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Heavy ion contributions to organ dose equivalent for the 1977 galactic cosmic ray spectrum

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Abstract

Estimates of organ dose equivalents for the skin, eye lens, blood forming organs, central nervous system, and heart of female astronauts from exposures to the 1977 solar minimum galactic cosmic radiation spectrum for various shielding geometries involving simple spheres and locations within the Space Transportation System (space shuttle) and the International Space Station (ISS) are made using the HZETRN 2010 space radiation transport code. The dose equivalent contributions are broken down by charge groups in order to better understand the sources of the exposures to these organs. For thin shields, contributions from ions heavier than alpha particles comprise at least half of the organ dose equivalent. For thick shields, such as the ISS locations, heavy ions contribute less than 30% and in some cases less than 10% of the organ dose equivalent. Secondary neutron production contributions in thick shields also tend to be as large, or larger, than the heavy ion contributions to the organ dose equivalents.
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1. Introduction

Some of the most significant issues concerning astronaut safety in space relate to the effects of space radiation on human crews. This means that future exploratory human missions will have crews spending more time in space, outside the protection afforded by the Earth's magnetosphere, resulting in much higher exposures to space radiation. In turn, this requires more accurate predictions of exposure risks, which will require a better understanding of the various factors that influence these risks. One of the ever present radiation environments in space are galactic cosmic rays (GCR). GCR particles originate outside of our solar system and cover the naturally occurring elements up to uranium. Their spectra in the heliosphere are modulated by solar activity, with the more intense spectra associated with periods of minimum solar activity during the approximate 11 years solar cycle. Because of a sharp decline in spectral abundance for ions heavier than iron, only elements up to nickel ($Z = 28$) are of much concern.

Health effects from GCR particles are primarily due to chronic exposures to them. GCR radiation doses, even during periods of maximum GCR intensity, are well below levels of concern for acute radiation syndrome effects. The main concern, as pointed out in a recent comprehensive review of radiation protection in space (Durante and Cucinotta, 2011) is late effects including an increased risk of carcinogenesis, central nervous system (CNS) damage, and cardiovascular damage. The complex GCR environment consists of protons, alpha particles and heavier ions, as well as their interaction products, including secondary neutrons. These particles range in energy up to several TeV/nucleon and have varying biological effectiveness in damaging tissue. To account for differences in response

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by various tissues, a radiation protection quantity of interest is effective dose E, given by

$$E = \sum_T w_T H_T, \qquad (1)$$

where w_T is a tissue weighting factor, which accounts for the total detriment to the body from exposures to a particular tissue T (organ), and H_T is the organ dose equivalent, which for space radiations, is given by (ICRU, 1993)

$$H_T = \frac{1}{m}\int_0^m dm \int L dL\, Q(L)\phi_T(L), \qquad (2)$$

where m is the organ mass, L is the linear energy transfer (LET) or stopping power, ϕ_T is the particle fluence through the organ, and Q is the quality factor which relates the absorbed dose to the biological effectiveness of the particles producing the dose (ICRP, 1991).

Studies of risks to astronauts from space radiations are numerous. Many of them present calculated or measured total exposures in dose, organ dose equivalent, or effective dose behind various simple shields of uniform areal densities (Cucinotta et al., 2010; Simonsen et al., 1990; Lin et al., 2009; Townsend et al., 1992) or more complicated, realistic shielding geometries (Wilson et al., 1995; Simonsen et al., 1991; Townsend et al., 2011; Wilson et al., 2007). Other studies break out contributions by ion species or groupings (Cucinotta et al., 2010; Townsend et al., 1992; Shinn et al., 1994; Townsend et al., 1994; Wilson, 2000), but for simple shield geometries. Major findings from these latter studies include the substantial contributions to risk from the so-called HZE (High charge (Z) and Energy) components, which have significant biological risk uncertainties; Durante and Cucinotta quote the uncertainties as being 4 times the point values at a 95% confidence level (Durante and Cucinotta, 2011). In this work, earlier studies are extended by estimating organ dose equivalent contributions, by ion groupings, from exposures to a GCR solar minimum environment for various shielding geometries, including distributions involving simple spheres, locations within the Space Transportation System (STS; space shuttle) and the International Space Station (ISS). The motivation is to investigate the contributions by ion groups to organ dose equivalent for shielding provided by realistic spacecraft structures. Dose equivalent to organs contributes to computed effective dose values.

2. Computational methods

As GCR ions pass through a material, the ions interact with the media, deposit energy, and fragment into lighter particles. For the present study, focus is on organ dose equivalent estimates for several major organs. While organ dose equivalent itself is one measure of the total radiation risk and also contributes to effective dose, it is important to know the distribution of particles contributing to the organ dose equivalent, since biological risks and their related uncertainties are different for different types of particles. Hence, in this work, the contributions to the organ dose equivalents, from incident ions and their interaction products (secondaries), are presented for several charge groups based on their atomic numbers (Z). These charge groups are $Z = 0$ (neutrons), $Z = 1$ (protons), $Z = 2$ (helium), $3 \leqslant Z \leqslant 10$, $11 \leqslant Z \leqslant 20$, and $21 \leqslant Z \leqslant 28$. Anything with an atomic number greater than two is considered to be a heavy ion.

The shielding geometries studied consisted of aluminum spheres of three different thicknesses, and various locations in the STS and in the International Space Station (ISS). The STS and ISS models were aluminum equivalent models; that is, the actual materials used in these models were replaced by an equivalent mass of aluminum.

These computations used the 1977 GCR solar minimum spectrum based on the Badhwar–O'Neill model (O'Neill, 2010) for the incident space radiation environment. It was assumed that the environment isotropically impacted each vehicle. The human geometry models used were the Computerized Anatomic Female (CAF) model (Yucker and Huston, 1990; Yucker and Reck, 1992) and the Female Adult voXel model (FAX) (Kramer et al., 2009), utilizing the point distributions generated by Slaba et al. (2009). For this study, organ averaged dose equivalent was calculated for a few of the human organs and/or tissues of interest. The organs considered were the organs for which NASA has established exposure limits: the blood forming organs (BFO); central nervous system (CNS), taken as the hippocampus part of the brain; lens of the eye; heart; and skin (NASA, 2007). These organs run the gamut of light body self shielding (skin and lens) to heavy body self shielding (heart). Dose equivalent was computed using the ICRP (International Commission on Radiological Protection) Publication 60 quality factor (ICRP, 1991). The transport calculations used the HZETRN 2010 space radiation transport code (Wilson et al., 1991; Wilson et al., 2005; Slaba et al., 2010).

The vehicles included three aluminum spheres with areal densities 1, 5, and 30 g/cm^2 where the body was placed at the center of the sphere (sphere_1g, sphere_5g, sphere_30g) and three spheres of the same areal densities where the body was placed against the wall of the sphere (sphere_off_1g, sphere_off_5g, sphere_off_30g). For the latter cases, the spheres were constructed so that they would each have the same habitable volume as the Multi-Purpose Crew Vehicle (MPCV), 316 cubic feet (8.95 m^3) (NASA, 2011). Thus, each sphere had an inner radius of 1.288 m. In addition, six locations in the STS (shuttle) where detectors have historically been placed (sts_dloc1-6), for example see Benton and Benton (2001), were investigated. Five locations in the ISS 6A configuration were also used: two points in the Destiny (Lab) module laboratory area (Liulin_103, Liulin_107); two points in the Unity (Node1) module (Liulin_104, Liulin_108); and one point in the Zvezda (SM; service module) module on panel number 327 (TEPC-sm_p327). The numbers in the four Liulin points' names refer to established detector locations in