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The rate of dielectric breakdown weathering of lunar regolith in permanently shadowed regions

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ABSTRACT

Large solar energetic particle events may cause dielectric breakdown in the upper 1 mm of regolith in permanently shadowed regions (PSRs). We estimate how the resulting breakdown weathering compares to meteoroid impact weathering. Although the SEP event rates measured by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter (LRO) are too low for breakdown to have significantly affected the regolith over the duration of the LRO mission, regolith gardened by meteoroid impacts has been exposed to SEPs for $\sim 10^6$ yr. Therefore, we estimate that breakdown weathering's production rate of vapor and melt in the coldest PSRs is up to $1.8 - 3.5 \times 10^{-7}$ kg m^{-2} yr^{-1}, which is comparable to that produced by meteoroid impacts. Thus, in PSRs, up to 10–25% of the regolith may have been melted or vaporized by dielectric breakdown. Breakdown weathering could also be consistent with observations of the increased porosity ("fairy castles") of PSR regolith. We also show that it is conceivable that breakdown-weathered material is present in Apollo soil samples. Consequently, breakdown weathering could be an important process within PSRs, and it warrants further investigation.

1. Introduction

The Moon's permanently shadowed regions (PSRs) may be more active than previously thought. Although they are not directly exposed to sunlight or the solar wind, they are still subjected to meteoroid impacts, as is the rest of the Moon's surface. Also, they are exposed to penetrating particle radiation: galactic cosmic rays (GCRs) and solar energetic particles (SEPs), both of which are nearly isotropic because, for the energies considered, they have gyroradii on the order of or much larger than the Moon's radius. This can be seen in data from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) (Spence, 2010) aboard the polar orbiting Lunar Reconnaissance Orbiter (LRO) (Chin, 2007): the orbit does not significantly affect the measured SEP flux (Joyce et al., 2013). This particle radiation can cause radiolysis of the water ice mixed into the PSR regolith (Jordan et al., 2013; Schwadron, 2012) and deep dieletrically charge the regolith itself (Jordan et al., 2015, 2014).

Regolith within PSRs is so cold that its electrical conductivity is extremely low ($\sim 10^{-17}$ S m^{-1}), creating discharging timescales of two to three weeks (Jordan et al., 2015). These long timescales may enable large solar energetic particle (SEP) events to charge the upper ~ 1 mm of regolith to the point of dielectric breakdown (reviewed in the next section); sufficiently large events are estimated to occur approximately once a year (Jordan et al., 2014). In addition, the regolith is mixed by meteoroid impacts, causing all regolith within the gardened (i.e., thoroughly mixed) zone to be exposed to SEPs for ~ 1 Myr (Jordan et al., 2013). Therefore, all gardened regolith has experienced $\sim 10^6$ potentially breakdown-inducing SEP events (Jordan et al., 2015). The resulting breakdown weathering should vaporize some of the regolith and cause some grains to fragment along mineralogical boundaries (Andres et al., 2001; Jordan et al., 2015).

It remains unclear how breakdown weathering compares with impact weathering in lunar PSRs. To address this, we begin by comparing estimates for the energy budgets of both processes and then their production rates of vapor and melt. We conclude with some comments on how breakdown weathering could be consistent with remote observations of PSR regolith, which seems to require some sort of environmentally controlled process (Lucey, 2014). We also suggest laboratory experiments and additional remote observations to help resolve open questions regarding breakdown weathering.

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2. Dielectric breakdown

Dielectric breakdown is a well-known phenomenon in the space environment, as it relates to spacecraft engineering (e.g., Balmain, 1987). It occurs when energetic charged particles are rapidly deposited in sufficient fluences within a spacecraft's dielectric components. It is the leading cause of anomalies on spacecraft orbiting in Earth's magnetosphere (Koons et al., 1999), and it even occurred dozens of times on Voyager 1 as it passed through Jupiter's radiation belts (Leung et al., 1986).

Although breakdown has been well studied in spacecraft exposed to energetic particles, it has rarely been considered as a process that may affect the surfaces of airless bodies in the Solar System. The main example is the laboratory work of Campins and Krider (1989), who investigated whether electrons in Jupiter's radiation belt could cause breakdown on Io's surface. They exposed natural mineral sulfur in a vacuum to 10–30 keV electrons (which penetrate to ~0.1 mm) at fluxes similar to those found in the Jovian magnetosphere. They found that breakdown did occur; the sparking was even visible in a dark room. Although Campins and Krider (1989) suggested this process could occur elsewhere in the Solar System, this was not followed up until recent work indicated that breakdown may occur in lunar PSRs during large SEP events (Jordan et al., 2015, 2014).

Although many specifics of the breakdown process remain unresolved, the general phenomenon and its criteria are well-characterized. (For an introduction to breakdown in terrestrial applications, see Budenstein (1980). For reviews of how it affects spacecraft, see Frederickson (1983) and Garrett and Whittlesey (2000).) If energetic particles build up in a dielectric more quickly than the dielectric can dissipate the accumulated charge, the internal electric field increases. Once the field's strength reaches $\sim 10^6 - 10^7$ V/m, breakdown begins for most solids (Sørensen et al., 1999). (Note that these values are for dielectrics irradiated in space by energetic particles, and are lower than for most terrestrial studies.)

