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The possible contribution of dielectric breakdown to space weathering on Phobos

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Abstract

The origins of Phobos and Deimos are uncertain; both are so space weathered that their surface compositions are difficult to determine using spectral reflectance measurements. We show how the winter temperatures and associated conditions in the polar regions of Phobos could make the regolith susceptible to space weathering from dielectric breakdown caused by solar energetic particles (SEPs). During SEP events, charged particles accumulate throughout the top ~1 mm of the regolith, which has low conductivity, and create subsurface electric fields that act to dissipate any net buildup of charge. The faster the net charge accumulates, the larger the electric field needed to dissipate it. If the magnitude of the subsurface electric field exceeds $\sim 10^6$ V m^{-1}, then dielectric breakdown is likely. This process rapidly dissipates the buildup of charge by vaporizing electrically conducting channels through the regolith. Dielectric breakdown is expected to be more prevalent in colder regions, where the electrical conductivity of the regolith is lower and the dissipation of charge is consequently slower. If the regolith on Phobos is made of silicates, or possibly phyllosilicates, we predict that dielectric breakdown weathering has melted or vaporized 5–10% of the impact gardened regolith in the polar regions, although this percentage depends on how long the regolith has been exposed to SEPs. This, in addition to the long exposure time of the regolith to other forms of space weathering, may help explain why both Phobos and Deimos are highly space weathered compared to other airless bodies in the Solar System, such as Earth's Moon.

Keywords: Phobos; Regoliths; Space weathering; Solar energetic particles

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1. Introduction

The origin of Phobos and Deimos is a mystery: are they composed of Martian material, or are they captured asteroids (e.g., Murchie et al., 2015)? To answer this question, it is necessary to determine their compositions. This has proven difficult because no sample has been acquired from either object, and all data have been obtained via remote sensing observations.

Remote sensing, though, is subject to ambiguities, because both objects have been so space weathered—more than some have expected (e.g., Fraeman et al., 2012; Murchie et al., 2015). Space weathering is the effect of the space environment on the physical, chemical, and nuclear properties of the regolith of an airless body. Energetic charged particles, the solar wind, ionizing electromagnetic radiation, and meteoroid impacts all change regolith properties (e.g., see reviews by Hapke (2001) and Pieters and Noble (2016)). These space weathering processes

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modify the spectra of regoliths in ways that depend on their compositions, thus limiting the usefulness of spectral reflectance measurements. (Neutron and gamma-ray spectrometers, which measure bulk compositions, are not limited in this way but have yet to be flown to either satellite.)

This creates a dilemma. We must know how space weathering has affected the observed spectra to determine the composition, but we need to know the composition to determine how space weathering has affected the spectra. Hence the uncertainty surrounding the composition of Phobos. (We focus on Phobos because it has been more closely studied than Deimos.) Perhaps it has a regolith similar to the Moon's (Rivkin et al., 2002), is composed of phyllosilicates (Giuranna et al., 2011), or is more similar to D-type asteroids or CM carbonaceous chondrites (Fraeman et al., 2012, 2014). Its composition, however, will presumably remain a mystery until samples are collected, because regoliths of small bodies have likely evolved differently than that on the Moon (e.g., Pieters et al., 2014).

Despite these ambiguities, it is important to constrain the composition and origin of Phobos to understand not just its history in particular, but also the ways in which planet-moon systems can form. One way to do this is to identify the types of space weathering that affect these moons. For example, some forms of space weathering have only recently been identified, such as thermal breakdown (Delbo et al., 2014) and dielectric breakdown by energetic charged particles (Campins and Krider, 1989; Jordan et al., 2014, 2015, 2017). To help constrain the composition of these moons, we must determine whether these processes have affected their regoliths.

In previous work, we have shown that, in the Moon's permanently shadowed regions (PSRs), regolith may be significantly weathered by dielectric breakdown, that is, by the rapid vaporizing of electrically conductive channels that dissipate a buildup of charge (Jordan et al., 2017). Breakdown may occur when the Moon is sporadically bombarded with solar energetic particles (SEPs), which are energetic charged particles—mostly protons and electrons—accelerated to high energies in solar flares or the shocks of coronal mass ejections (e.g., Reames, 1999). These SEPs penetrate ~ 1 mm into the regolith, or many grains deep, and thus cause deep dielectric charging. In PSRs, the regolith is so cold that it cannot dissipate the charge buildup caused by these SEPs. During large SEP events, the resulting subsurface electric field may become strong enough to cause dielectric breakdown (Jordan et al., 2014, 2015). Over time, dielectric breakdown weathering may melt and vaporize as much of the impact gardened regolith in the Moon's PSRs as do meteoroid impacts (Jordan et al., 2017).

Like the Moon, Phobos experiences environmental conditions that suggest it may have regions susceptible to dielectric breakdown. It is exposed to SEPs, although at slightly lower fluxes than is the Moon because it is farther from the Sun. It has a high obliquity with respect to the Sun, so its polar regions spend significant fractions of the Martian year in shadow. The polar regions are thus very cold (< 100 K) during their winter seasons (Kührt and Giese, 1989) and likely have low electrical conductivity. It is also covered in fine-grained material, with estimates of mean grain sizes ranging from 160 to 240 μm (Kührt et al., 1992) to 1 mm (Gundlach and Blum, 2013). Consequently, we investigate how dielectric breakdown may play a role in the evolution of the regolith on Phobos.

2. Dieletric breakdown weathering

When energetic charged particles penetrate an electrically insulating material, or dielectric, they create electric fields inside the material; that is, they cause deep dielectric charging. The dielectric can dissipate such charging on a characteristic timescale equal to the ratio of its permittivity (the material's dielectric constant times the permittivity of free space) and its electrical conductivity (e.g. Buhler et al., 2007).

If the flux of charged particles is so great that they accumulate in the material more quickly than they can be dissipated by the material's inherent conductivity, then the internal electric field will increase. Furthermore, if enough charged particles are deposited within the discharging timescale, the material must change its overall mode of conductivity. When the fluence (time-integrated flux) is $\gtrsim 10^{10}$ charged particles cm^{-2}, the internal electric field can increase to greater than $\sim 10^6$ V m^{-1} (Garrett and Evans, 2001; Green and Dennison, 2008). Under this field, the material rapidly changes its mode of conductivity: rather than dissipating charge via the material's inherent conductivity, the field explosively vaporizes channels through the material to dissipate the charging. This process requires only nanoseconds to microseconds (Bradwell and Pulfrey, 1968; Balmain, 1980) and is called dielectric breakdown (for a review of this process, see Budenstein (1980)).

The conditions for dielectric breakdown are well understood because it is a leading cause of anomalies on spacecraft orbiting Earth (Koons et al., 1999). If Earth's radiation belts change intensity or location, then otherwise safe spacecraft can receive greatly enhanced fluxes of energetic particles. Consequently, deep dielectric charging and dielectric breakdown have been the subjects of much interest in designing spacecraft.

One instrument in particular, the Internal Discharge Monitor (IDM) on the Combined Release and Radiation Satellite (CRRES), was used to study the conditions for breakdown (Frederickson et al., 1992). It carried a variety of materials used in spacecraft construction and orbited in the radiation belts to expose them to energetic electrons (these peak between 200 and 400 keV, so they have energies similar to SEP electrons, as seen in Section 4.1). Throughout the mission, breakdown occurred over 4000 times, and it was found that 2×10^{10} electrons cm^{-2} could cause breakdown in some of the materials with sufficiently long discharging timescales. This fluence ($\sim 10^{10}$ electrons