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Computation of cosmic ray ionization and dose at Mars. I: a comparison of HZETRN and Planetocosmics for proton and alpha particles.

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Abstract

The ability to evaluate the cosmic ray environment at Mars is of interest for future manned exploration. To support exploration, tools must be developed to accurately access the radiation environment in both free space and on planetary surfaces. The primary tool NASA uses to quantify radiation exposure behind shielding materials is the space radiation transport code, HZETRN. In order to build confidence in HZETRN, code benchmarking against Monte Carlo radiation transport codes is often used. This work compares the dose calculations at Mars by HZETRN and the Geant4 application Planetocosmics. The dose at ground and the energy deposited in the atmosphere by galactic cosmic ray protons and alpha particles has been calculated for the Curiosity landing conditions. In addition, this work has considered Solar Energetic Particle events, allowing for the comparison of varying input radiation environments. The results for protons and alpha particles show very good agreement between HZETRN and Planetocosmics.

Keywords: Cosmic Rays, Mars, Dosimetry

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1. Introduction

The Galactic Cosmic Rays (GCR) and Solar Energetic Particle (SEP) events affect the evolution of the climate of Mars, the operation of satellites, and the human exploration of the planet. They can affect the chemistry at ground (Molina-Cuberos et al., 2001; Poch et al., 2013; Atreya et al., 2006; Delory et al., 2006), which can destroy complex organic materials (Pavlov et al., 2002; Kminek and Bada, 2006; Pavlov et al., 2012), explaining why no observations of such molecules have been reported so far (ten Kate, 2010) even if simple organics have been detected (Webster et al., 2014). The energetic inputs also have an impact on the planetary atmosphere evolution by modifying the escape rates and the chemistry of the upper atmosphere (Sheel et al., 2012; Ulusen et al., 2012). The SEP events observed at Mars (Falkenberg et al., 2011) are shown to affect the satellite activity, for example by creating blackout for radar observation of the Martian surface (Withers, 2011; Norman et al., 2014). Albeit rare, huge SEP events could have huge effects on the atmosphere in the long run, through enhancement of atmospheric escape –which will be studied in details by MAVEN–, and could be fatal to astronauts at the surface of the planet. One of such SEP events was the Carrington one, which occured in 1859 with a fluence of 1.88×10^{10} cm^{-3} (McCracken et al., 2001; Smart et al., 2006) it lasted for several days (Smart et al., 2006). It is believed to be a once in 500 years event (Yermolaev et al., 2013). The occurence of a Carrington-class event would exceed permissible exposure limits at the surface of Mars (Townsend et al., 2013).

Therefore, several missions to Mars contain dedicated instrumentation to better understand these energetic particle precipitations. For example, the Curiosity mission measures GCR and SEP dose at the surface of Mars using its RAD instrument, and the MAVEN mission will use its SEP instrument to measure these events at its Martian orbit (Jakosky, 2014; Kim et al., 2014; Rafkin et al., 2014).

To support these missions, and to better prepare future human exploration, it is necessary to provide accurate models for the computation of particle flux, absorbed dose, and ionization by GCR and SEP. To help understand vehicle design trades and to better access future mission exposure, it is important to have tools that are well characterized and computationally efficient. One such model is HZETRN (Wilson et al., 1991; Slaba et al., 2010a,b; Norman et al., 2013), which has been developed by NASA for use in radiation exposure studies. The speed and efficiency of HZETRN is due to a series of approximations which simplify the radiation transport to a one dimensional problem. Recent work by Wilson et al. (2014), however, has begun to relax these approximations and a three dimensional version of HZETRN is being developed. On the other hand, the Planetocosmics model (Desorgher et al., 2005; Gronoff et al., 2009, 2011) is a fully three dimensional model, but is slower due to its Monte Carlo solving scheme.

In this paper, the HZETRN and Planetocosmics models are presented (Section 2), and used to compute GCR and SEP ionization and dose at ground for several conditions (Section 3). This process allows the comparison of HZETRN to Planetocosmics in order to benchmark the exposure quantities of interest to future exploration activities and science missions.

2. The models

2.1. HZETRN

HZETRN is a radiation transport code for space radiation boundary conditions that solves the Boltzmann transport equation within the straight-ahead and continuous slowing down approximations (Wilson et al., 1991; Slaba et al., 2010a,b; Norman et al., 2014). The version of HZETRN used in this analysis utilized the updated bidirectional transport algorithm for neutrons wherein both inward (toward the surface) and outward (away from the surface) moving neutrons are accounted for (Slaba et al., 2010a). In addition, the extension of HZETRN to include pions, muons, electrons, positrons, and gammas was used (Norman et al., 2012; Norman et al., 2013).

