LUNAR SURFACE CHARGING AND POSSIBLE DIELECTRIC BREAKDOWN IN THE REGOLITH DURING TWO STRONG SEP EVENTS.

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Summary: We investigate conditions under which dielectric breakdown may occur in the lunar regolith. Such "breakdown weathering" could result in significant physical and chemical alterations of the regolith and may contribute to the process of space weathering on airless bodies such as the Moon and asteroids [1]. We study two particular solar energetic particle events (SEPs) during which strong surface charging and deep dielectric charging are both expected. These two SEP events (from January and March, 2012) have the strongest radiation dose rates observed to date by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument on the Lunar Reconnaissance Orbiter (LRO) spacecraft in orbit about the Moon. By applying well-tested techniques [2] to Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) spacecraft observations during these times, we estimate the potential difference between spacecraft and surface, correcting for the spacecraft potential. We use this value along with a deep dielectric charging model [1] to estimate the subsurface electric field and assess the likelihood that dielectric breakdown occurred.

Background: Lunar surface charging, which occurs due to the surface being exposed to space plasmas and solar photons, has been well studied both from theoretical considerations [*e.g.,* 3] as well as Lunar Prospector (LP) observations [*e.g.,* 4-6]. In the absence of significant secondary electron emission, measurements and theory agree both that the dayside charges to a potential of +5-10 V due to photoemission, and that the nightside, which is dominated by electron thermal currents, charges to a negative potential on the order of the electron temperature.

These studies, however, have only focused on how various processes charge the uppermost layer of the Moon, whereas deep dielectric charging of the regolith has only been considered very recently [1]. During SEP events, deep dielectric charging occurs when the energetic charged particles are deposited in the subsurface. The extremely low conductivity of the lunar regolith, especially on the nightside and in the polar regions, implies that the deposited charges can remain separated for prolonged intervals before dissipating. If the electric field within the insulator, i.e. the regolith, is great enough ($>10^6$ V/m) it will cause the material to ionize leading to electrostatic discharges [7]. A strong electric field of this order measured at the surface during an SEP event may imply that dielectric breakdown is occurring beneath. Laboratory testing suggests that if such dielectric breakdown occurs frequently it could play a significant role in weathering the surface [8].

SEP events: We specifically select the SEP events from 21-28 January 2012 and 5-15 March 2012 for this study as they showed the highest radiation dose rates observed by CRaTER in the 5 years that the instrument has been in operation. Due to the high flux of high energy particles, significant charging of the surface and subsurface may have occured at these times. Each of these events included two or more interplanetary coronal mass ejections (ICMEs) interacting in quick

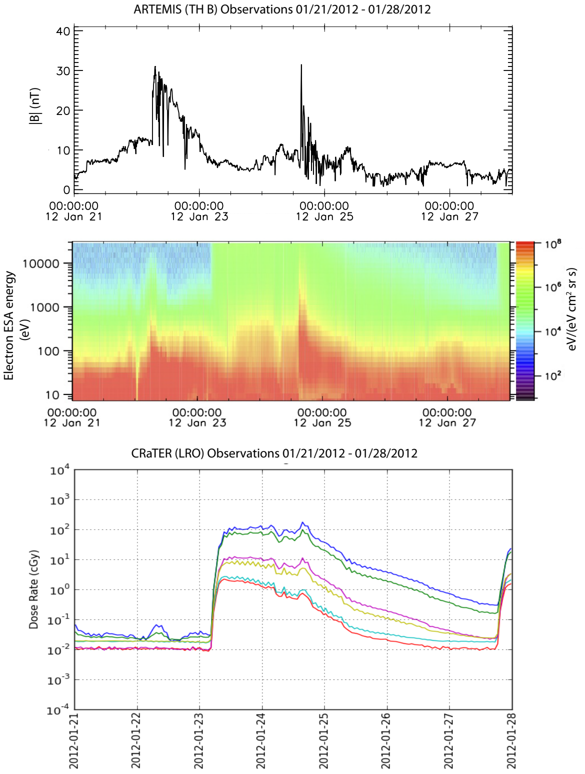

Figure 1. 21-28 January 2012 SEP event. Top: Magnetic field magnitude as measured by the Magnetometer on ARTEMIS-P1. Middle: Electron energy flux spectrogram as measured by the ESA instrument on ARTEMIS-P1. Bottom: SEP dose rates measured by the CRaTER instrument on LRO. The different colored lines show the 6 different CRaTER detectors.

