MSL-RAD

Summary of model calculations and comparison to RAD data

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Overview

1. Update on the comparison of the calculated particle fluxes and dose rates with MSL-RAD data

2. “1st Mars Space Radiation Modeling Workshop” held in June 2016 in Boulder

3. Development of a parameterized radiation model for the Martian atmosphere at DLR
1. Update on the comparison of calculation/MSL-RAD measurements

Update on the comparison of the calculated particle fluxes and dose rates with MSL-RAD data (Now published: Matthiä et al. *SWSC* 6, A13, 2016)
Setup for the simulations

- **Atmosphere:**
  - 22 g/cm²
  - Composition (mass %): 95.7% CO₂, 2.7% N₂, 1.6% Ar (Mars-Gram 2001)

- **Soil:** ≥ 20m, composition from OLTARIS

- **GCR-Input:** DLR and Badhwar/O’Neill 2010:

- **Particles:** neutron (10⁻⁸ MeV to 10⁴ MeV), proton (1 MeV to 10⁵ MeV), gamma (10⁻³ MeV to 10⁴ MeV), e⁻⁺ (10⁻³ MeV to 10⁴ MeV), deuteron, triton, ³He, ⁴He, Li/Be/B, C/N/O, Z=9-13, Z≥14 (all 1 MeV/n to 10⁵ MeV/n)

- 4π, zenith angle < 30°
GCR input spectra: DLR and Badhwar/O’Neill 2010

19. August 2012 (DoY 232, 2012) until 17. February 2013 (DoY 048, 2013) [182 days]
Proton, deuteron, triton, $^3$He, $^4$He

Summary

- Zenith angle ≤30°
- **MSL-RAD data**: *Ehresmann et al.* 2014
- **GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS**
Neutron and photon

- **MSL-RAD data**: Köhler et al. 2014
- **Neutrons**: (GEANT4, PHITS, HZETRN, OLTARIS2013)
  - Good agreement above 1GeV
  - Lower neutron fluxes from OLTARIS2013 below 1GeV (upward fluxes are missing)

- **Photons**:
  - Good agreement GEANT4/PHITS
  - HZETRN significantly lower (higher) at energies < 10MeV (>1GeV)
<table>
<thead>
<tr>
<th></th>
<th>MSL-RAD [Hassler et al., 2014]</th>
<th>GEANT 4.10.p02</th>
<th>PHITS</th>
<th>OLTARIS2013</th>
<th>HZETRN/OLTARIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>absorbed dose rate [mGy/d]</td>
<td>0.21 ± 0.04</td>
<td>0.19</td>
<td>0.20</td>
<td>0.16</td>
<td>0.18</td>
</tr>
<tr>
<td>dose equivalent rate [mSv/d]</td>
<td>0.64 ± 0.12</td>
<td>0.52</td>
<td>0.60</td>
<td>0.52</td>
<td>0.54</td>
</tr>
<tr>
<td>Quality factor</td>
<td>3.05 ± 0.26</td>
<td>2.7 (3.0)</td>
<td>3.0 (3.4)</td>
<td>3.2</td>
<td>3.0 (3.2)</td>
</tr>
</tbody>
</table>

**NOTE:** Values in parenthesis are the derived quality factors for a restricted zenith angle θ<30°.
2. “1st Mars Space Radiation Modeling Workshop” held in June 2016 in Boulder
1st Mars Space Radiation Modeling Workshop

- Organised by SWRI, NASA, DLR, CAU

- At SWRI, Boulder, June 28 - 30, 2016

- **Goal**: Extension of model comparison
  - new set of experimental data,
  - **15 Nov 2015 – 15 Jan 2016**

- Similar approach as before

- Models:
  - FLUKA (K. Lee, NASA)
  - GEANT4 (D. Matthiä, DLR)
  - GEANT4/HZETRN (A. Firan, R. Rios, NASA)
  - HETC-HEDS (W. de Wet, L. Townsend; Univ. of Tennessee)
  - HZETRN (T. Slaba, NASA)
  - MCNP6 (L. Heilbronn, H. Ratliff, M. Smith; Univ. of Tennessee)
  - PHITS (J. Flores-McLaughlin, NASA)

