HOW DIELECTRIC BREAKDOWN MAY WEATHER THE LUNAR REGOLITH AND CONTRIBUTE TO THE LUNAR EXOSPHERE.

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Introduction: The lunar regolith is exposed to many forms of space weathering. One possible weathering process is dielectric breakdown, in which solar energetic particles (SEPs) charge the top ~1 mm of regolith to the point of dielectric breakdown—the formation of electrically conductive channels of vaporized material that dissipate the charging [1,2].

The conditions needed for dielectric breakdown are well-understood, because this process is the leading cause of anomalies on spacecraft exposed to high fluxes of energetic charged particles [3]. To experience breakdown, an electrically insulating material, or dielectric, must be charged by ~10^{10} charged particles cm^{-2} deposited in the bulk of the material within that material's discharging timescale [4]. (The discharging timescale is the ratio of the dielectric's permittivity to its electrical conductivity, and it is the characteristic time needed to dissipate any charge buildup.) If this condition is met, then the electric field within the dielectric will exceed ~10^6 V/m [4]. This field causes most solids to undergo breakdown by explosively vaporizing conductive channels to dissipate the deep dielectric charging [5].

Large SEP events are predicted to cause dielectric breakdown in the top ~1 mm of lunar regolith, both because they can have fluences exceeding 10^{10} particles cm^{-2} [6] and because they can deposit these particles within the discharging timescale of very cold regolith [1]. The discharging timescale of the regolith increases with decreasing conductivity, and the conductivity of lunar soil decreases with decreasing temperature [7]. Consequently, permanently shadowed regions (PSRs), which can be <50 K [8], likely have discharging timescales on the order of weeks [1]--much longer than the typical SEP event (~3 days) [9].

Previously, we predicted that dielectric breakdown has melted or vaporized about 10-25% of impact gardened regolith in PSRs [10]. This is comparable to weathering by meteoroid impacts, which has affected ~10% of the gardened regolith [11, 10]. But the nightside of the Moon can also be <100 K and can be accessed by SEPs, which have gyroradii on the order of the Moon's diameter. In this study, therefore, we estimate the fraction of regolith that may have been affected by dielectric breakdown as a function of latitude. Furthermore, we predict the possibility that Earth-based instruments could detect the vapor that breakdown may release into the lunar exosphere during a large SEP event.

Breakdown on the lunar nightside: To predict the fraction of regolith melted or vaporized by dielectric breakdown, we follow the method developed in [10]. We estimate the rate at which breakdown energy is deposited into the top 1 mm of regolith by using the rates of SEP events as a function of fluence, which has been estimated by [6, 2]. SEPs, however, have affected more than just the current top 1 mm of regolith, because the regolith is mixed, or gardened, by meteoroid impacts. Consequently, all gardened regolith has, on average, been exposed to SEPs for ~10^6 yr [e.g., 12].

The nightside of the Moon can drop to temperatures <100 K, which correspond to discharging timescales longer than ~3 days. The discharging timescales on the nightside are shown in Fig. 1 as a function of local solar time and latitude. During any SEP event with a fluence exceeding ~10^{10} cm^{-2}, regolith may experience breakdown if its discharging timescale is equal to or longer than the duration of a typical SEP event. Warmer regions have shorter discharging timescales and thus have higher fluence thresholds for undergoing breakdown.

As we showed in [10], the fraction of regolith affected by breakdown equals the energy deposited by

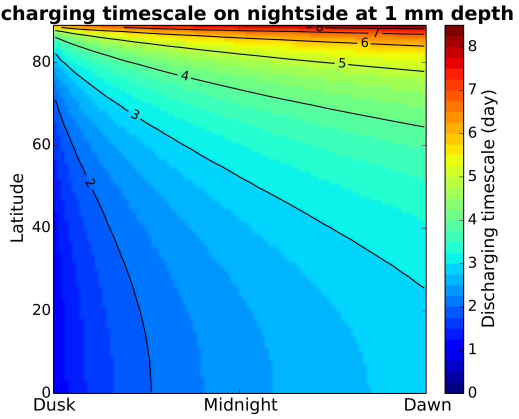

Fig. 1. The discharging timescale of the regolith on the nightside of the Moon.

dielectric breakdown (i.e., the rate of breakdown energy deposition times the exposure time to SEPs) divided by the energy needed to affect the regolith ($\sim 10^9$ J m^{-3} [12]). We find that dielectric breakdown can occur at all latitudes (Fig. 2). We predict that breakdown weathering has melted or vaporized 2-5% of gardened regolith near the equator and 6-12% near the poles. Globally, dielectric breakdown could have affected 4-7% of the gardened regolith.

Breakdown's contribution to the lunar exosphere: We now determine whether dielectric breakdown during a *single* SEP event could contribute enough vapor to the lunar exosphere to enable the change to be detected by instruments on Earth. The fluence of an event determines what fraction of the lunar surface can be affected by breakdown. A threshold event (fluence of $\sim 10^{10}$ cm^{-2}) will affect regions with temperatures <100 K, or ~0.25 of the lunar surface. In these regions, the event will vaporize about 10^{-9} per unit volume of the regolith in the top 1 mm. A larger event, on the other had, can affect warmer regions and thus more of the lunar surface. Furthermore, in these regions, a larger event can vaporize a greater fraction per unit volume of regolith.

