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Evaluation of HZETRN on the Martian surface: Sensitivity tests and model results

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ABSTRACT

The Mars Science Laboratory Radiation Assessment Detector (MSLRAD) is providing continuous measurements of dose, dose equivalent, and particle flux on the surface of Mars. These measurements have been highly useful in validating environmental and radiation transport models that will be heavily relied upon for future deep space missions. In this work, the HZETRN code is utilized to estimate radiation quantities of interest on the Martian surface. A description of the modeling approach used with HZETRN is given along with the various input models and parameters used to define the galactic cosmic ray (GCR) environment and Martian geometry. Sensitivity tests are performed to gauge the impact of varying several input factors on quantities being compared to MSLRAD data. Results from these tests provide context for inter-code comparisons presented in a companion paper within this issue. It is found that details of the regolith and atmospheric composition have a minimal impact on surface flux, dose, and dose equivalent. Details of the density variation within the atmosphere and uncertainties associated with specifying the vertical atmospheric thickness are also found to have minimal impact. Two widely used GCR models are used as input into HZETRN and it is found that the associated surface quantities are within several percent of each other.

1. Introduction

For future missions to Mars, models will be heavily relied upon to quantify expected radiation levels within complicated shielding geometries during transit and on the planetary surface. It is therefore prudent to continuously verify and validate such models to improve uncertainty assessments and gain insight into possible systematic model errors. Several models have already been compared to measurements from the Mars Science Laboratory Radiation Assessment Detector (MSLRAD) (Hassler et al., 2012) obtained in-transit to Mars (Zeitlin et al., 2013) and on the surface (Matthia et al., 2016). It has been generally found that the models are in reasonable agreement with MSLRAD measurement data if integrated quantities such as dose or dose equivalent are considered (Zeitlin et al., 2013; Matthia et al., 2016).

Although such comparisons are highly useful in providing a simple and relevant measure of model uncertainty, integrated exposure quantities can obscure certain details. For example, the recent work of Matthia et al. (2016) showed that Monte Carlo (MC) simulation codes and the deterministic code HZETRN vary widely in the prediction of secondary light ion (^{2}H, ^{3}H, ^{3}He) spectra over the full energy range of interest to space applications ($\sim$1 MeV/n up to 10^5 MeV/n). The proton and ^{4}He energy spectra computed with the codes were in excellent agreement above $\sim$500 MeV/n, where transport results are dominated by primary galactic cosmic ray (GCR) ions and influenced mainly by total nuclear cross sections and atomic stopping powers having relatively small uncertainties (Tai et al., 1997; Sihver et al., 2012). However, at lower energies measured by MSLRAD (less than $\sim$100 MeV/n), where nuclear production makes a significant contribution to observed particle spectra, the codes showed larger variation and uncertainty. Such differences may be important to fluence-based risk assessment models (Cucinotta et al., 2013) and pertinent biological responses such as cardiovascular disease and central nervous system detriment.

Although the comparisons between MSLRAD data and various models published to date generally show that the models are capable of providing reliable assessments of the radiation environment on the Martian surface, further improvements and continued validation and uncertainty quantification efforts are still needed. Such efforts inevitably lead to improved models with reduced uncertainties, thereby leading to more optimal vehicle and habitat designs with reduced exposure, mass, and cost. As discussed in

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the summary paper for this special issue (Hassler et al., 2017), a workshop was held in Boulder, CO in June 2016 with the purpose of comparing widely used transport codes to new and unpublished MSLRAD data that were not available to the modeling teams. Only certain input parameters, boundary conditions, and output requirements were specified prior to the workshop as discussed by Hassler et al. (2017). This type of independent or "blind" validation effort is highly useful and informative and has the advantage of removing unintentional bias or ad-hoc empirical adjustments from model results.

In this work, the modeling approach used to evaluate HZETRN in this set of comparisons is described. A brief summary of HZETRN is provided, along with a description of the geometry and boundary condition specification. A complete set of input models and parameters used to generate the HZETRN results compared to MSLRAD data in Matthia et al. (2017) are provided in the Appendix. Notably, although certain input parameters and conditions were specified to the modeling teams prior to the workshop, other components needed to perform the relevant calculations were intentionally left unspecified. For example, each team was free to choose a model to describe the primary GCR particle spectra, atmosphere and regolith composition, and other related factors. Leveraging the high degree of computational efficiency associated with HZETRN (Slaba et al., 2013a; Slaba and Blatting 2014), sensitivity tests were performed to determine to what extent some of the unspecified factors influence quantities of interest on the Martian surface. The impact of uncertainty associated with certain fixed input parameters (e.g. vertical atmospheric thickness) used by all modeling teams was also investigated. Results of these tests are useful in providing context for the summary comparison paper of Matthia et al. (2017) contained within this issue so that variation between codes and differences against MSLRAD data can be more clearly interpreted.

