion at asperities (Secs. II and III).

(2) *Thermal and dielectric structure.* A two channel  $k(T, \rho)$  (solid network + pore radiative) reproduces Diviner day/night asymmetry and depth trends; ChaSTE anchors centimeter-depth  $k$  at high southern latitude. Densification from  $\sim 1.4$  to  $\sim 1.9 \text{ g cm}^{-3}$  raises  $\epsilon'$  by  $\sim 10\%$ – $30\%$  (LPR consistent), and charge-relaxation times span  $10^2$ – $10^6 \text{ s}$  across realistic  $\sigma$  (Secs. V and VI).

(3) *Adhesion-limited lofting.* Adhesion exceeds gravity by  $>10^7$  for  $a \sim 1 \text{ }\mu\text{m}$  at representative  $W$  and  $R$ , so preliberation (vibration, microimpacts, gas shear) is typically required. The adhesion-aware field requirement  $E_{\text{req}}(a) \simeq C_{\text{no}} a^2 + C_{\text{adh}}/a$  [with  $C_{\text{no}}$  and  $C_{\text{adh}}$  given in Eq. (27)] explains why typical

sheath fields ( $10^2$ – $10^3 \text{ V m}^{-1}$ ) do not detach adhered grains (Fig. 2 and Table III).

(4) *Near-surface (0–3 m) transport.* Once detached, micron/submicron grains can execute short hops or “hover” at heights set by the sheath-field integral and scale length; Eqs. (46) and (47) bound apex/hover heights and explain the observed first-meters environment near strong gradients (Sec. VIII C and Table V).

(5) *Mobilization budgets.* Meteoroid ejecta maintain a persistent, dawn-enhanced cloud (with stream-driven spikes), electrostatic hopping is intermittent and localized, and rocket plumes produce brief, intense episodes with the highest  $v_{\text{ejecta}}$  (Sec. VIII and Fig. 3).

(6) *Regional priors that matter.* Fe/Ti, maturity, packing, and  $T$  differ systematically across maria, highlands, swirls, pyroclastics, and PSRs, shifting  $k$ ,  $\epsilon'$ ,  $\tan \delta$ ,  $(\phi, c)$ , and charging behavior; Tables VII and VIII provide design ranges and recommended reference values (Secs. IX and X).

(7) *Measurement priorities.* Coregister  $E$  fields, grain charge, PSD, and flux at illumination/plasma boundaries; time-resolve dust flux during meteoroid streams; centimeter-scale thermophysics in PSRs; and standardized plume-surface monitors with stereo imaging and ejecta counters.

The practical impact of this synthesis is threefold. First, it provides region-specific reference values that span maria, highlands, swirls, pyroclastics, and PSRs, based on Apollo through present missions. Second, it supplies bridging relations that propagate grain-scale structure into  $k(T, \rho)$ ,  $\epsilon'$ , and lofting thresholds including adhesion. Third, it identifies colocated measurements that most efficiently retire risk:  $E$  field and charge with PSD at illumination boundaries; time-resolved dust flux during meteoroid streams; centimeter-scale thermophysics in PSRs; and standardized plume-surface monitors with stereo imaging and ejecta counters on CLPS and Artemis landers.

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## DATA AVAILABILITY

No data were created or analyzed in this study.

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