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The simulation of radiation effects to astronauts due to solar energetic particles in deep space

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ABSTRACT

The exposure to interplanetary radiation poses a serious health risk to astronauts, especially for long-term missions. Protecting the astronauts from these particles has been the key issue to the manned space mission. High-energy space particles can penetrate the protective layer of a spacecraft, and probably cause deleterious effects to the astronauts. To estimate the size of these effects, a credible simulation of radio-protection is required. Using the Geant4 software toolkit, we have modeled the interaction processes and predicted the total energy deposit in a phantom (astronaut) as well as the similar information associated with secondary effects, due to Solar Energetic Particles (SEPs) at ~1 AU caused by the large SEPs events in October 1989 and August 1972. In addition, we compared the characteristics of the energy deposit due to SEPs and Galactic Cosmic Rays (GCRs) and explained the differences between them by physical mechanism analysis.

1. Introduction

The harsh conditions considered in the space environments include energetic particle radiation, plasmas, absence of air (especially in human spaceflights), debris, all of which pose severe challenges for astronauts and precision payloads. The space radiation environment is distinct from others and it cannot be produced up to date such experimental conditions on the ground due to the high energy of these space particles. The radiation environment, consisting of trapped radiation belts, galactic cosmic rays, and solar energetic particles, leads to effects such as radiation damage, single-event upsets in electronics, background in detectors, and health hazards to astronauts in human spaceflights. In interplanetary space, the radiation environment is of two sources: the galactic cosmic rays originating from outside of the solar system and the solar energetic particles associated with the acceleration of coronal mass ejection (CME) [1] and possible acceleration in the solar surface due to a large disturbance [2]. The CREME detector on Concorde detected the event of 29 September 1989 and also four periods of enhancement during the events of 19–24 October 1989. The results show that instantaneous rates were enhanced by up to a factor of ten compared with quiet-time cosmic rays, while flight-averages were enhanced by up to a factor of six [3].

The spacecraft is subjected to the radiation effects caused by GCRs, and SEPs can give this harmful circumstance with significant enhancements. The trend towards more deep space missions means the assessment of radiation effects on delicate equipments and the influence of shielding must be accurate. And in particular, the high energy radiation on human body due to these particles can induce potentially lethal effects [4]. However, both the prediction and calculation of these influences are difficult because of the wide range of energies and particle species involved (including large numbers of secondary effects generated by interactions). Detailed computer codes of radiation transport, which simulate the detailed physical interaction processes of particles as they pass through matter, are generally required.

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Development of such codes started largely in support of early nuclear programs, but today's generation of these codes can treat a wide range of particle species and interaction processes applicable to the space environment. The most recent addition to the list of such codes is Geant4, which has been designed from the outset as an integrated toolkit to provide comprehensive, fully three-dimensional treatment of the wide range of physical processes in high energy physics (HEP) [5]. With advances in computer and network technologies, research scientists are developing some useful tools, such as MULASSIS [5], SHIELDOSE [6], and HZETRN [7], to analyze the effects of radiation shielding on humans.

One of the key physical parameters quantifying the ionization effects of radiation on both materials and the human body is the energy deposition. In an earlier work, we estimated the total energy deposit due to GCR protons and helium nuclei in a phantom (astronaut) in a vehicle concept model and also evaluated the energy deposit given by secondary effects in these radiation conditions [8]. We present in this paper the evaluations of the total energy deposit in a phantom as well as the energy associated with secondary effects due to solar event protons and helium nuclei at $\sim$1 AU. Consulting the work developed by S. Guatelli and M.G. Pia [9], a specific vehicle model has been used, modified to reflect the current trend in space engineering in China. The physics model we adopted is based on our previous work [10,11] and the LISA charging work [12]. In the following sections, we will describe in detail the geometry, materials, incident flux and physics processes that are used in the model. The characteristics of simulation results are presented in Section 2. In the final section, some discussions and prospect of this kind of research are given.

2. Radioprotection simulation models

2.1. Incident flux models

The interplanetary ionizing radiation environment is mainly of two populations of particles, namely GCRs and SEPs. This work focuses on the evaluations of energy deposit in an astronaut model by the SEPs in deep space environments.

The solar wind, which blows at speeds of 300–800 km/s, corresponds to proton energies of 0.5–3 keV. The protons in solar energetic particle events can have energy spectra that span the region from about 10 keV to $>$10 GeV. In large SEPs events, omni-directional fluencies of $>$30 MeV protons can exceed 10^{10} /cm^2 at $\sim$1 AU; protons of this energy can penetrate spacecraft walls and astronaut space suits giving rise to damage. The events can have rapid onsets and durations from several hours to several days. Although protons are the dominant particle species in SEPs events, there are also ions of elements throughout the periodic table [13].

In this work, the fluxes of the two most abundant SEPs primaries, protons and helium nuclei, generated by CREME96 for near-Earth interplanetary locations, have been adopted. These SEPs fluxes are predicted at about 1 AU, which correspond the envelope of October 1989 and August 1972 solar particle events spectra (CREME96) [9], shown in Fig. 1.

2.2. Physical models

The main mechanism that allows an energetic particle to deposit energy as it passes through matter is ionization. The physics processes used in our simulation are broadly divided into electromagnetic (EM) and hadronic interactions. As a result of their high energy and hadronic nature, these interactions bring forth complex nuclear reactions, which have large final-state multiplicities, producing a plethora of secondaries. To avoid infrared divergence, some electromagnetic processes require a threshold below which no secondary will be generated. As a result of this requirement, the production threshold of 1 mm distance is defined in our physics model for gammas, electrons and positrons [10–12,14].

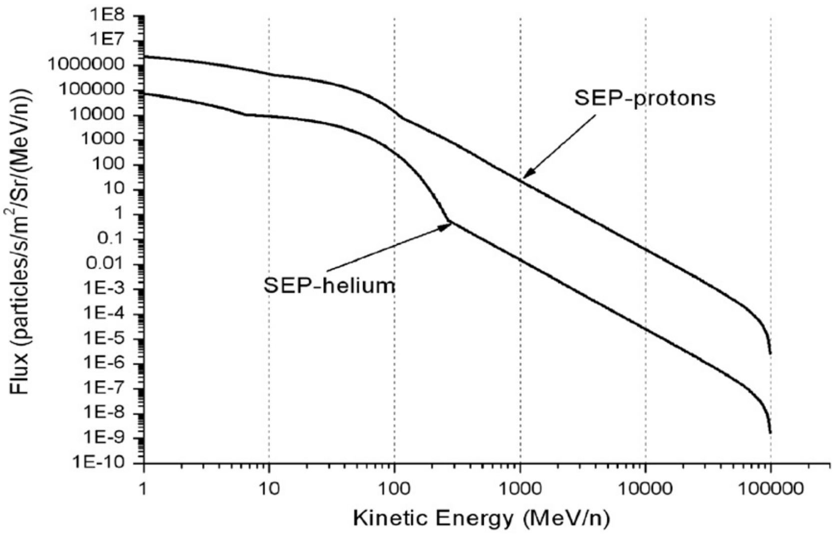

Fig. 1. Differential energy spectra for SEP protons and helium nuclei at 1 AU.