**Comparison paper submitted to LSSR**
Modeling workshop papers, accepted in LSSR

• Introduction
  • Hassler et al., “Mars science laboratory radiation assessment detector (MSL/RAD) modeling workshop proceedings”

• Measurements:
  • Ehresmann et al., “The charged particle radiation environment on Mars measured by MSL/RAD from November 15, 2015 to January 15, 2016”
  • Guo et al., “Measurements of the neutral particle spectra on Mars by MSL/RAD from 2015-11-15 to 2016-01-15”

• Models:
  • de Wet & Townsend, “A calculation of the radiation environment on the Martian surface” (HETC-HEDS)
  • Flores-McLaughlin, “Radiation transport simulation of the Martian GCR surface flux and dose estimation using spherical geometry in PHITS compared to MSL-RAD measurements”
  • Matthiä & Berger, “The radiation environment on the surface of Mars – Numerical calculations of the galactic component with GEANT4/PLANETOCOSMICS”
  • Ratliff et al., “Simulation of the GCR spectrum in the Mars curiosity rover's RAD detector using MCNP6”
  • Slaba & Stoffle, “Evaluation of HZETRN on the Martian surface: Sensitivity tests and model results”

• Summary:
  • Matthiä et al., “The radiation environment on the surface of Mars - Summary of model calculations and comparison to RAD data”

- Measured integral charged particle fluxes

- Measured differential particle fluxes

<table>
<thead>
<tr>
<th>Ion species</th>
<th>RAD fluxes [cm⁻² s⁻¹ sr⁻¹]</th>
<th>Minimum energy [MeV/nuc]</th>
<th>GCR flux [cm⁻² s⁻¹ sr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z = 1 (protons and other)</td>
<td>0.267( ± 0.030)</td>
<td>135( ± 15)</td>
<td>0.226</td>
</tr>
<tr>
<td>Z = 2 (²He, ⁴He)</td>
<td>1.86( ± 0.24) 10⁻²</td>
<td>135( ± 15)</td>
<td>2.30 10⁻²</td>
</tr>
<tr>
<td>Z = 3–5 (Li, Be, B)</td>
<td>1.99( ± 0.40) 10⁻⁴</td>
<td>175( ± 25)</td>
<td>3.31 10⁻⁴</td>
</tr>
<tr>
<td>Z = 6–8 (C, N, O)</td>
<td>6.26( ± 1.20) 10⁻⁴</td>
<td>250( ± 25)</td>
<td>1.31 10⁻³</td>
</tr>
<tr>
<td>Z = 9–13 (F to Al)</td>
<td>1.10( ± 0.20) 10⁻⁴</td>
<td>300( ± 25)</td>
<td>2.51 10⁻⁴</td>
</tr>
<tr>
<td>Z = 14–24 (Si to Cr)</td>
<td>5.48( ± 0.20) 10⁻⁵</td>
<td>400( ± 25)</td>
<td>1.53 10⁻⁵</td>
</tr>
<tr>
<td>Z = ≥ 25 (Mn, Fe and higher)</td>
<td>1.20( ± 0.11) 10⁻⁵</td>
<td>550( ± 25)</td>
<td>5.54 10⁻⁵</td>
</tr>
</tbody>
</table>
• Measured neutron and gamma spectra above ~7 MeV

• Dose rate from neutrons between 7 MeV and 740 MeV

<table>
<thead>
<tr>
<th></th>
<th>Dose rate</th>
<th>Dose equivalent rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power law inversion</td>
<td>5.6 ± 0.8 µGy/d</td>
<td>25.3 ± 3.3 µSv/d</td>
</tr>
<tr>
<td>Full inversion</td>
<td>4.7 ± 0.9 µGy/d</td>
<td>22.0 ± 4.1 µSv/d</td>
</tr>
<tr>
<td>Averaged final</td>
<td>5.1 ± 1.0 µGy/d</td>
<td>23.6 ± 4.1 µSv/d</td>
</tr>
<tr>
<td>Mean total dose measured</td>
<td>233 ± 12 µGy/d</td>
<td>610 ± 45 µSv/d</td>
</tr>
</tbody>
</table>
Highlights from de Wet & Townsend (2017), “A calculation of the radiation environment on the Martian surface”

