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Galactic cosmic ray simulation at the NASA Space Radiation Laboratory

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ABSTRACT

Most accelerator-based space radiation experiments have been performed with single ion beams at fixed energies. However, the space radiation environment consists of a wide variety of ion species with a continuous range of energies. Due to recent developments in beam switching technology implemented

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at the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL), it is now possible to rapidly switch ion species and energies, allowing for the possibility to more realistically simulate the actual radiation environment found in space. The present paper discusses a variety of issues related to implementation of galactic cosmic ray (GCR) simulation at NSRL, especially for experiments in radiobiology. Advantages and disadvantages of different approaches to developing a GCR simulator are presented. In addition, issues common to both GCR simulation and single beam experiments are compared to issues unique to GCR simulation studies. A set of conclusions is presented as well as a discussion of the technical implementation of GCR simulation.

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1. Introduction

The health effects of space radiation on astronauts represent a major limiting factor for long-duration human space missions beyond Low Earth Orbit (LEO) (Durante, 2014). Beyond LEO, the most important sources of space radiation consist of galactic cosmic rays and Solar Particle Events (SPE). GCR nuclei of average energy can penetrate a substantial thickness of materials, on the order of 10s to 100s of centimeters of water or aluminum. If a nuclear interaction between a primary GCR ion and a target nucleus occurs, the lighter secondary products will lose energy at a lower rate, and therefore will be able to penetrate even further. For this reason, it is not possible to provide sufficient shielding material to fully absorb all types of radiation in space. In addition, the relative biological effectiveness of nuclei will change as a function of depth of penetration, because the composition and energy of the nuclei changes due to atomic and nuclear interactions. The Linear Energy Transfer (LET) of each nucleus also changes as it loses energy and slows down inside the material being penetrated.

The major GCR particle types include hydrogen (H), helium (He), carbon (C), oxygen (O), neon (Ne), silicon (Si), calcium (Ca), and iron (Fe). The energy spectra of all GCR particles are very broad with the region extending from approximately 10 MeV/n to 50 GeV/n being of primary importance to space applications (Grahn, 1973; Slaba and Blattnig, 2014; Durante and Cucinotta, 2011). GCR exposures occur at low fluence rate, with each cell in an astronaut's body being "traversed by a proton about every three days, helium nuclei once every few weeks, and high atomic number (Z) and energy (HZE) nuclei about once every few months" (NASA, 2015a). The cells are not traversed at random and the traversals are not statistically independent. The traversal of a cell nucleus usually correlates with the simultaneous traversal of very large numbers of additional cell nuclei (on the order of 10^9) in the tissue along the track of the same particle. These fluence rates correspond to tissue doses or effective dose-rates of about 0.3–0.6 mGy/day and 1–1.8 mSv/day, respectively. However, the use of absorbed dose (or dose-rate) is misleading, because the energy lost by each incident particle is deposited in a highly non-uniform way, both physically and temporally. Dose-rate effects may best be understood in terms of particle fluence rate (commonly referred to as particle flux); any such effects will be dependent on the endpoint considered, and the time constants of the chemical kinetics involved.

SPEs consist primarily of protons and, much like GCR, have a broad energy spectrum with the energy region of most importance to human space flight extending out to a few hundred MeV. The SPE spectra include much smaller components of helium and heavy nuclei. The shapes of the energy spectra, as well as the total fluence, vary considerably from event to event. Over the course of an SPE, dose-rates can fluctuate between 0–100 mGy/hr inside the protection of a vehicle. SPE dose-rates can also differ by several-fold between tissue sites because of the variable energy spectra of the protons or other nuclei. Similar to the case for GCR, the use of dose or dose-rate to characterize protons in space can be misleading from a biological point of view, except in cases where the proton fluence is high enough to ensure that the target organism has been irradiated uniformly. Note, however, that statements concerning dose and dose-rate for SPE are also dependent on the space vehicle or space habitat analyzed and the SPE spectrum chosen. There are large variations across both of those variables.

Energy deposition in biomolecules, cells, and tissues is distinct when comparing protons and HZE nuclei to common forms of terrestrial radiation. For the particles comprising space radiation, energy deposition is highly localized along the trajectory of each particle with lateral transport of energetic electrons (delta-rays) away from the nuclei's path. The rate of energy deposition per unit length of a particle trajectory is described as LET. The unit generally used in radiobiology for LET is the kilo-electron volt per micrometer, or keV/μm. The LET of charged particles changes as a function of particle velocity, β, or kinetic energy, and its charge, Z, approximately in proportion to Z^2/β^2. As the velocity (or energy) of a particle increases, the LET decreases to a minimum near a velocity of approximately 90% of the speed of light; at higher energies the LET increases very slowly due to relativistic effects. High-energy charged particles lose energy when they traverse any material. As they slow down, the LET increases to a maximum and then very rapidly decreases to zero. The low-energy maximum in the LET occurs very close to the point where the charged particle loses its remaining energy and stops. Nuclear fragmentation and other nuclear interactions, including projectile fragmentation of the primary ion and target fragmentation of tissue constituents, occur as ions traverse tissue. For proton and HZE nuclei irradiation, target fragmentation, including secondary neutron production, introduces an additional high LET component into the radiation field.

Space radiation risks of concern to NASA are carcinogenesis (increased risk to fatal cancers), acute (in-flight) and late (i.e. after a mission) risks to the central nervous system (CNS), degenerative tissue risks such as cardiovascular disease, and acute radiation syndromes. For cancer and acute risk estimates, human epidemiology data with gamma-ray and X-ray exposures play a key role in risk estimation models. Acute risks are a concern for SPE, while cancer, CNS, and cardiovascular risks, etc., are a concern for both GCR and SPE. The current model of cancer risks used by NASA, NSCR 2012 (Cucinotta et al., 2013) scales cancer incidence or mortality rates estimated from epidemiology data to the effects for the low dose-rates and radiation types in space using a dose- and dose-rate effectiveness factor (DDREF) and radiation quality factor, respectively. There are large uncertainties in this model, which, in order of decreasing importance are as follows: the radiation quality factors, dose and dose-rate dependencies, the transfer of risk across populations, the determination of space radiation organ exposures, and the various errors in human data sources. In addition, there are uncertainties related to the underlying assumptions of the model due to possible qualitative differences between high- and low-LET radiations, the validity of the assumptions of linearity and additivity of effects for different radiation components, and the possible synergistic risks from other flight factors on radiation risks. Because solar protons are largely low LET, and the proton