REEVALUATING HOW CHARGED PARTICLES CAUSE SPACE WEATHERING ON THE MOON. A. P. Jordan[1,2], [1]EOS Space Science Center, University of New Hampshire, Durham, NH, USA (first author email address: a.p.jordan@unh.edu), [2]Solar System Exploration Research Virtual Institute, NASA Ames Research Center, Moffett Field, CA, USA.

Introduction: Airless bodies throughout the Solar System are exposed to a variety of space weathering processes, including meteoroid impacts, ionizing radiation, and plasmas. Much experimental work focuses on how plasmas like the solar wind affect regoliths, and they help form the foundation for understanding how the solar wind affects the Moon.

Growing evidence suggests that such experiments cause changes that may not apply directly to the bodies being simulated, because they use fluxes and fluences of charged particles that are many orders of higher than those found in nature [1-5]. These fluxes and fluences are known to cause dielectric breakdown (or "sparking") in electrically insulating materials [6-7]. Consequently, such experiments likely do not simulate space weathering by the solar wind, which does not cause breakdown; rather, they may simulate dielectric breakdown weathering caused by solar energetic particle (SEP) events. It is necessary to reevaluate how charged particles cause space weathering on the Moon.

Conditions for dielectric breakdown: Decades of experiments in the laboratory or onboard spacecraft have shown that, in agreement with theory, dielectric breakdown occurs if $\geq 10^{10}$ charged particles cm^{-2} are deposited in a dielectric (i.e., electrical insulator) within that dielectric's discharging timescale [e.g., 6-7]. In other words, if a material is deep dielectrically charged at a rate greater than the rate at which it can dissipate the charging, then the internal electric field can grow until it causes breakdown—the rapid dissipation of internal charge via melting and vaporization. This condition for breakdown applies to most solid insulators, as it depends on microscopic imperfections in the materials, like inclusions, cracks, or sharp protrusions [e.g., 8].

Potential for breakdown in experiments: Experiments typically use fluences that are 6-8 orders of magnitude higher than the threshold for breakdown, with fluxes that are high enough to deposit $\sim 10^{10}$ charged particles cm^{-2} in ~0.001 s [e.g., 2, 9-11]. Such experiments risk causing dielectric breakdown in the targets. Despite this, most experiments mention no measures to prevent charging and breakdown [11].

There are some exceptions. First, some experiments neutralize the incident beam [e.g., 9]. This prevents the target from charging, but it also changes the nature of the incident particles. It is unclear how neutral atoms could cause the same type of weathering as the ions and electrons found in plasmas.

Second, other experiments keep the sample electrically neutral by using a low-energy electron flood gun [e.g., 10]. While this method does prevent the entire target from charging, it does not prevent a strong electric field from building inside the sample. In fact, unless the electron gun and the ion beam penetrate to the exact same depth, the combination can create significant internal charging, causing dielectric breakdown (Fig. 1) [12].

Reevaluating experiments: It is therefore likely that such experiments (except those using neutralized beams) cause dielectric breakdown and do not cause the same type of weathering as the solar wind causes on the Moon. The solar wind bombards the dayside, where the high temperatures decrease the soil's discharging timescale enough to prevent breakdown.

This does not mean, however, that such experiments are irrelevant. They may instead simulate SEPs causing dielectric breakdown. In fact, a number of such experiments have shown that breakdown can occur in materials found on airless bodies [13-16], and breakdown has been predicted to occur on a number of airless bodies, including the Moon [11, 13-14, 17-18].

Breakdown weathering on the Moon: Dielectric breakdown has been predicted to be an important source of weathering on the Moon [17]. Solar energetic particles (SEPs) can deep dielectrically charge the top ~1 mm of soil. In regions that are cold enough ($\leq$120 K), the discharging timescale of the soil is longer than typical SEP events; thus, SEP events with fluences $\geq 10^{10}$ charged particles cm^{-2} can cause dielectric breakdown in cold regions of the Moon. Breakdown may have melted and/or vaporized ~10% of gardened soil—comparable to micro-meteoroid impacts [17]. In fact, a combination of breakdown and impacts—but no solar wind—can explain how the reflectance of the maria increases with latitude [19].

If this hypothesis is correct, it should be reflected in the rims found on lunar grains. Impacts should create depositional rims that are compositionally distinct from the host grains. Dielectric breakdown, too, can eject melt and vapor [e.g., 20], so it should also contribute to the creation of deposited rims. In addition, breakdown in space weathering experiments amorphizes material in situ [14]; thus, it can create amorphous rims where breakdown runs along the surfaces of grains. Consequently, there should be a *continuous* spectrum of grain rims running from amorphous rims (breakdown only) to depositional rims (impacts + breakdown).

This is what is found. Keller and McKay [21] found not just two types of rims but "a continuum between 'pure' amorphous rims and 'pure' inclusion-rich rims." Between the end-members are "intermediate" rims, which share characteristics of both and are almost as common. Furthermore, although Keller and McKay argued that the inclusion-poor rims were formed by the solar wind, they found that such rims always include elements that are not indigenous to the host grain. This suggests a non-local component to the weathering process, which is to be expected, since breakdown should travel along multiple grains [22]. Consequently, breakdown and impacts alone can explain weathered rims on lunar grains.

