LRO/CRATER DISCOVERIES OF THE LUNAR RADIATION ENVIRONMENT AND LUNAR REGOLITH ALTERATION BY RADIATION

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Introduction: Since the launch of the Lunar Reconnaissance Orbiter (LRO) in 2009, the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) has directly measured the lunar radiation environment [1] and mapped albedo protons (~100 MeV) coming from the Moon [2]. Particle radiation has widespread effects on the lunar regolith ranging from chemical alteration of lunar volatiles [e.g., 3, 4] to the formation of subsurface electric fields with the potential to cause dielectric breakdown that could modify the regolith in permanently shaded craters [5]. *LRO/CRaTER's direct measurements are transforming our understanding of the lunar radiation environment and its effects on the Moon's surface.*

Radically New Radiation Environment Ushers In a New Era of Lunar Exploration: The solar wind is currently exhibiting extremely low densities and magnetic field strengths, representing states that have never been observed during the Space Age. The highly abnormal solar activity between cycles 23 and 24 has caused the longest solar minimum in over 80 years and continues into the unusually small solar maximum of cycle 24. As a result of the remarkably weak solar activity, we have also observed the highest fluxes of galactic cosmic rays in the Space Age, and relatively small solar energetic particle events [1]. The implication of these highly unusual solar conditions for human space exploration is that galactic cosmic ray (GCR) radiation remains a worsening factor that limits mission durations or requires greater shielding. While solar energetic particle (SEP) events in cycle 24 present some hazard, the accumulated doses for astronauts are well below current dose limits (Figure 1). Ironically, during a mission near solar maximum, astronauts would experience relatively low levels of GCR radiation due to heightened modulation and relatively low probabilities of large SEP events. If current trends prevail, *we may be entering an era in which weak solar energetic particle events coupled with reduced levels of galactic cosmic radiation during solar maxima uniquely enable the return of humans to the lunar surface.* This era will likely continue through at least one solar cycle [1] with ~5 year solar maximum windows opening around 2018 and possibly 2029.

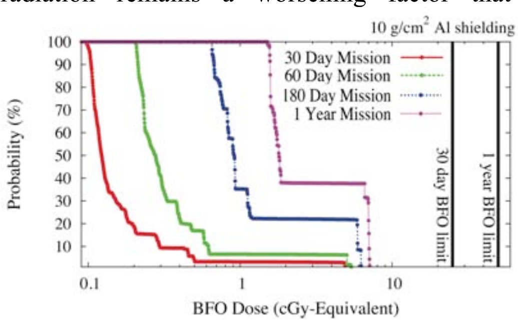

Figure 1. Probability (%) versus integrated Blood Forming Organ (BFO) dose for 30 day to 1-year missions in deep space (e.g., cruise to Mars). *Low SEP probabilities in the next solar maximum may usher in a new era of human exploration*.

Albedo Proton Maps: Lunar albedo protons are produced by nuclear spallation, through GCR bombardment of the lunar regolith. Albedo protons provide a totally new method for mapping compositional variations across the lunar surface (Figure 2). Recent work [6,7] examines the angular (off-nadir) and spatial distribution of albedo protons, and their relationship to regolith composition and volatile content.

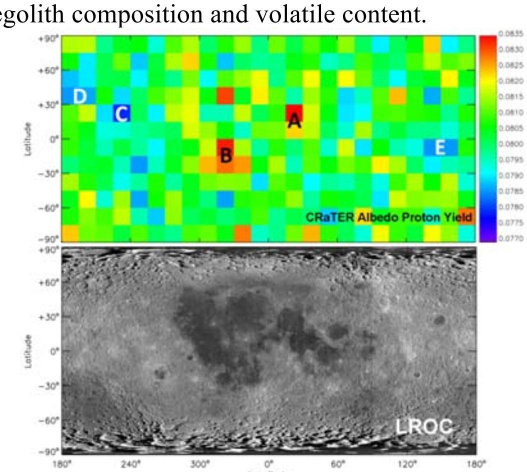

Figure 2. [From 7] *Top*: Lunar albedo proton yield map with anomalous yield regions "A" - "E". Region A is near Mare Serenitatis and B is near SE Oceanus Procellarum. Regions C, D and E are in the highlands. *Bottom*: Visible wavelength global mosaic from the Lunar Reconnaissance Orbiter Camera (LROC).

Lunar Surface Charging and Dielectric Breakdown. Lunar surface charging occurs due to the surface being exposed to space plasma and solar photons [*e.g.* 8-10]. The dayside charges to +5 to +10 V due to photo-emission, whereas the nightside is negatively charged due to the dominance of the electron thermal currents except where significant secondary electron emission occurs. Deep dielectric charging [5] of the regolith is largely due to energetic particles and GCRs depositing charge in the subsurface (to ~1 m for GCRs). The extremely low conductivity of the lunar regolith (particularly in cold regions) can result in the formation of large electric fields to dissipate the accumulated charge. Sufficiently large electric fields lead to electrostatic discharges [5,11], and potentially, modification of regolith [5,12,13], particularly in permanently shaded craters where conductivities are extremely low [5, Figure 3]. Recent work [13,14] focuses on understand modification of the regolith and quantifying surface charging using measured electron distributions measured from ARTEMIS and developing sophisticated charge-layer models that incorporate surface and deep dielectric effects. These models inform a better understanding of the frequency, distribution and effects of discharging on the lunar surface.