Previous work has validated HZETRN for secondary particle flux in Earth's atmosphere (Norman et al., 2012; Norman et al., 2013) and it was shown that there was good agreement with experiment for secondary muons and reasonable agreement for electrons and positrons given the approximations used. In addition, Slaba et al. (2013) compared HZETRN on a minute-by-minute basis to International Space Station dosimeter measurements and found good agreement once secondary mesons and leptons were included in the calculation and after accounting for environment and geometrical input error. HZETRN has also been extensively benchmarked against fully three dimensional Monte Carlo codes for slab geometries (Heinbockel et al., 2011a,b; Lin et al., 2012; Slaba et al., 2013), with results showing that HZETRN generally agrees with the Monte Carlo codes to the extent that they agree with each other.

2.2. Planetocosmics

The Planetocosmics model (Desorgher et al., 2005) is a Geant4-based model dedicated to the computation of cosmic rays ionization in planetary atmospheres. It computes the energy deposition by energetic particles following a Monte Carlo scheme and using the physical processes provided by Geant4. For the present work, the Planetocosmics model has been modified to use the Geant 4.9.6 library with the physics list QGSP_BERT_HP which has been recommended for space radiation applications (Slaba et al., 2013, and references therein). The tracking cuts for all particles has been set to 1 keV. A comparison with the results for lower energy cuts and with the coupled Planetocosmics/Aeroplanets code (Gronoff et al., 2011; Gronoff et al., 2012) allowed to demonstrate that the resulting dose is not affected by this approximation. In addition, several detector modifications have been made to compute the dose at ground: a water layer of a thickness of 1 cm was added at the ground and the energy deposition in that layer is scored.

Since Planetocosmics is a Monte Carlo model, it can be launched either by taking the energy of the precipitating particle randomly, with a probability distribution adapted to the precipitation spectra, or it can be launched against a discretized energy grid. The latter scheme is used since it allows one to reuse the simulations for different energy spectra. The procedure consists of launching about 100 simulations (which each contain thousands of particles) for each energy bin. This allows the average and standard deviation to be computed for each simulation group. Upon completion of each set of simulations, the results are multiplied by the precipitation spectra and integrated, returning the expected result (Gronoff et al., 2009, 2011). For the present work, the alpha and proton precipitation have been simulated up to 1 TeV/nucleon, without any approximation such as the one in Nordheim et al. (2015); Dartnell et al. (2007); Dartnell et al. (2007); Desorgher et al. (2005) where the ionization by an alpha particle is replaced by the ionization by 4 protons above 10 GeV/nucleon.

The error bars and the uncertainties presented for the Planetocosmics simulations correspond to the propagation of the statistical variation of the Monte Carlo simulations. The higher energy simulations (above 50 GeV) present larger error bars since the Monte Carlo simulations for these particle require more resources, and therefore less statistics were available for them.

2.3. Martian atmosphere

This work follows closely that of Norman et al. (2014). The atmospheric composition was kept constant at 95.7% CO_2, 2.7% N_2, and 1.6% Ar (Owen et al., 1977). The density was modeled using the Mars Climate Database (MCD) version 4.3 using the Mars year 24 (MY24) dust scenario. The MY24 dust scenario is meant to be a baseline scenario without a global dust storm present, which tries to reproduce the Martian atmosphere and its dusty component for the Mars Years 24-25. The Gale Crater for the Curiosity landing time were input into the MCD, and a density profile was produced and can be seen in Figure 1. This profile has been taken for comparison purposes for both the benchmarking activity and comparison to Curiosity observations.