- Results from HETC-HEDS using a cylindrical geometry

- Differential particle fluxes
Highlights from Flores-McLaughlin (2017), “Radiation transport simulation of the Martian GCR surface flux and dose estimation using spherical geometry in PHITS compared to MSL-RAD measurements”

- Results from PHITS for a spherical geometry
- Zenith angle dependence

- Differential particle fluxes
- Dose rates

- Results from GEANT4 for a box geometry
- Differential particle fluxes
- Analysis of upward/downward flux

- Dose rates (per particle type)
Ratliff et al. (2017), “Simulation of the GCR spectrum in the Mars curiosity rover's RAD detector using MCNP6”

- Results from MCNP6
- Dose rates (per particle type)
- Differential particle fluxes

### Table 2
Tabulated dose (D) and dose equivalent (H) values for 4π calculations.

<table>
<thead>
<tr>
<th>Particle</th>
<th>$D_{4\pi}$ ($\frac{\mu d\phi}{d\Omega}$)</th>
<th>$H_{4\pi}$ ($\frac{\mu dH}{d\Omega}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>200.00 ± 0.52%</td>
<td>200.00 ± 0.52%</td>
</tr>
<tr>
<td>Deuteron</td>
<td>11.13 ± 2.39%</td>
<td>11.18 ± 2.39%</td>
</tr>
<tr>
<td>Triton</td>
<td>2.52 ± 4.41%</td>
<td>2.86 ± 4.27%</td>
</tr>
<tr>
<td>$^4$He</td>
<td>15.34 ± 0.98%</td>
<td>40.78 ± 2.32%</td>
</tr>
<tr>
<td>$^3$He</td>
<td>3.59 ± 3.56%</td>
<td>15.58 ± 4.31%</td>
</tr>
<tr>
<td>Li, Be, B</td>
<td>2.06 ± 2.13%</td>
<td>19.04 ± 4.70%</td>
</tr>
<tr>
<td>C, N, O</td>
<td>5.52 ± 1.29%</td>
<td>25.19 ± 2.97%</td>
</tr>
<tr>
<td>$Z = 9-13$</td>
<td>2.18 ± 1.24%</td>
<td>23.89 ± 1.71%</td>
</tr>
<tr>
<td>$Z = 14-24$</td>
<td>1.83 ± 1.17%</td>
<td>37.48 ± 1.14%</td>
</tr>
<tr>
<td>$Z = 25-28$</td>
<td>0.69 ± 2.64%</td>
<td>4.11 ± 2.51%</td>
</tr>
<tr>
<td>N</td>
<td>0.0642 ± 92.64%</td>
<td>0.3240 ± 91.68%</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>2.65 ± 20.09%</td>
<td>2.65 ± 20.09%</td>
</tr>
<tr>
<td>$e^-$</td>
<td>1.69 ± 6.69%</td>
<td>9.44 ± 8.42%</td>
</tr>
<tr>
<td>$e^+$</td>
<td>15.16 ± 1.66%</td>
<td>15.16 ± 1.66%</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>18.36 ± 1.47%</td>
<td>18.36 ± 1.47%</td>
</tr>
<tr>
<td>$\mu^+$</td>
<td>10.15 ± 1.83%</td>
<td>10.15 ± 1.83%</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>11.69 ± 1.70%</td>
<td>11.69 ± 1.70%</td>
</tr>
<tr>
<td>Total</td>
<td>307.34 ± 0.43%</td>
<td>473.13 ± 0.51%</td>
</tr>
</tbody>
</table>

- Results from HZETRN
- Influence of regolith composition

Table 3
Integrated exposure quantities on the Martian surface using regolith definitions from Table 1.

