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A calculation of the radiation environment on the Martian surface

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ABSTRACT

In this work, the radiation environment on the Martian surface, as produced by galactic cosmic radiation incident on the atmosphere, is modeled using the Monte Carlo radiation transport code, High Energy Transport Code—Human Exploration and Development in Space (HETC–HEDS). This work is performed in participation of the 2016 Mars Space Radiation Modeling Workshop held in Boulder, CO, and is part of a larger collaborative effort to study the radiation environment on the surface of Mars. Calculated fluxes for neutrons, protons, deuterons, tritons, helions, alpha particles, and heavier ions up to Fe are compared with measurements taken by Radiation Assessment Detector (RAD) instrument aboard the Mars Science Laboratory over a period of 2 months. The degree of agreement between measured and calculated surface flux values over the limited energy range of the measurements is found to vary significantly depending on the particle species or group. However, in many cases the fluxes predicted by HETC–HEDS fall well within the experimental uncertainty. The calculated results for alpha particles and the heavy ion groups $Z = 3–5$, $Z = 6–8$, $Z = 9–13$ and $Z > 24$ are in the best agreement, each with an average relative difference from measured data of less than 40%. Predictions for neutrons, protons, deuterons, tritons, Helium-3, and the heavy ion group $Z = 14–24$ have differences from the measurements, in some cases, greater than 50%. Future updates to the secondary light particle production methods in the nuclear model within HETC–HEDS are expected to improve light ion flux predictions.

1. Introduction

Understanding the radiation environment, and the associated biological risk, on the Martian surface is an important milestone in mankind's efforts to send humans to the Red Planet. While radiation sources on the Martian surface, as on Earth, include both terrestrial and extraterrestrial components, the thin Martian atmosphere causes its extraterrestrial component to dominate. The two extraterrestrial radiation sources in the Martian environment are solar energetic particles (SEPs) and galactic cosmic radiation (GCR). The SEP-induced contributions to the surface radiation environment are the result of transients in space weather and are irregular and infrequent. Thus, they are not considered in this work. The free-field GCR-induced radiation environment on the Martian surface, as experienced by the Mars Science Laboratory (MSL) Rover, is predicted using the High Energy Transport Code—Human Exploration and Development of Space (HETC–HEDS). Calculated charged particle and neutron fluxes are compared to measurements taken by the RAD instrument aboard MSL.

1.1. Galactic cosmic radiation

The term galactic cosmic radiation refers to charged particles that originate outside the Heliosphere, and are speculated to be the products of stellar supernovae throughout the galaxy. Although it is composed of roughly 89% protons and 9% alpha particles as shown in Fig. 1, the GCR spectrum includes all naturally occurring elements. The GCR flux is relatively constant, varying mainly at lower energies only as a function of the eleven-year solar cycle. When the fully ionized galactic cosmic rays enter an atmosphere, they are slowed by atomic interactions. However, occasional high-energy nuclear collisions produce showers of lighter secondary and tertiary particles, many of which survive to the surface. Both the particles incident on the outer atmosphere and their secondaries may undergo further nuclear collisions in the regolith, producing more fragments that contribute to the surface flux.

1.2. HETC–HEDS

This radiation transport code is developed specifically for space applications and is the product of a collaborative effort between Oak Ridge National Laboratory and the University of Tennessee (Charara et al., 2008). HETC–HEDS uses Monte Carlo methods to simulate charged particle transport through matter. The particle species considered for transport include heavy ions, protons, neutrons, pions, and

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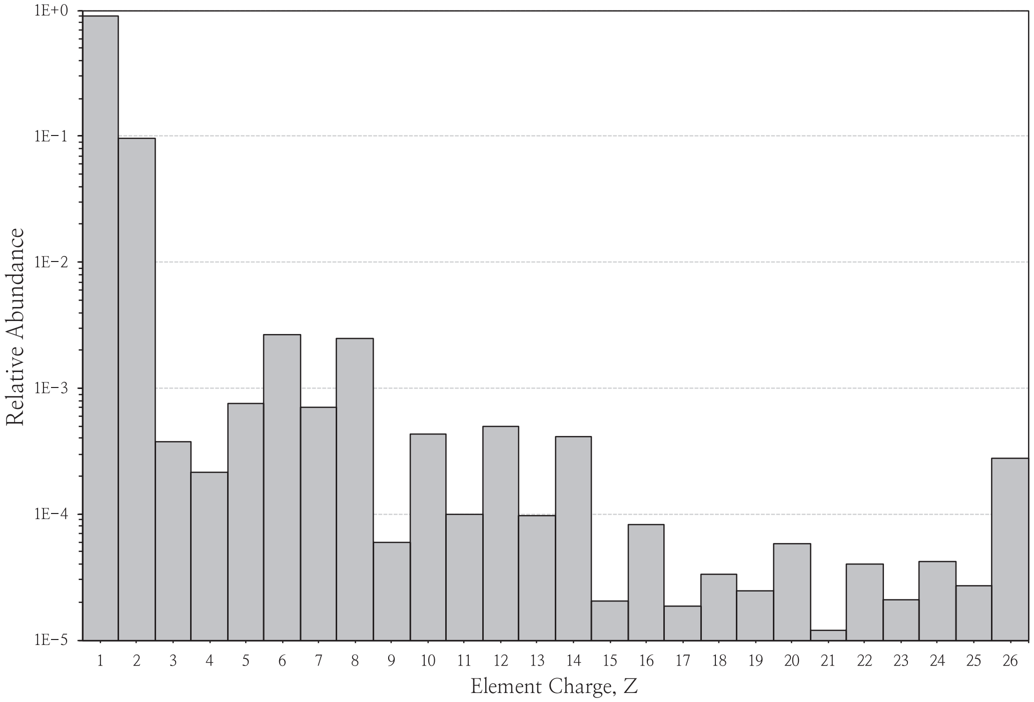