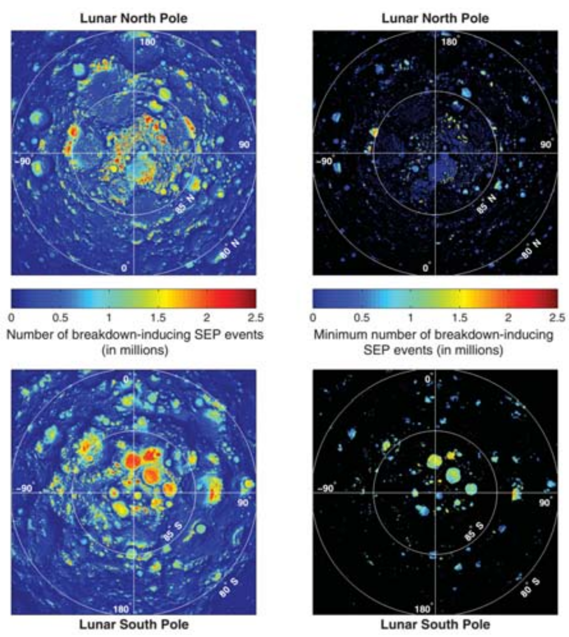

Figure 3. Estimated number of breakdown-inducing SEP events in gardened regolith at poles: (*Left*) based on average temperature at 2 cm depth, and (*Right*) based on annual surface temperature (blackened regions on right have temperature >200K) [From 5].

Understanding the Causes and Effects of SEP Anisotropies at the Moon. Anisotropies during SEP events lead to uneven exposure of lunar regolith to energetic particles. However, the effects of these anisotropies have remained largely unexplored. Recent work uses the temporal oscillations in SEPs from lunar shadowing observed by CRaTER to derive SEP anisotropies and infer exposure variations across the lunar regolith. Figure 4 shows the results of calculations of the energetic particle scattering mean free paths during the Jan 6, 2014 SEP event. This event is consistent with previous observations of small SEP events [e.g. 15], where the anisotropy persists, as opposed to larger events where proton-generated Alfven waves scatter the particles to isotropy. Quantification of SEP anisotropies allows determination of an important source of variability for charging of the regolith.

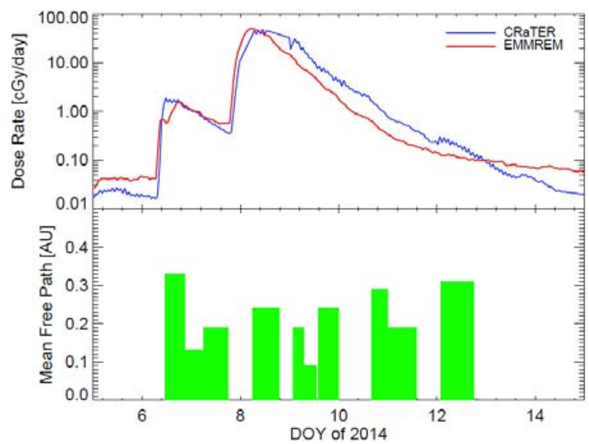

Figure 4. (*Top*) CRaTER observed temporal oscillations due to lunar shadowing of anisotropic SEPs. (*Bottom*) Model calculations provide estimates of the scattering mean free path in these events, revealing the lack of self-excited waves that limit SEP anisotropies.

References: [1] Schwadron et al. (2014) *Space Weather*, *12,* 622. [2] Wilson, J. K. et al. (2012) *JGR, 117*, E00H23. [3] Schwadron et al. (2012) *JGR*, *117,* E00H13. [4] Jordan et al. (2013) *JGR, 118,* 1257. [5] Jordan et al. (2014) *JGR, 119,* 1806. [6] Looper et al. (2014), Fall AGU, SH24A-07 . [7] Wilson et al. (2015) *LPSC*, March. [8] Halekas et al. (2002) *GRL, 29,* 1435; [9] Halekas et al. (2005) *GRL, 32,* L09102; [10] Halekas et al. (2007) *GRL, 34,* L02111; [11] Budenstein et al. (1980), *IEEE Trans. Electr. Insul.*, *EI-15*(3), 225; [12] Campins and Krider (1989) *Science*, *245*, 622; [13] Jordan et al., (2015) *LPSC,* March, [14] Winslow et al. (2015) *LPSC,* March; [15] Reames et al. (2001) *ApJ*, *550*, 1064.