This hypothesis may also explain why experiments predict that the solar wind forms rims in timescales that are 3-4 orders of magnitude shorter than the ages of the rims themselves [23-24]. If the above hypothesis is true, then the relevant flux is not that of the solar wind, but that of SEPs that cause dielectric breakdown. The long-term average flux of breakdown-causing SEPs is ~4 orders of magnitude lower than that of the solar wind, thus explaining the age of amorphous rims.

Tests of this hypothesis: There are a number of ways to test this hypothesis further [11, 19]; I mention two here. If a material is too electrically conductive, then breakdown is less likely. Consequently, metals—and, by inference, more metallic minerals—should not experience breakdown [14]. Is this why ilmenite lacks fully amorphized rims [e.g., 25]?

Another test would be the longitudinal dependence in the weathering of craters [26]. If the magnetotail affects SEP access to the Moon, then breakdown would create a different longitudinal dependence. There is some evidence that the process causing the asymmetric weathering in craters occurs, not on the dayside, but on the nightside—consistent with breakdown weathering (see Fig. 2b,d, and h of [26]). The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) [27] onboard the Lunar Reconnaissance Orbiter (LRO) could test this.

Conclusion: Many experiments have attempted to simulate how charged particles cause space weathering on airless bodies throughout the Solar System, but these experiments create conditions that are known to cause dielectric breakdown. By reevaluating these experiments in the light of breakdown, it is possible to explain several aspects of space weathering on the Moon. Consequently, applying the results of charged particle experiments requires knowing whether the location being simulated is exposed to dielectric breakdown weathering.

References: [1] Willman, M., et al. (2010), *Icarus, 208*(2), 758-772. [2] Zhu, Y., et al. (2014), *Chin. J. Geochem., 33,* 351-356. [3] Matsumoto, T., et al. (2015), Space Weathering of Airless Bodies Workshop, Abstract # 2045. [4] Keller, L., et al. (2016), 47th LPSC, Abstract # 2525. [5] Christoffersen, R., et al. (2020), 51st LPSC, Abstract # 2084. [6] Frederickson, A., et al. (1992), *IEEE T. Nucl. Sci., 39,* 1773-1782. [7] NASA (2017), NASA-HDBK-4002A. [8] Budenstein, P. (1980), *IEEE T. Electr. Insul. 3,* 225-240. [9] Dukes, C., et al. (1999), *JGR, 104,* 1865-1872. [10] Loeffler, M., et al. (2009), *JGR Planets, 114,* E03003. [11] Jordan, A. P., submitted to *Icarus.* [12] Cazaux, J., and Lehuede, P. (1992), *J. Electron Spectrosc., 59,* 49-71. [13] Campins, H., and Krider, E. (1989), *Science, 245,* 622-624. [14] Lemelle, L., et al. (2003), *Geochim. Cosmochim. Ac., 67(10),* 1901-1910. [15] Shi, J., et al. (2010), *Nucl. Instrum. Meth. B., 268(19),* 2888-2891. [16] Shusterman, M. et al. (2021), *52nd LSPC*, Abstract # 2141. [17] Jordan, A. P., et al., (2019), *Icarus, 319*, 785-794. [18] Jordan, A. P., et al. (2018), *Adv. Space Res., 62(8),* 2187-2198. [19] Jordan, A. P. (2021), *Icarus*, in press. [20] Frederickson, A. (1983), *IEEE T. Electr. Insul., 3,* 337-349. [21] Keller, L., and McKay, D. (1997), *Geochim. Cosmoc. Ac., 61(11)*, 2331-2341.[22] Jordan, A. P., et al. (2014), *JGR-Planets*, *119*, 1806-1821. [23] Christoffersen, R., and Keller, L. (2015), 46th LPSC, Abstract # 2084. [24] Keller, L., and Zhang, S. (2015), Space Weathering of Airless Bodies Workshop, Abstract # 2056. [25] Borg, J., et al. (1980), in *The Ancient Sun*, 431-461. [26] Sim, C., et al. (2017), *GRL, 44*, 11,273-11,281. [27] Spence, H., et al. (2010), *Space Sci. Rev., 150,* 243-284.

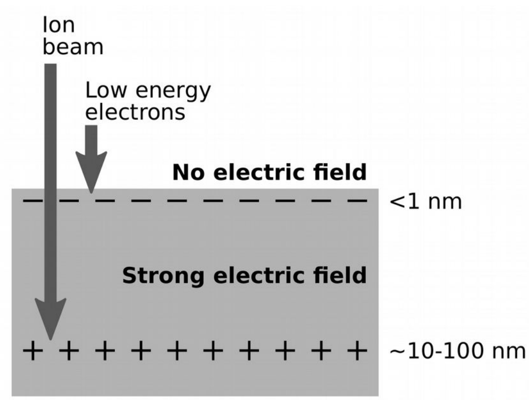

Fig. 1. Cartoon showing how an electron gun can neutralize a target irradiated by an ion beam, yet still create an internal electric field that could cause dielectric breakdown (from [11]).