2. Model overview

2.1. HZETRN

HZETRN (Wilson et al., 1991, 2016; Slaba et al., 2016) is a deterministic transport code providing numerical solutions to the time-independent, linear Boltzmann equation (Wilson et al., 1991). The transport formalism allows for a converging sequence of physical approximations to be considered, allowing highly efficient computational procedures to be implemented. Typical run times for full GCR calculations range from seconds to minutes on a single CPU. The version of the code used herein utilizes a bi-directional transport approach for neutrons and light ions (Slaba et al., 2010), allowing back-scattered albedo neutron contributions to be represented. Heavier ions are treated within the straight-ahead approximation (Wilson et al., 1991), as are the pion, muon, and electromagnetic cascade components (Norman et al., 2013). Recent improvements to the code include more detailed 3D corrections for neutrons and light ions (Wilson et al., 2016), which were not included here but may be considered in future work. The NUCFRG3 (Adamczyk et al., 2012) model is used for describing nuclear fragmentation of heavy ions. Light ion and neutron interaction models are described elsewhere (Wilson et al., 1991; Cucinotta, 1993; Cucinotta et al., 1996). The most recent version of the code, capable of reproducing the results presented herein, is HZETRN2015 and can be obtained through the website: https://software.nasa.gov. A web-based tool utilizing HZETRN2015 with additional capabilities for specifying geometry, boundary conditions, and response functions is also available at https://oltaris.nasa.gov.

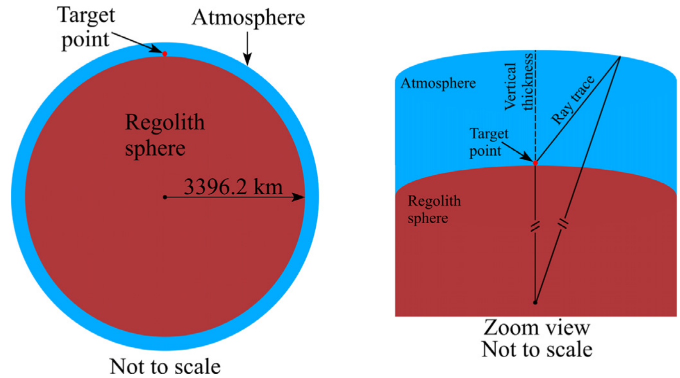

Fig. 1. Mars surface geometry in full view (left) and zoom view (right).

2.2. Geometry setup

The implementation of HZETRN for Mars surface calculations considers the atmospheric geometry and variable density profile in a ray-by-ray computational procedure as described by Slaba et al. (2013b). As shown on the left side of Fig. 1, the geometry is defined by a regolith sphere with a radius of 3396.2 km (average Mars radius) surrounded by a spherical shell representing the Martian atmosphere. A target point is placed on the surface at the interface between the atmosphere and regolith. Although not shown in the figure, the GCR boundary condition is assumed to impinge isotropically on the sphere.

In order to couple this geometry to HZETRN within the bi-directional transport formalism, ray-tracing procedures are utilized. First, incoming GCR ions impinging from below the horizon are assumed to be fully blocked by the Martian surface and are therefore neglected (i.e., they are assumed to make no contribution to the exposure on the surface). For GCR ions impinging from the remaining upper 2π solid angle, the ray-trace path length through the atmosphere is needed for transport calculations and may be computed if the vertical thickness is known (see right side of Fig. 1 and geometric relationships from Simonsen et al. (1990)). Simple extensions to the basic geometric relationships have been incorporated so that density variations occurring along the ray-trace path can be computed, thereby allowing pion and muon decay rates to be properly evaluated. To improve computational efficiency, a constant thickness of 300 g/cm^2 was assumed for all path lengths through the regolith sphere. This thickness has been found to be sufficiently large to reach equilibrium in the albedo neutron field without unnecessarily increasing computational cost in transport calculations.

These ray-trace procedures are performed prior to transport code execution over a large number of rays ($\sim 10^3$) each of which account for the same fraction of the full solid angle. In general, the ray-by-ray transport calculation becomes a series of slab calculations with a target point placed between an atmosphere shield with varying density and backed by 300 g/cm^2 of regolith. Precise definitions of the atmosphere composition, regolith composition, vertical thickness, and density profile along the vertical ray are discussed later in this report in the context of sensitivity studies.

3. Sensitivity tests

As discussed by Hassler et al. (2017), only certain input conditions were precisely specified to the modeling teams. These fixed conditions were:

- the dates over which the measurements were taken (November 15, 2015 – January 15, 2016),

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