Radiation Dosage From Solar Energetic Particles Around a Lunar Crater

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Introduction: The Moon has a harsh radiation environment that poses significant challenges to future science and exploration activities. Exposure hazards from space radiation are primarily due to galactic cosmic rays (GCRs) and solar energetic particles (SEPs) that are incident at the lunar surface from all directions. The Lunar Reconnaissance Orbiter's (LRO) Cosmic Ray Telescope for Effects of Radiation (CRaTER) instrument has been observing space radiation around the Moon since 2009 [1]. The CRaTER observations show a steady GCR flux with intermittent SEP events that have much higher fluxes. During solar minimum GCRs have a higher flux, while SEP events are less common. On the other hand, during solar maximum the SEP events have a higher rate, but the GCR flux is lower. This is due to variations in solar activity. GCRs have characteristic energies spanning from 1 MeV to 10s of GeV [2]. SEPs, however, have much lower energy ranges of 50 keV to 100s of MeV.

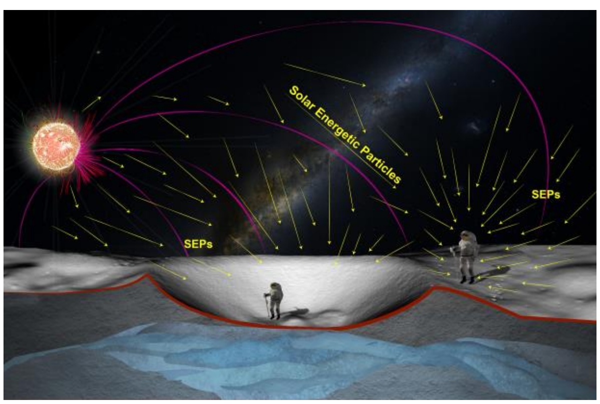

Figure 1: *Illustration of how natural shielding from surrounding terrain effects radiation exposure at the lunar surface in and around a crater during a solar energetic particle (SEP) event. Inside the crater, the high elevation of the crater walls blocks SEPs incident at shallow angles.*

The level of exposure at a given location on the Moon is dependent on the amount of space radiation incident from above the local horizon (Figure 1). This means that radiation dosage depends on the surrounding terrain for any location on the surface, so it can vary substantially from point to point. Here we consider the radiation exposure around simple lunar craters that are representative of the types of landforms that will be encountered by future landed missions (e.g., the Artemis program) [3]. Of particular concern will be radiation exposure to biological targets, such as astronauts, and to critical electronic systems.

Methods: We use Geant4 Monte Carlo simulations [4] to compute the dose response for spherical targets composed of water (H_2O) and silicon (Si), as proxies for biological and electronic systems, respectively. These targets are surrounded by shells of aluminum of varying thickness to approximate the effects of shielding by space suits, rovers, and habitats. To determine the dose from SEP protons (e.g., in rads), we convolve the Geant4-computed dose responses with the fluence spectrum (integrated flux) for the infamous October 1989 SEP event [5]. This is widely regarded as the best event to use for predicting the worst case dose.

To determine the topographical effects, we created a 20 km diameter simple crater, similar to Shackleton Crater at the lunar South Pole. This provides a good proxy for the location of Artemis Base Camp 004, which is planned to be near the rim of Shackleton Crater. Measuring the local horizon for each location on a grid, we calculate the solid angle of the visible sky. This fraction can be multiplied by the dose computed from the Geant4 dose responses convolved with SEP spectrum. This gives the radiation dose received from SEP protons at each surface point.

Discussion and Conclusions: Radiation doses from sporadic, short-lived SEP events can be substantially larger than doses from the steady GCR background, thus resulting in acute radiation exposure. During the most extreme SEP events, such as those in October 1989 or August 1972, the radiation dosage at the lunar surface would be greater than the NASA astronaut 30-day radiation exposure limit [5]. However, such exposure can be significantly reduced by shielding from surrounding terrain. Therefore, for protection from SEP events, the shielding effects of surrounding terrain is an important consideration when selecting sites for permanent habitats, as well as for choosing routes and contingency planning during surface operations.

References: [1] Schwadron, N. A., et al. (2018) *Space Weather*, *16*, 289–303. [2] Case, A. W., et al. (2013), *Space Weather*, 11, 361– 368. [3] NASA's Lunar Exploration Program Overview (Sept 2020) NP-2020-05-2853-HQ. [4] Allison, J., et al. (2006) IEEE Trans. Nucl. Sci., 53 (1), 270–278. [5] Townsend, L.W. et al (2018) Life Sciences in Space Research, 17, 32-29