succession. Figure 1 exemplifies the January 2012 SEP event, showing the magnetic field strength and the 5 eV-30 keV electron flux as measured by the P1 spacecraft of ARTEMIS, and the dose rate as measured by CRaTER on LRO. Strong enhancements in both the magnetic field strength and the electron flux are observed due to the ICMEs, and the SEP dose rate is observed to jump nearly 4 orders of magnitude at approximately the same time as the strongest enhancements in the ESA electron fluxes occur. Very similar characteristics are observed during the March 2012 SEP event as well, although the situation is slightly complicated because the Moon is in Earth's magnetotail at the time.

Measuring surface charging: Negative surface charging and the associated potential difference between the surface and the spacecraft, can be measured from two separate effects on the electron distribution if the electrons are magnetically connected to the surface [6]. First, parallel electric fields lead to an energy dependence in the loss cone, *i.e.,* both adiabatic and electrostatic reflection influence the loss cone boundary. By measuring the difference in the size of the loss cone for the different energy ranges, the potential difference can be estimated [9]. Second, space plasmas impacting the surface produce low-energy secondary electrons that are accelerated upwards along magnetic field lines by parallel electric fields. This high-flux, field-aligned beam of electrons has an energy corresponding to the potential difference between the spacecraft and the surface. By detecting such a beam and measuring its energy, the potential difference can be determined. Figure 2 shows a good magnetic connection interval from the January 2012 SEP event. Pitch angle distributions are shown for four energy ranges, exemplifying the presence of energy dependence in the loss cones. We use these observations to estimate the potential difference between the surface and the spacecraft, correcting for charging of the spacecraft itself (the ARTEMIS spacecraft potential is directly measured in sunlight and derived from ion and electron data in shadow).

Discussion: We compare our surface charging measurements with surface charging predictions (based on current balance at the surface due to ambient plasma currents and secondary emission) and the deep dielectric charging model of [1]. We test if the deep dielectric charging predictions correlate with discrepancies between the measurements and surface charging predictions to assess if breakdown could have occurred during these strong SEP events. The results may be used in conjunction with the charging model to predict under what surface electric potential values dielectric breakdown in the subsurface might occur for different conductivity values of the regolith. Combining these results with the frequency of occurrence of strong SEPs [*e.g.,* 10] it will be possible to predict how frequently dielectric breakdown might occur in different regions of the Moon and compare to estimates made by [1].

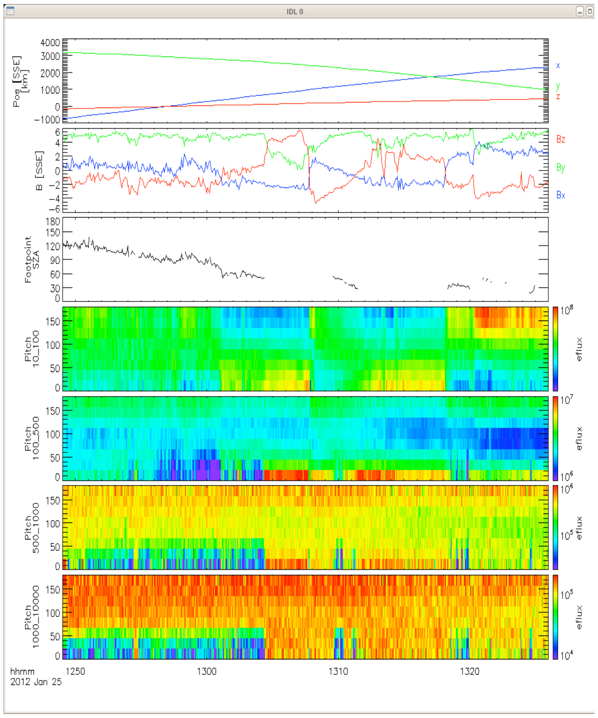

Figure 2. Pitch angle distributions for the January SEP event. Figure shows ARTEMIS spacecraft position and magnetic field vector in selenocentric solar ecliptic coordinates, the magnetic field footpoint solar zenith angle (if magnetically connected to the surface), and pitch angle distributions for several energy ranges (shown in eV).

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