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Comparisons of several transport models in their predictions in typical space radiation environments

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Abstract

We have used several transport codes to calculate dose and dose equivalent values as well as the particle spectra behind a slab or inside a spherical shell shielding in typical space radiation environments. Two deterministic codes, HZETRN and UPROP, and two Monte Carlo codes, FLUKA and Geant4, are included. A soft solar particle event, a hard solar particle event, and a solar minimum galactic cosmic rays environment are considered; and the shielding material is either aluminum or polyethylene. We find that the dose values and particle spectra from HZETRN are in general rather consistent with Geant4 except for neutrons. The dose equivalent values from HZETRN and Geant4 are not far from each other, but the HZETRN values behind shielding are often lower than the Geant4 values. Results from FLUKA and Geant4 are mostly consistent for considered cases. However, results from the legacy code UPROP are often quite different from the other transport codes, partly due to its non-consideration of neutrons. Comparisons for the spherical shell geometry exhibit the same qualitative features as for the slab geometry. In addition, results from both deterministic and Monte Carlo transport codes show that the dose equivalent inside the spherical shell decreases from the center to the inner surface and this decrease is large for solar particle events; consistent with an earlier study based on deterministic radiation transport results. This study demonstrates both the consistency and inconsistency among these transport models in their typical space radiation predictions; further studies will be required to pinpoint the exact physics modules in these models that cause the differences and thus may be improved.

Keywords: Transport code; Space radiation; Radiation shielding; Solar particle events; Galactic cosmic rays

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1. Introduction

For space missions, solar particle events (SPE) and galactic cosmic rays (GCR) are major sources of space radiation to astronauts and electronics. SPE are random in nature and mostly consist of protons, while GCR particles include high energy charged hadrons and nuclei including protons, alpha particles and heavier ions such as Fe ions. Transport codes have been constructed to calculate the transport of different radiation particles such as

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neutrons, protons and heavy ions through materials. These transport codes are able to calculate the modified radiation environment due to nuclear interactions such as those in the shielding material and in the human body. Transport models that can be used for space radiation calculations include both deterministic codes, such as HZETRN (High Z and Energy TRaNsport) (Wilson et al., 1995) from NASA and UPROP (Severn Communications Corporation, 1989) from the Naval Research Laboratory, and Monte Carlo codes such as FLUKA (Fassò et al., 2005; Battistoni et al., 2007), GEANT4 (Agostinelli et al., 2003), HETC (Townsend et al., 2005), MCNPX (James et al., 2009) and PHITS (Iwase et al., 2002). Deterministic radiation transport codes for hadrons and nuclei are typically one-dimensional, but they can treat three-dimensional radiation fields and geometry approximately using the ray tracing algorithm. The Monte Carlo transport codes are three-dimensional, thus in principle they can treat three-dimensional problems exactly. Furthermore, one-dimensional deterministic transport usually describes event-averaged quantities such as the inclusive spectra of particles and the event-averaged dose, while Monte Carlo models can describe both event-averaged quantities and individual events. Therefore, these two types of transport codes can complement each other in that deterministic codes are much faster but the results from Monte Carlo codes can be more accurate and detailed.

Given these multiple transport models, it is worthwhile to study how different the results from these transport models will be in typical space radiation calculations, especially because it is important to reduce the uncertainties of our projections of the space radiation risk for the planning and success of space missions. One can then further investigate the sources of these differences, which may be differences in specific physics modules, particular ion fragmentation cross sections, and/or the computational algorithm. So far most space radiation calculations are separate calculations that use either a deterministic code or a Monte Carlo transport code. Recently there have been studies (Heinbockel et al., 2011a, b) that have compared three transport codes, HZETRN, HETC and FLUKA, where dose, dose equivalent and particle spectra at different depths in a 30 g/cm^2 water slab target behind a 20 g/cm^2 aluminum slab shield have been compared in a SPE environment (Heinbockel et al., 2011a) and in a GCR environment (Heinbockel et al., 2011b).

In this study we compare two deterministic codes (HZETRN and UPROP) and two Monte Carlo transport codes (FLUKA and GEANT4) in their predictions of dose (i.e. absorbed dose), dose equivalent and particle energy spectra behind shielding in typical space radiation environments. Like the recent studies (Heinbockel et al., 2011a, b) on comparisons of transport codes, our study also does not include comparisons between model predictions and experimental data, which would be essential for evaluating the accuracy of the transport codes for validation. Two different geometries are used in this study (as shown in Fig. 1): unidirectional beam irradiation on a semi-infinite shielding slab, or isotropic irradiation on a spherical shell; and by using the latter geometry we can compare the transport models in their predictions of radiation at different locations inside a three-dimensional geometry. Two SPE environments, one with a soft spectrum and one with a hard spectrum, and one GCR environment are included. The shielding material is either aluminum or polyethylene (CH_2). Our main goals are to investigate how different the one-dimensional deterministic results are from the three-dimensional Monte Carlo results in these typical space radiation calculations, and whether a three-dimensional geometry (the spherical shell) affects these comparisons.

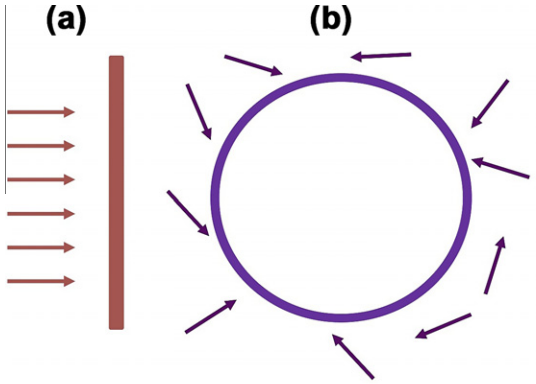

Fig. 1. Two Geometries for the simulations: (a) a semi-infinite slab under uniform and unidirectional irradiation; (b) a spherical shell under isotropic irradiation.

2. Simulation methods

The HZETRN code (Wilson et al., 1995; Slaba et al., 2010; Heinbockel et al., 2011a, b) includes the interactions and transport of ions from proton to nickel as well as neutrons. The HZETRN code currently does not include leptons or mesons. The code takes the straight-ahead approximation for the nuclear fragmentation process, i.e. it assumes that the nuclear fragments do not change their directions relative to the incoming direction of the projectile nucleus. For three-dimensional radiation fields and geometries, the one-dimensional transport can be used with the ray tracing algorithm, which essentially samples the distribution of path-length (and material composition) with a large number of rays over the full solid angle and then combines the distribution with the corresponding one-dimensional transport results along each ray. The 1995 version of HZETRN (Wilson et al., 1995) is used for this study. Note that recent HZETRN versions' treatment of neutrons (Slaba et al., 2010; Heinbockel et al., 2011a, b) goes beyond the straight-ahead approximation by having both forward and backward cross sections for neutron productions; therefore the recent versions are able to simulate backscattered neutrons.