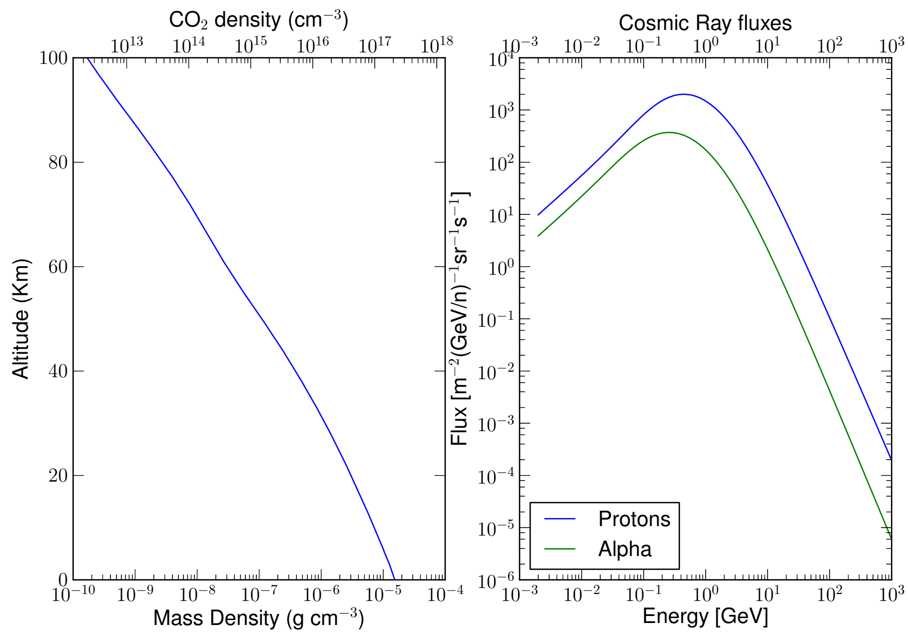

Figure 1: The atmospheric profile and cosmic ray spectra used for this study

3. Benchmarking results

HZETRN has been developed and updated to quickly and efficiently solve the radiation transport problem for the space environment. To help understand the affect that the approximations used in HZETRN have on the accuracy of results, this benchmarking effort will compare HZETRN to Planetocosmics in the atmosphere and on the surface of Mars. This work will focus on comparing the dose due to space radiation deposited in human tissue and the ionization rate in the atmosphere.

3.1. Geometry and physical setup for benchmarking

The simulations have been performed for conditions where the magnetic field is negligible, corresponding to a location far from the crustal magnetic fields of Mars, which is valid for the Curiosity condition. This fact also facilitates the comparison between the two models. For HZETRN, the calculation is done in a 1-D configuration, following the vertical; the particle precipitation is assumed to follow the vertical axis. For Planetocosmics, the calculation is done in a 3-D configuration with the assumption of a spherical geometry; 8 angles of precipitation with respect to the vertical are considered, following (Gronoff et al., 2011), to address the isotropic hypothesis.

3.2. Galactic cosmic ray ionization

The GCR spectra used as input for both transport models has been computed with the Bahdwar and O'Neill model (O'Neill, 2010) (Figure 1) adapted for the location of Mars (a heliospheric radius of 1.54 A.U.), and using the solar modulation parameter $\Phi = 706$ MV adapted for the Curiosity landing condition and corresponding to a moderate solar activity (Norman et al., 2014). For this work, only the spectra of hydrogen and helium ions were considered. The cutoff rigidity due to the weak magnetic field of Mars is negligible for the current study.

The energy deposition has been computed by both Planetocosmics and HZETRN using a 35 eV per ion-electron pair production parameter to yield the ionization rate. The result is shown in Figure 2. The two models are in excellent agreement for the ionization by both protons and alpha particles: below 40 km altitude, the disagreement is of the order of 10% for the alpha particles, and 5% for the protons. In both cases, HZETRN gives a slightly higher ionization rate. This difference can be explained by the differences in the physical models used for the nuclear interactions, as well as by the geometry (1-D for HZETRN) and the numerical approximations in the two models. For practical purposes, such a difference is negligible considering the uncertainties in the atmosphere density and in the cosmic ray precipitation spectra.

