Deep dielectric charging and breakdown of lunar polar regolith

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Abstract. Galactic cosmic rays (GCRs) and solar energetic particles (SEPs) penetrate the regolith (layer of soil and dust) covering the Moon’s surface and cause deep dielectric charging. To gain insight into this process, we have developed a data-driven, deep dielectric charging model using data from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER), which is onboard the Lunar Reconnaissance Orbiter (LRO), and the Electron, Proton, and Alpha Monitor (EPAM) on the Advanced Composition Explorer (ACE). The model results indicate that GCRs produce a persistent electric field (~700 V m⁻¹) within the top tens of centimeters of regolith, while large SEP events could potentially generate episodic subsurface electric fields (≥10⁶ V m⁻¹) capable of causing dielectric breakdown within the top millimeter of regolith. We also propose that this “breakdown weathering” may have significantly affected the regolith in the Moon’s permanently shadowed regions (PSRs).

1. Introduction
Deep dielectric charging is well-known as an important process to mitigate in spacecraft engineering, but its effects have rarely been studied for the many airless bodies that exist throughout the solar system. Because these bodies lack protective atmospheres, their surfaces are directly exposed to the space environment. This allows dielectric surface materials on airless bodies to be charged by penetrating energetic charged particles, which creates subsurface electric fields due to the materials’ insulating properties. In some radiation environments, these electric fields could be capable of causing dielectric breakdown, or sparking [1]. The Moon’s regolith is a layer of dielectric soil and dust covering the surface, and it is expected to have an extremely low conductivity at the cold temperatures that occur near the poles, especially within permanently shadowed regions (PSRs) that never receive direct sunlight. Therefore, it is anticipated that energetic charged particles from the space environment can significantly charge the subsurface regolith in lunar PSRs. In this paper, we briefly review our work done to address this gap in understanding deep dielectric charging in the lunar regolith [2, 3], and we refer readers to both those papers for further details.

2. Energetic charged particles
Charging and breakdown in the regolith depend, in part, on the flux and fluence (time-integrated flux) of the incident energetic charged particles. At the Moon, there are two populations to consider. The first is galactic cosmic rays (GCRs), which are typically accelerated in supernovae shocks. For this work, we consider only the proton component (~87% of all GCRs), which has a peak flux at ~200 MeV and a total flux of ~2–4 particles cm⁻² s⁻¹ [4]. GCRs penetrate and charge the regolith down to tens of centimeters [5]. For GCR data, we use the Cosmic Ray Telescope for the Effects of Radiation (CRaTER), which is onboard the Lunar Reconnaissance Orbiter (LRO) [6].

The other population is solar energetic particles (SEPs), which comprise ions (~50 keV–10 GeV) and electrons (~1 keV–10 MeV) in roughly equal quantities; their peak fluxes are at
much lower energies than that of the GCRs [7]. SEPs are accelerated up to even relativistic energies in solar flares and the shocks of coronal mass ejections. They occur sporadically and their fluxes can exceed GCR fluxes by many orders of magnitude. For SEP data, we use LRO/CRaTER and the Electron, Proton, and Alpha Monitor (EPAM) on the Advanced Composition Explorer (ACE) [8]. SEPs detected by these instruments penetrate about 1 mm into the regolith, with the electrons typically going slightly deeper [2].

3. Electrical properties of the lunar regolith
Charging and breakdown in the regolith also depend on its electrical properties. We assume regolith to be ohmic, that is, having a discharging timescale \( \tau = \varepsilon / \sigma \), where \( \varepsilon \) is its permittivity and \( \sigma \) is its conductivity. The regolith typically has a permittivity of \( \varepsilon \approx 2 \varepsilon_0 \) [9]. Its electrical conductivity depends on temperature: \( \sigma = \sigma_0 e^{\alpha T} \), where \( \sigma_0 = 6 \times 10^{-18} \text{ S m}^{-1} \), \( \alpha = 0.0237 \text{ K}^{-1} \), and \( T \) is the temperature in kelvin [10]. At the temperatures found in PSRs (~50 K) [11], the conductivity is predicted to be \( \sim 10^{-17} \text{ S m}^{-1} \), so the regolith’s discharging timescale is expected to be \( \sim 20 \) days.

