PARTICLE RADIATION ENVIRONMENTS AND THEIR EFFECTS AT PLANETARY SURFACES: LESSONS LEARNED AT THE MOON BY LRO/CRATER AND EXTENTION TO OTHER PLANETARY OBJECTS.

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Introduction: We examine the energetic particle ionizing radiation environments and their effects at airless planetary surfaces throughout the solar system. Energetic charged particles fill interplanetary space and bathe the environments of planetary objects with a ceaseless source of sometimes powerful but always ever-present ionizing radiation. In turn, these charged particles interact with planetary bodies in various ways, depending upon the properties of the body as well as upon the nature of the charged particles themselves.

Energetic Particle - Planetary Surface Interactions: We focus on the interaction of energetic particles with the surfaces of planets that are surounded by extremely tenuous atmospheres and weak intrinsic planetary-scale magnetic fields. For this study, we define energetic charged particles as those with sufficient energy to penetrate significantly (at least 100 millimeters and up to several meters) into the planet's regolith. For the most part, we consider protons and electrons as they are present in the greatest quantity and are principally important for the various physical mechanisms we consider; in some limited cases we introduce the importance of light and heavy ions, but typically only qualitatively. For practical purposes, the energetic particles of interest herein are those with energies greater than ~1 MeV. The depth of penetration of such charged particles depend on their incident energy. At sufficiently high energies (>500 MeV protons, for instance), this population not only penetrates substantially into a planet's regolith in an energy-dependent manner, but they also lose energy through nuclear interactions, in turn producing secondary nuclear by-products, including neu-trons.

Energetic Particle Sources – GCR and SEP: Such highly energetic charged particles have two primary sources near planetary bodies – galactic cosmic rays (GCR) and solar energetic particles (SEP). GCR provide an incessant source of extremely energetic particles, emanating from outside our solar system and produced in asso-ciation with processes occurring at supernova explosions throughout our galaxy. This source of energetic charged particles waxes and wanes slowly (over the ~11 year solar cycle) and comparatively weakly (well less than a factor of 10) both in space and time throughout the solar system. GCR intensities are largest near the edge of the solar system; the interplanetary magnetic fields and solar wind pose obstacles for GCR entry to the inner solar system which thus creates a radial gradient. Near any planetary body, the intensity of the galactic cosmic rays are further moderated by both any intrinsic planetary magnetic fields and the presence of an atmosphere. GCRs are dominated by protons, though from a radiation effects perspective, the lighter and heavier ions remain important despite their comparatively small numbers because or their capacity to inflict greater biological damage in human interactions. Their contributions to dose and dose rate risks to human explorers are well documented. However, for the processes we consider at planetary surfaces, we restrict our quantitative analysis to GCR protons.

Energetic charged particles are also produced episodically in association with explosive events on the Sun. Particles are accelerated through the strong electric fields in association with the shock waves produced near the Sun and also further from the Sun as coronal mass ejections (CMEs) are launched from magnetically unstable regions in the solar corona. These impulsive bursts of energetic charged particles, called solar energetic particles (SEP), stream outward from the Sun, producing many order of magnitude increases in high energy particle fluxes, lasting hours to days. SEPs race away from the Sun through interplanetary space, with the chance of encountering and interacting with planetary objects in their path. SEP intensities are strongest closest to the Sun, and fall off in intensity with distance from the Sun as the particle trajectories diverge to fill the increasing volume of interplanetary space. As with GCR, we focus on protons when we include the effects of positively charged particles. In the case of SEPs, we also must consider the role of electrons, as they are important to understanding the differential charging environment of the regolith with depth on such short timescales.

Energetic charged particles can also become efficiently trapped around planetary bodies that possess strong intrinsic magnetic fields. For example, in the case of Earth, charged particles can become trapped in Earth's strong dipole field relatively close to the planet. The component of trapped particles that also have extremely high energies is what we term the Van Allen radiation belts. Other planets with strong intrinsic magnetic fields (e.g., Jupiter and the other gas giants) also have powerful radiation belts. The distance to which particles can remain trapped is a function of the strength of the planet's dipole moment and the strength of the solar wind flow pres-sure upstream of the object. In Earth's case, this trapping boundary extends outward to approximately geostationary orbit (~6.6 Earth radii, or, ~1/10th of the way to Moon's orbit). Trapped radiation belt particles vary dynamically, posing a final source of ionizing radiation for the planetary bodies they surround, both for the planet itself as well as for any moons embedded within it. Though this population represents a third interesting source of energetic particles for the moon's of the gas giants, it is beyond the scope of this work. Finally, we do not consider lower energy charged particles, also known to be important for some interactions with planetary surfaces, such as from the solar wind or from magnetospheric plasmas surrounding some of these objects; those particles and their interactions are also explicitly beyond the scope of this paper and have been explored extensively by others.

Science Goal and Approach: Our focused goal is to provide a comparison of how GCR and SEP intensities vary throughout the solar system, and how they interact directly with the surfaces of similar atmospherless planetary objects that are not shielded by intrinsic magnetic fields. In this study, we use Earth's Moon as the most well-studied object for such effects, enabled by the extensive radiation mesurements obtained by NASA's Lunar Reconnaissance Orbiter (LRO).

Lessons Learned from LRO/CRaTER: The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) [1] has been immersed in the radiation environment of the Moon since its launch on NASA's Lunar Reconnaissance Orbit-er (LRO) [2] in June 2009. CRaTER measures the linear energy transfer (LET) of extremely energetic particles traversing the instrument, a quantity that describes the rate at which particles lose kinetic energy as they pass through matter. A significant portion of the kinetic energy converts into deleterious ionizing radiation through interactions with matter, thus posing a radiation risk for human and robotic space explorers subjected to deep space energetic particles. CRaTER employs strategically placed solid-state detectors and tissue equivalent plastic (TEP), a synthetic analog for human tissue, to quantify radiation effects pertinent to astronaut safety.

Though designed to measure principally galactic cosmic rays and solar energetic particles coming from zenith and deep space, CRaTER observations can and have been used also to discover an energetic proton albedo coming from the lunar surface [3,4,5]. Ultimately, CRaTER observations have been used to directly measure the collective radiation environment, including all sources. From these primary data, the effects of the particles on the Moon have been explored quantitatively. These include various physical mechanisms, such as the chemical weathering [6,7] of the lunar volatiles in the regolith, as well as the effects of deep dielectric breakdown [8], just to name two.

Summary: We summarize the physics of GCR and SEP interactions with the Moon and how these processes depend also on the physical properties of the lunar surface (e.g., bulk composition, meteoritic gardening rates, temperature, etc.). Based on this core knowledge, we then quantify how these same processes operate at similar objects throughout the solar system, including at Mercury, in the Mars system, at Ceres as a core asteroid belt representative, and at the Pluto system.

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