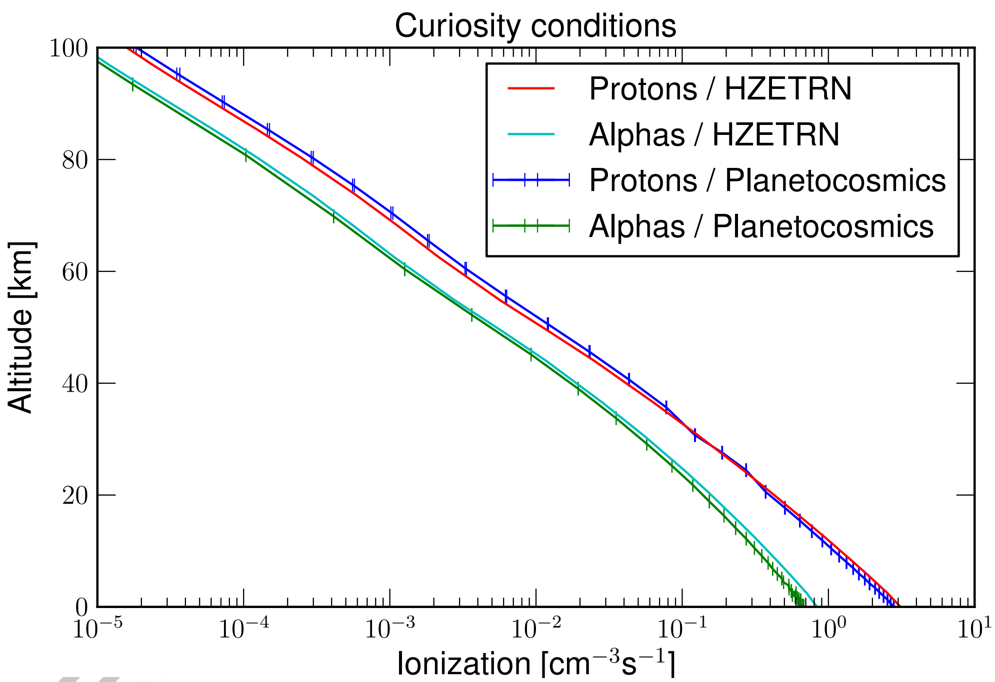

Figure 2: Cosmic ray ionization

3.3. Galactic cosmic ray dose at ground

The dose per fluence computation of Planetocosmics is presented in Figure 3. It represents the dose absorbed at the ground level as a function of the kinetic energy of the particle at the top of the atmosphere. The integration of that function multiplied by the flux allows a fast computation of the dose absorbed at the ground. The uncertainties in these functions are computed from the statistical uncertainties in the Monte Carlo scheme. They are propagated during the numerical integration to give the model uncertainty of the dose at ground. Such uncertainties are therefore very small in comparison with the uncertainties in the spectra, atmosphere, and the approximations in the physics used for the computation.

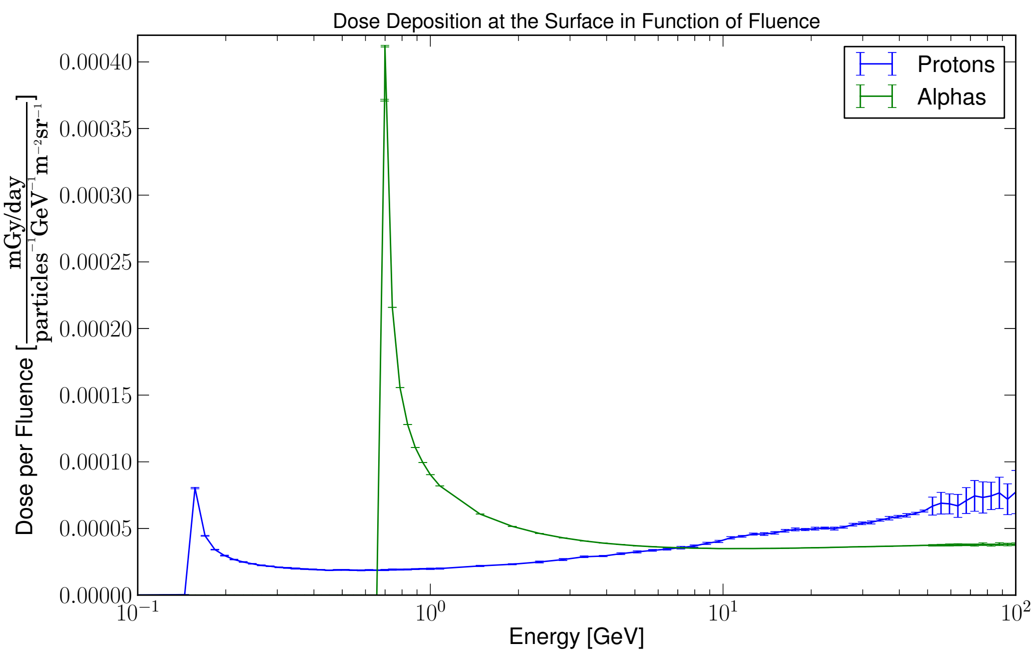

Figure 3: The dose per fluence at the Martian ground in function of the kinetic energy of the proton and alpha particles. (n.b.: for practical purpose, the results are shown in function of the energy of the particle, and not energy per nucleon)