The regolith’s intrinsic properties make it conducive to dielectric breakdown for two main reasons. First, its grains tend to be jagged in shape, and such cusps can increase local electric fields by 1–2 orders of magnitude with respect to the overall electric field [12]. Second, its grains frequently contain inclusions, usually solid but sometimes gaseous [13, 14]. These inclusions also can increase local electric fields, thus decreasing the regolith’s dielectric strength [e.g., 15].

4. Modeling deep dielectric charging of regolith
We developed a one-dimensional, time-dependent, data-driven model to estimate the electric fields in the regolith due to GCRs and SEPs (for more details, see [2]). The model’s inputs and outputs are shown in Figure 1 for four cases. \( J_{EP}^+ \) and \( J_{EP}^- \) are the incident current densities from positively and negatively charged energetic particles, respectively, and can be provided by spacecraft measurements (e.g., LRO/CRaTER and ACE/EPAM). \( \kappa^+ \) and \( \kappa^- \) are the areal charge densities of the two charged layers. \( J_{\text{gap}} \) is the current density between the two charge layers, and \( J_{\text{interior}} \) is the current density below the deeper, negative charge layer.

![Figure 1](image)

After demonstrating the model’s characteristics with simple test scenarios, we then used spacecraft measurements. We input GCR data from LRO/CRaTER from June 2009 to March 2011 and found that the GCRs created a persistent electric field peaking at 700 V m\(^{-1}\) in the regolith within PSRs during solar minimum. We then input ACE/EPAM data from three very large SEP events: the Bastille Day storm in July 2000, the storm in November 2001, and the Halloween storms of 2003. The maximum subsurface electric fields were estimated to be on
the order of $10^6$–$10^7$ V m$^{-1}$ — possibly strong enough to induce dielectric breakdown. The fluence required to cause breakdown in most solids is $\sim10^{10}$–$10^{11}$ particles cm$^{-2}$, if deposited well within the discharging timescale [e.g., 16]. This criterion was met in all three events.

We also use LRO/CRaTER data as a proxy for the fluences of lower energy, and thus more numerous, SEPs [3]. We find that, since LRO arrived at the Moon, two SEP events (in January 2012 and in March 2012) have occurred that may have caused breakdown within PSRs (Figure 2). Therefore, this indicates that breakdown could be an ongoing space weathering process in the Moon’s polar regions.

5. Breakdown weathering of lunar regolith
We assessed the likely prevalence of dielectric breakdown at the Moon by estimating the frequency of breakdown-inducing SEP events. This was achieved by combining maps of the annual average, near-surface temperature at the Moon’s polar regions [11] with the Jet Propulsion Laboratory (JPL) fluence model, which estimates the frequency of SEP events with a given fluence [17]. We convert the temperature maps to regolith discharging timescales using the relation described in Section 3. We then adapted the proton fluence model to find the frequency at which breakdown-causing SEP events occur (about one event per year within PSRs). Finally, we incorporate the effect of meteoroid impacts, which thoroughly mix or
“garden” the regolith, thus bringing deeper material to the surface [18]; all gardened regolith has been exposed to SEPs for roughly 1 Myr [19]. Therefore, the gardened regolith within PSRs has likely experienced ~10⁶ breakdown-inducing SEP events (Figure 3).

This repeated breakdown may be an important form of space weathering. It can fragment regolith grains, particularly along mineralogical boundaries [15], which may explain the unexpectedly porous regolith possibly detected by LRO’s Lyman Alpha Mapping Project (LAMP) [20]. We are currently working to better understand how breakdown weathering may affect the regolith, and determine whether breakdown events could be observed with existing lunar spacecraft or with ground-based instruments.

6. Conclusion

We have developed a data-driven model whose results indicate that both GCRs and SEPs deep dielectrically charge the lunar regolith within PSRs. GCRs are predicted to produce a persistent electric field (~700 V m⁻¹) within the top tens of centimeters of regolith, while large SEP events may create episodic subsurface electric fields (≥ 10⁶ V m⁻¹) — capable of causing dielectric breakdown within the top millimeter of regolith. We also show that meteoritically mixed regolith within PSRs has likely experienced ~10⁶ breakdown-inducing SEP events. This breakdown weathering may have significantly affected the physical and chemical properties of the regolith in the Moon’s PSRs.

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