As the electric field increases, gas-filled conducting channels form rapidly within the dielectric, propagating through it faster than the sound speed (Knaur and Budenstein, 1980). These tree-like channels typically begin near inhomogeneities within the dielectric, e.g., metallic inclusions that increase the local electric field by up to an order of magnitude, or near gas voids with lower dielectric strength. In rocks, the channels tend to propagate along mineralogical boundaries (see the review in Jordan et al. (2015)). The conducting channels shorts out the electric field in a volume much greater than the channels itself (Budenstein et al., 1969), causing the field to dissipate almost entirely (Bradwell and Pulfrey, 1968). The channels expel their gas in a puff of plasma and neutral material (e.g., Balmain, 1980; Frederickson, 1983).

In the case of the regolith, SEPs penetrate ~1 mm into the regolith, which is much deeper than the typical grain size (Jordan et al., 2014). Breakdown would then occur throughout this layer (see Fig. 1). Note that we focus only on the dust layer, which comprises grains $< 100\,\mu$m (Colwell et al., 2007), and not on rocks, because rocks have an electrical conductivity that is about four orders of magnitude greater than soils (Olhoeft et al., 1974). Their discharging timescales are thus too short to make breakdown possible.

During breakdown, the electric field energy density drives Joule heating (Boggs, 2004; Ohring, 2015). In the regolith, the energy density of the electric field immediately before breakdown is

$$u_{BW} = \frac{1}{2}\epsilon E^2 \tag{1}$$

where ϵ is the regolith's permittivity (approximately $2\epsilon_0$ (Olhoeft and Strangway, 1975)) and E is the subsurface electric field strength. This energy density dissipates rapidly in the breakdown channels through Joule heating, which is described by

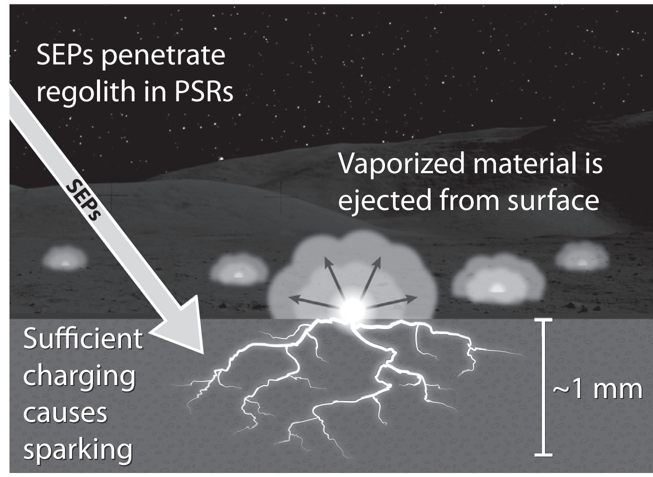

Fig. 1. Cartoon showing how SEPs may cause dielectric breakdown in regolith in a PSR. Tiny breakdown events could occur throughout the floor of the PSR.

$$\vec{J}\cdot\vec{E} = -\frac{\epsilon}{2}\frac{\partial E^2}{\partial t} = -\frac{\partial u_{BW}}{\partial t} \tag{2}$$

where $\vec{J}$ is the current density, and t is time. The field rapidly drops to near zero within a timescale of nanoseconds to microseconds (Bradwell and Pulfrey, 1968), during which the electric field energy density is converted to heat. This timescale is $\tau = \epsilon/\sigma_c$, where σ_c is the conductivity of the breakdown channels (e.g., Jordan et al., 2014). Experiments with lunar simulant indicate that breakdown takes approximately 50 ns to go from a peak voltage of almost 6 kV to about zero (Kirkici et al., 1996). Though the actual decay timescale is shorter, we can assume τ to be 50 ns. In this case, the conductivity of the channels is $\sim 10^{-4}$ siemens per meter (S m^{-1})—similar to some semiconductors. Since the timescale is shorter, however, the conductivity is likely higher. Regardless, $\sim 10^{-4}$ S m^{-1} is many orders of magnitude greater than $\sim 10^{-17}$ S m^{-1}, which is the expected conductivity of regolith in PSRs (Jordan et al., 2014).

In this paper, we estimate the fraction of regolith affected (vaporized and/or melted) by individual breakdown discharges that occur episodically during a breakdown-causing SEP event. (As depicted in Fig. 1, a single breakdown event creates many discharges throughout PSRs.) That is, we estimate V_{BW}/V_{reg}, where V_{BW} is the volume of material affected by a breakdown event and V_{reg} is the volume of all the regolith irradiated by the SEPs. A breakdown event releases energy $\mathcal{E}_{BW}$, which is the sum of the energy released by all the individual discharges. $\mathcal{E}_{BW}$ is only a fraction of the energy $\mathcal{E}_{reg}$ needed to affect all the regolith by melting and/or vaporizing. Therefore,

$$\frac{\mathcal{E}_{BW}}{V_{BW}} = \frac{\mathcal{E}_{reg}}{V_{reg}} = u_{reg} \tag{3}$$

where u_{reg} is the energy density needed to affect all the regolith. The electrostatic energy density released during a single breakdown event in the entire volume of irradiated regolith is

$$u_{BW} = \frac{\mathcal{E}_{BW}}{V_{reg}} \tag{4}$$

Combining this result with Eq. (3) gives

$$\frac{V_{BW}}{V_{reg}} = \frac{u_{BW}}{u_{reg}} \tag{5}$$

That is, the fraction of regolith affected by a breakdown event is the ratio of the electrostatic energy density released during breakdown to the energy density needed to affect all the regolith. And