The dose due to the cosmic ray protons computed by Planetocosmics is 0.11 ± 0.0005 mGy/day, to be compared with the 0.107 mGy /day computed by HZETRN. The dose due to the alpha particles is $0.02377 \pm$ 5e-06 mGy/day, to be compared with the HZETRN output of 0.0295 mGy /day. This 20% difference between the two models is likely due to a difference in the physical approximations used. A similar issue for HZETRN was mentioned in Ehresmann et al. (2014), where it was shown that HZETRN is overestimating alpha particle flux on the surface compared to MSL RAD measurements. While the impact of this difference to total dose is small, this is a topic currently being investigated.

If all the GCR nuclei are taken into account, and not only protons and alphas, the total dose is on the on the order of 0.2 mGy/day in HZETRN (Norman et al., 2014).

The Planetocosmics model is therefore in good agreement with the HZETRN model for the proton and alpha induced doses at the ground. These doses (in Gy) translate into dose equivalent (in Sv) by weighting the dose deposited in function of the Linear Energy Transfer (LET) of the ionizing particle. The Planetocosmics model supports the previous calculations by HZETRN showing that unprotected astronauts would be submitted to 1 mSv/day at the surface of Mars (Norman et al., 2014), which means 350 mSv/yr.

3.4. SEP ionization

The SEP events are responsible for huge increase, several order of magnitude, in the ionization and dose deposition in the lower atmosphere of Mars. It is therefore necessary to account for their effect, and to compare the HZETRN and Planetocosmics models for the SEP conditions. Several SEP spectra were considered, following Norman et al. (2014), and are presented in Figure 4; these spectra are based on the work by Sheel et al. (2012), Smart et al. (2006), and from the European Space Agency's Space Environment Information System website SPENVIS (Kruglanski et al., 2010). In contrast to the GCR spectra, these spectra consist only of proton precipitation, and decrease monotonically as a function of the energy, with the exception of the spectra intended to reproduce the Carrington event that presents a peak at 10 MeV. For the ionization in the lower atmosphere and the dose at the ground, the most important part of these spectra lies in the MeV-GeV range, while it was in the 1-10 GeV range for the GCR (O'Neill, 2010).

The ionization due to these SEPs is presented in Figure 5. The agreement between HZETRN and Planetocosmics is excellent, the differences, presented in percent as dashed lines, are of the order of 5-10 percent below 40 km altitude. The ionization at the ground due to these SEP is two to four orders of magnitude higher than the GCR ionization, leading to important variations of dose at the ground. The Planetocosmics and HZETRN models gives very similar results as shown in Table 1.