Fig. 1. GCR composition. The relative abundance of each element in the GCR spectrum for energies above 10 MeV/A.

mesons (Miller and Townsend, 2005). The source code is written in the FORTRAN computer programming language. The nuclear model used by the code to handle nuclear fragmentation is a modified form of NUCFRG2 code (Miller and Townsend, 2005; Wilson et al., 1986), and (Wilson et al., 1994). The overly simplistic light ion production model in the NUCFRG2 code has since been updated in NUCFRG3 (Adamczyk et al., 2012), which will be incorporated into HETC–HEDS in future work. More details of the nuclear model in HETC–HEDS are provided by Miller (2004), Miller and Townsend (2004a), Miller and Townsend (2004b) and Miller and Townsend (2005).

2. Method

Contributions to the surface flux from each incident ion species of the GCR spectrum are calculated independently to optimize computation resources while still ensuring convergent statistics for each species. One million source particles are sampled for each incident GCR species. The boundary conditions used to sample source particles during transport are normalizations of the GCR flux for the ion in question. The resulting tallies from each incident ion are then combined according to their relative abundances (see Fig. 1), and renormalized to match the total average GCR flux for the time frame being evaluated, 1.49×10^5 particles/(cm^2-day). All particles, including all secondaries produced, are tracked until they either escaped the volume of interest, or slowed to a transport cutoff energy of 1.0 MeV/A.

2.1. Source spectra

The GCR fluxes used in this study are provided by the model developed at DLR, the German Aerospace Center (Matthiä et al., 2013). The time frame studied covers the dates of November 15, 2015 through January 15, 2016. The differential spectra from the GCR model are integrated over their respective energy regimes to obtain total average flux for each incident energy bin, then normalized to form the distribution of weights used for the transport boundary condition. Incident ion energies considered range between 10 MeV/A and 1 TeV/A in 167 bins. Charged particles with incident kinetic energy less than 10 MeV/A are not likely to contribute significantly to the surface flux. Thus, these low energy particles are excluded from the transport calculation source term to maximize calculation efficiency, and the total GCR fluxes used for output renormalization are corrected accordingly.

2.2. Geometry

The geometric construction of the transport model is designed to be physically representative of the conditions experienced by an incident GCR particle in the Martian environment, with the assumptions of charged particle equilibrium and negligible energy loss through a thin silicon detector layer. The geometry consists of a 1 km radius cylindrical volume composed of five vertically stacked layers as illustrated in Fig. 2. The radius is chosen to be large enough that escape from the volume of interest via the outer surface of the cylinder is minimized. This effectively mimics a one-dimensional transport model, thus allowing for the assumption of charged particle equilibrium. Source particles are placed at the top of the uppermost layer at the center point of the disk. Source particle initial direction is sampled from an isotropic distribution in the downward hemisphere. The first, and uppermost, layer represents everything between free space and a point 5 m above the surface at an elevation of 4431 m below mean altitude (Matthiä et al., 2016). The first layer is 10 m thick, and is given a density such that the entire layer corresponds to 23 g/cm^2 of material. The second and fourth layers share a density of 2×10^{-5} g/cm^3 (Williams, 2016). Together they span a height of 5 m and represent the surface atmosphere conditions. The third layer bisects the second and fourth layers. It is a thin layer of silicon, representing Detector A on the RAD instrument (Matthiä et al., 2016). This detector layer is 300 μm thick and is positioned between the two layers representing the surface atmosphere at a height of 1 m above the regolith layer. The silicon layer is assumed to be sufficiently thin such that it negligibly influences the free field fluxes. It is included in the model to provide the ability to model energy deposition in detector A for detector response purposes. Although detector response is not modeled or considered in this study, the silicon layer is still included so that the generated run tapes can be analyzed for this purpose in the future. The fifth, and bottom, layer is 3 m thick and represents the Martian regolith. This thickness allows ample material for the production of secondary particles, while mitigating the loss of calculation efficiency from particles that are both created and stopped within the regolith.