<table>
<thead>
<tr>
<th>Regolith definition</th>
<th>Dose in tissue (mGy/day)</th>
<th>Dose equivalent (mSv/day)</th>
<th>Neutron effective dose (mSv/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default SEG</td>
<td>0.172</td>
<td>0.539</td>
<td>0.163</td>
</tr>
<tr>
<td>Viking 1</td>
<td>0.174</td>
<td>0.579</td>
<td>0.176</td>
</tr>
<tr>
<td>Phoenix</td>
<td>0.167</td>
<td>0.452</td>
<td>0.124</td>
</tr>
<tr>
<td>Mawrth Vallis</td>
<td>0.173</td>
<td>0.563</td>
<td>0.174</td>
</tr>
</tbody>
</table>

* The neutron effective dose column was obtained by folding the neutron spectra from Fig. 2 with isotropic neutron fluence to effective dose conversion coefficients from Pellicioni (2000).

- Influence of atmospheric composition
- Comparison of BON2014 and DLR2013 model

Table 4
Integrated exposure quantities on the Martian surface using the BON2014 and DLR2013 GCR models.

<table>
<thead>
<tr>
<th>GCR model</th>
<th>Dose in tissue (mGy/day)</th>
<th>Dose equivalent (mSv/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BON2014</td>
<td>0.172</td>
<td>0.539</td>
</tr>
<tr>
<td>DLR2013</td>
<td>0.177</td>
<td>0.560</td>
</tr>
</tbody>
</table>

Fig. 3. Charged particle fluxes on the Martian surface using the atmosphere definitions from Table 2. The neutron and Z = 14 flux results have been scaled by $10^{-3}$ and $10^{3}$, respectively, to improve plot clarity.
Summary paper, neutral particles

- **Neutrons:**
  - differences of one order of magnitude (PHITS, HETC-HEDS, MCNP6)

- **Photons:** large underestimation of MCNP6 – $\pi^0$ transport not simulated → Underestimation of the electromagnetic cascade

Matthiä et al. The radiation environment on the surface of Mars - Summary of model calculations and comparison to RAD data. *LSSR*, in press 2017
Summary paper, electron/positron

- Large underestimation of MCNP6 – $\pi^0$ transport not simulated → Underestimation of the electromagnetic cascade
- Order of magnitude differences at $E<10\text{MeV}$
Summary paper, protons and He

Protons

He

$E / \text{MeV}$

$f / \text{(s sr cm}^2\text{MeV})^{-1}$

$E / (\text{MeV/n})$

$f / \text{(s sr cm}^2\text{(MeV/n})^{-1}$
Matthiä et al. The radiation environment on the surface of Mars - Summary of model calculations and comparison to RAD data. *LSSR*, in press 2017
• Lower energy thresholds:

<table>
<thead>
<tr>
<th>$Z$</th>
<th>1</th>
<th>2</th>
<th>3-5</th>
<th>6-8</th>
<th>9-13</th>
<th>14-24</th>
<th>&gt;24</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (MeV/n)</td>
<td>120</td>
<td>120</td>
<td>150</td>
<td>225</td>
<td>275</td>
<td>375</td>
<td>525</td>
</tr>
</tbody>
</table>
Integral particle fluxes, ratio to RAD

- Mostly between 70% and 130% of RAD
- Tendency to under-predict $Z=2$, $Z\geq 6$
Dose rates and quality factor

• No dose rates from HETC-HEDS

• Absorbed dose rates
  • Models: 0.17-0.31 mGy/d
  • RAD: 0.23 mGy/d

• Dose equivalent rates
  • Models: 0.47-0.69 mGy/d
  • RAD: 0.71 mSv/d

• Quality factor
  • Models: 1.5-3.1
  • RAD: 3.05
• Neutrons and protons contribute with more than 50%
• MCNP6: no neutron dose, energy deposition through secondary protons
• MCNP6: low e+, -, high μ, π;
Comparison of calculated and measured dose rates