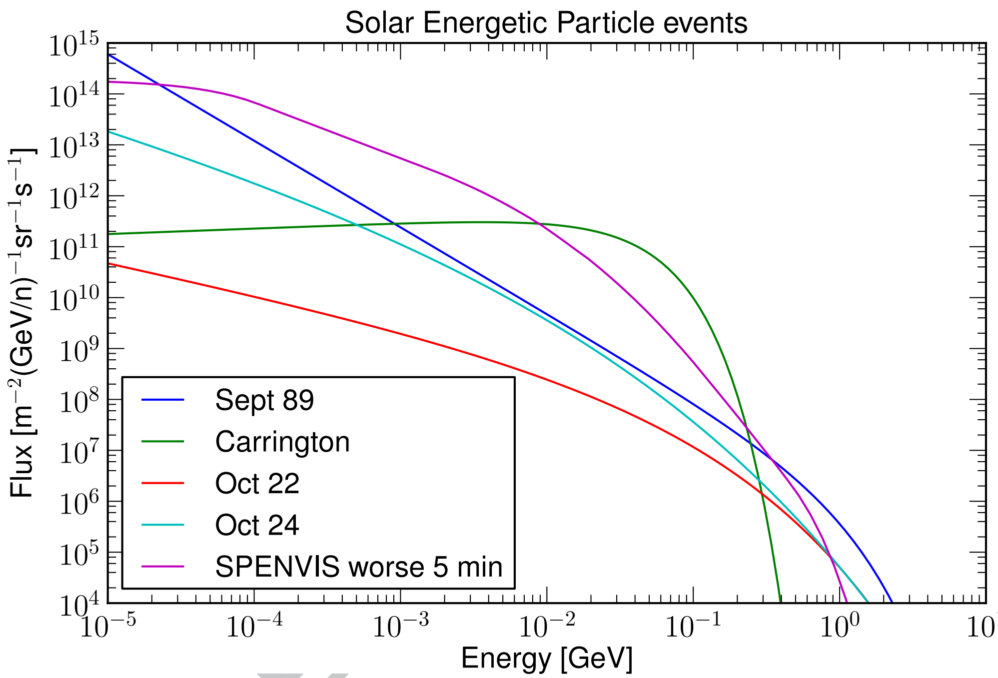

Figure 4: The SEP spectra used for this study

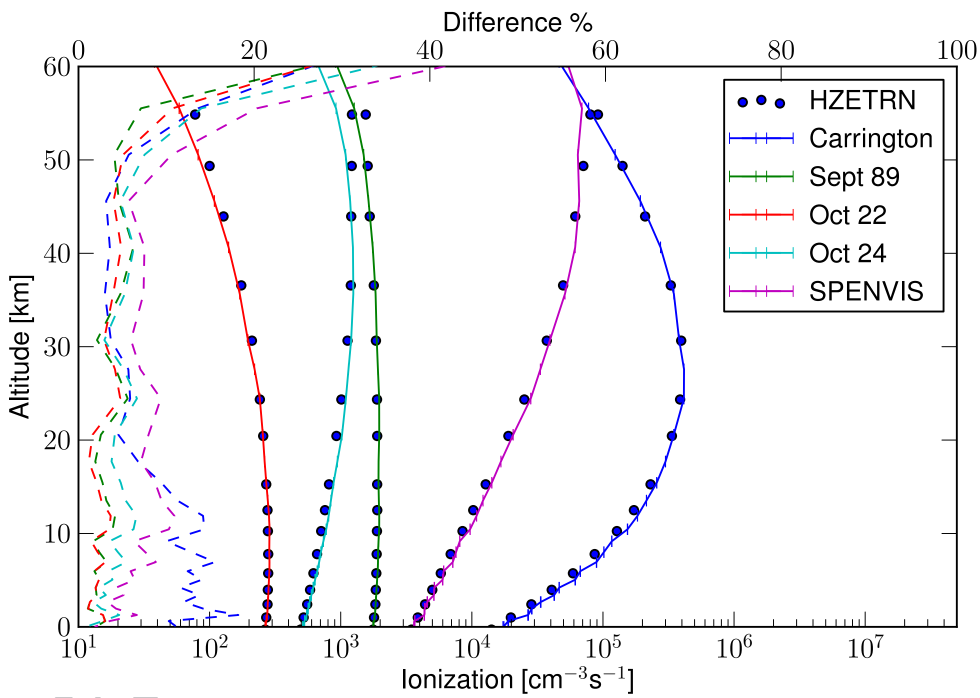

Figure 5: SEP ionization. The dashed lines represent the difference in percent between HZETRN and Planetocosmics

SEP event	Planetocosmics computation	HZETRN computation
Sept 89	69.0 ± 0.2 mGy/day	65.0 mGy/day
Carrington	755 ± 5 mGy/day	502 mGy/day
Oct 22	10.4 ± 0.05 mGy/day	9.40 mGy/day
Oct 24	20.1 ± 0.1 mGy/day	17.5 mGy/day
SPENVIS Oct 89 5min	147 ± 1 mGy/day	124 mGy/day

Table 1: Dose at the Martian surface during SEP events as computed by Planetocosmics and HZETRN

4. Discussion and Conclusion

The determination of the Martian surface and sub-surface radiation environment is an ongoing effort that started with numerical simulations (see e.g. Velinov and Mateev, 1991; Simonsen and Nealy, 1993; Molina-Cuberos et al., 2001; Saganti et al., 2004; Dartnell et al., 2007) and can now be compared with in-situ experiments thanks to the Curiosity/RAD experiment (Kim et al., 2014; Hassler et al., 2014). From these studies, the ionization at the ground range from 0.8 to 10 $cm^{-3}s^{-1}$, and the dose from 0.2 mGy/day, measured by Curiosity, to 0.5 mGy/day. These results are in agreement with our work, which gives a dose of 0.13 mGy/day and an ionization at the ground of 4 $cm^{-3}s^{-1}$, since we do not take into account the high-Z cosmic rays.