The surface area of the Moon is 3.79×10^{13} m^2. Consequently, the volume contained in the top 1 mm of regolith is 3.79×10^{10} m^3. About 0.25 of the lunar surface may be affected during a threshold event, so $\sim 10^{10}$ m^3 of regolith would have a temperature conducive to breakdown during such an event. Of this regolith, breakdown affects, i.e., melts or vaporizes, about 10^{-9}, thus affecting ~10 m^3 of regolith. The density of regolith in the top mm is about 1.5×10^3 kg m^{-3} [13], so breakdown could melt or vaporize $\sim 10^4$ kg during an SEP event.

Only the fraction of regolith that is vaporized contributes to the exosphere. Since we currently do not know what fraction is melted or vaporized, we assume the fraction vaporized to be about 10%, as is the case for hypervelocity meteoroid impacts [12]. The vaporized material is likely projected in all directions, because dielectric breakdown is an explosive process [e.g., 2]. Thus, only a fraction of vapor will be directed out of the regolith. If 10% of the breakdown vapor escapes, then breakdown would contribute about 100 kg to the lunar exosphere, or about 1% of the average mass of the exosphere.

An SEP event that has a fluence of 10^{11} cm^{-2} would affect 100 times as much of the regolith. (According to [6, 10], such events occurred six times in the Sun's active years between 1973 and 1991.) Furthermore, it would also be able to affect nearly half the lunar surface. Consequently, the vapor contribution to the atmosphere would be at least two orders of magnitude greater than that of an event with a fluence of 10^{10} cm^{-2}. In this case, breakdown could contribute to the exosphere a mass on the order of the typical lunar exosphere. We consider the timescale for this release and whether it could be detected by ground-based instruments.

Conclusion: Dielectric breakdown weathering may have melted or vaporized a few percent of all impact gardened regolith on the Moon. If so, it has played a significant role in the evolution of the regolith, a role that may, in the future, be identified in soil samples returned to Earth. Furthermore, breakdown during a large SEP event may contribute a detectable amount to the exosphere of the Moon.

References: [1] Jordan, A. P., et al. (2014), *JGR-Planets*, *119*, 1806-1821. [2] Jordan, A. P., et al. (2015), *JGR-Planets, 120,* 210-225. [3] Koons, H. C., et al. (1998), *6th Spacecraft Charging Technology*, 7–11. [4] Frederickson, A. R., et al. (1992), *IEEE T. Nucl. Sci., 39*, 1773-1782. [5] Sørenson, J., et al. (1999), *5th European Conf. RADECS*, 27-33. [6] Feynman, J., et al. (1993), *J. Spacecraft Rockets, 27*, 403-410. [7] Olhoeft, G. R., et al. (1974), *JGR, 79*, 1599-1604. [8] Paige, D. A., et al. (2013), *Science, 339,* 300-303. [9] Kecskeméty, K., et al. (2009), *JGR, 114,* A06102. [10] Jordan, A. P., et al. (2017), *Icarus, 283,* 352-358. [11] Jordan, A. P., et al., (2013), *JGR-Planets, 118*, 1257-1264. [12] Cintala, M. J. (1992), *JGR, 97*, 947-973. [13] Carrier, W. D., III, et al. (1991), Ch. 9 in *Lunar Sourcebook,* Cambridge Univ.

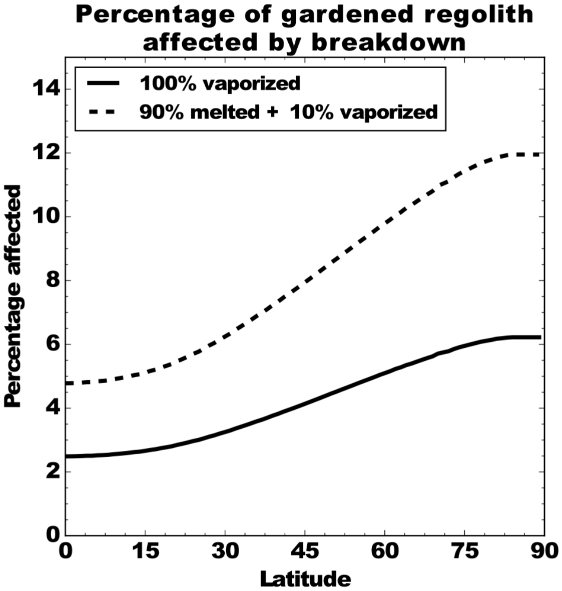

Fig. 2. The predicted percentage of gardened regolith that dielectric breakdown affects as a function of latitude for two cases: breakdown only vaporizes (solid curve), and breakdown vaporizes and melts in the same percentages as hypervelocity impacts (dashed curve).