**black:** first comparison, first 200 sol on Mars  
**red:** workshop results: 15 Nov 2015 - 15 Jan 2016

**NOTE:** Values in black parenthesis are the derived quality factors for a restricted zenith angle $\theta<30^\circ$.

<table>
<thead>
<tr>
<th></th>
<th>MSL-RAD</th>
<th>GEANT4</th>
<th>PHITS</th>
<th>OLTARIS2013</th>
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<td><strong>absorbed dose rate</strong> [mGy/d]</td>
<td>0.21±0.04</td>
<td>0.19</td>
<td>0.20</td>
<td>0.16</td>
<td>0.18 (-6%)</td>
<td>0.31*</td>
</tr>
<tr>
<td></td>
<td>0.23±0.01 (+10%)</td>
<td>0.21 (+11%)</td>
<td>0.25 (+25%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>dose equivalent rate</strong> [mSv/d]</td>
<td>0.64±0.12</td>
<td>0.52</td>
<td>0.60</td>
<td>0.52</td>
<td>0.54 (±0%)</td>
<td>0.47*</td>
</tr>
<tr>
<td></td>
<td>0.61±0.12 (-5%)</td>
<td>0.57 (+10%)</td>
<td>0.69 (+15%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Quality factor</strong></td>
<td>3.05±0.26</td>
<td>2.7</td>
<td>3.0</td>
<td>3.2</td>
<td>3.0</td>
<td>1.5*</td>
</tr>
<tr>
<td></td>
<td>2.62±0.14 (-14%)</td>
<td>2.8</td>
<td>2.8</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*revised values in Ratliff et al. (2017): 370 $\mu$Gy/, 996 $\mu$Sv/d, $Q=2.7$
3. Development of a parameterized radiation model for the Martian atmosphere

Based on pre-calculated tables for GCR primaries parameterized in solar activity and atmospheric shielding
Development of a parameterized radiation model

- Calculate dose rate vs depth for GCR (Z=1-28) for 3 solar modulations (low, medium and high activity)

- Calculate dose rate vs depth for GCR (H, He) for several solar modulation

- Use ratio to scale the result of GCR (H, He)

- Dose rate in Si, dose rate in tissue, dose equivalent rate
Development of a parameterized radiation model

- decrease of dose rates with depth (low solar activity)
- constant dose rates with depth (higher solar activity)
- surface effect – increase of dose rates
Development of a parameterized radiation model
Dose rate at the Martian surface (22 g/cm²)

• GCR intensity based on Neutron Monitor data!
Dose rate at the Martian surface (22 g/cm²): 2014/2015

- GCR intensity based on Neutron Monitor data!
Dose rate at the Martian surface (22 g/cm²): 2014/2015

1 Sept 2014, large on Mars, small at Earth
10 Sept 2014, small on Mars, large at Earth

[1] Forbush decreases
[2]
SEP on 10 Sep 2014, flare at N16W06

Enlil model
https://ccmc.gsfc.nasa.gov
https://www.ngdc.noaa.gov/enlil/

Solar wind density

Solar wind velocity

Energy spectrum and connection of Mars to the event/CME are likely causes for the low response measured by MSL
Summary

- Output of DLR and BO-10/BO-14 model similar (<5%); differences in dose rates ≤ 5%
- Reasonable agreement between different transport models for many particles but severe differences for others
- Calculated total dose rates are compatible with measurements, but in some cases large discrepancies in the contribution of individual particle types

- Promising results for the parameterized model for dose rate in Si and tissue (long term trends)
- Short term behavior not nicely reproduced – What could be used instead of NM data for the primary GCR intensity…?
Future work

- Continue model inter-comparison and validation applying the detector geometry

- Investigate possibilities to describe the primary GCR intensity at Mars to model the short term variations

- Investigate the discrepancies starting at around July 2015 between the parameterized model and RAD E dose rate

- Implementation of organ dose rates and solar particle events in the surface model