The strength of the present work is the comparison of two models for identical initial conditions, allowing a determination of the errors for the validation of the approximation in the HZETRN model. The comparison of the Planetocosmics and HZETRN models is summarized in Figure 6, which represents the dose computed by the two models as a function of altitude, and the corresponding difference in percent (dashed lines). The results are virtually identical for the alpha particles and the protons, demonstrating that the HZETRN approximations are well suited for the Martian environment. The very high doses computed for the SEP events demonstrate further the need for radiation shielding for these conditions, since dangerous doses could be reached for unprotected astronauts at the surface of Mars.

The presented baseline dose equivalent of 350 mSv / year is below the maximum allowed dose per year in the NASA (2014) standards for crew safety; but it is of the same order of magnitude, indicating that a careful analysis of the radiation should be made. The SEP events have the potential to break that limit. As an example, the Carrigton event would mean a dose equivalent of 1 Sv, which is the maximum dose equivalent permissible for astronauts in the best case for a one year mission considering cancer-risks.

For practical purposes, it is possible to use the dose per fluence presented in this study for a fast and easy computation of the dose at the ground due to the proton and alpha particles.

The present paper benchmarked NASA's space radiation transport code HZETRN against the GEANT4-based Planetocosmics Monte Carlo model for SPE and GCR light ions at Mars. Dose and ionization rate, both at the ground and throughout the atmospheric column, were the figures of merit. Good agreement was observed between the two transport models, with dose at the ground differences being bounded by 10%, except for the very large Carrington SPE that had approximately a 20% difference in dose at the ground. Larger differences in the GCR protons were seen at high altitudes, which was at least partially due to the use of only a single vertical ray for HZETRN.

Future work will include the computation of high-Z particle precipitation effects at Mars, and the corresponding comparison with HZETRN, allowing both the benchmarking of HZETRN at Mars and the computation of dose per fluence functions.

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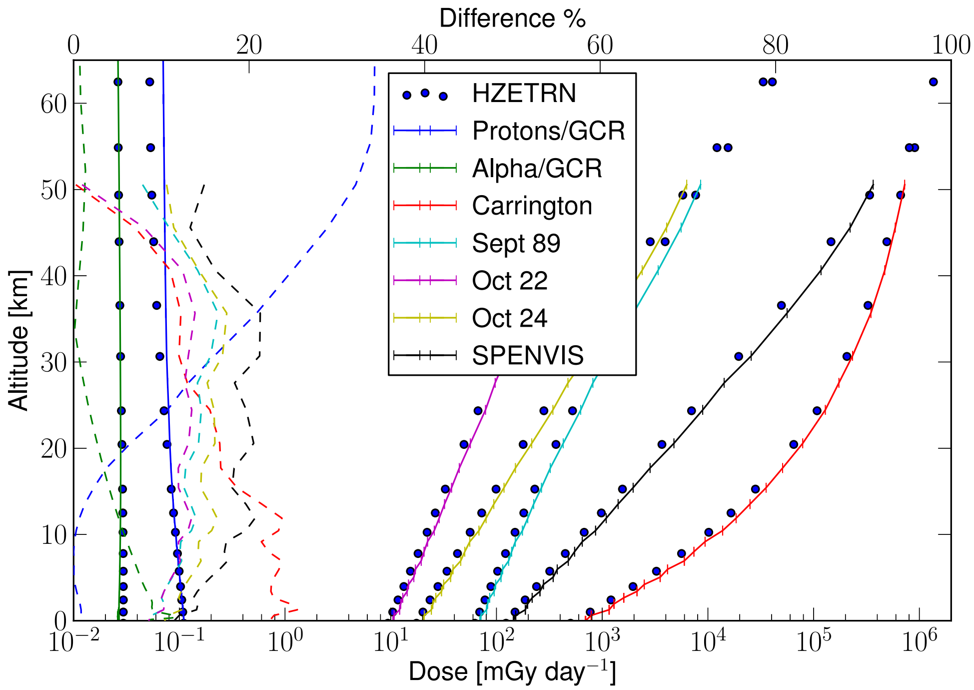

Figure 6: SEP and GCR induced dose as a function of altitude. The dashed lines represent the difference in percent between HZETRN and Planetocosmics

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- Dose and ionization by alpha and protons are computed by Planetocosmics and HZETRN
- The HZETRN model is benchmarked against Planetocosmics
- Good agreement is found between the models