Particle spectra on the Martian surface – A comparison of models and MSL-RAD measurements

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Overview

• Motivation:
  • Numerical models can be used as predictive tools for human exploration
  • Validation of numerical models against experimental data is essential

• Goals:
  • Test of different Galactic Cosmic Radiation (GCR) models
  • Validation of different transport models (GEANT4, PHITS, OLTARIS, HZETRN)
  • Particle flux and dose rates on ground
  • Comparison to RAD results
The setup for the simulations

- **Atmosphere:**
  - 22 g/cm²
  - Composition (mass %): 95.7% CO₂, 2.7% N, 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° (32.3° maximum in RAD)
GCR input spectra, DLR and Badhwar/O’Neill 2010

Proton, deuteron, triton

- Zenith angle ≤30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
- **proton:** G4/PHITS best agreement, HZETRN and OLTARIS2013 overestimate
- **deuteron:** all reasonable
- **triton:** G4 good, PHITS underestimates, HZETRN and OLTARIS2013 overestimates
- HZETRN and OLTARIS2013 identical (OLTARIS2013 provided only downward flux)
$^3$He, $^4$He (alpha)

- Zenith angle $\leq$30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
- $^3$He: G4/PHITS underestimate; HZETRN and OLTARIS2013 overestimate
- $^4$He: G4 good, PHITS slightly overestimates; HZETRN and OLTARIS2013 overestimate
Proton, deuteron, triton, $^3$He, $^4$He (alpha)

- Zenith angle ≤30°
- MSL-RAD data: Ehresmann et al. 2014
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
Li/Be/B, C/N/O, Z=9-13, Z=14-24, Z≥25

- Zenith angle ≤30°
- MSL-RAD data: Ehresmann et al. 2014
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
- Li/Be/B: PHITS underestimates
- C/N/O, Z=9-13: agreement reasonable
- Z=14-24: G4 good, PHITS, HZETRN and OLTARIS2013 overestimate
- Z>24: all underestimate
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 G4/PHITS
  - HZETRN significantly lower (higher) at energies < 10MeV (>1GeV)
Electron, muon, pion

- No experimental data
- $e^-/+: G4/PHITS$ agree, HZETRN lower
- $\mu^-/+:$ differences below $100$ MeV
- $\pi^-/+:$ differences of several orders of magnitude
Pre-calculated fluence-to-dose-conversion factors $c$

- 0.5 mm slab of
  - Tissue
  - Water
  - Si

$\dot{D} = \int dE \cdot c_D \cdot f$

$\dot{H} = \int dE \cdot c_H \cdot f$
Contribution of different particles to the dose rate

- Very low neutron dose in OLTARIS2013 (no upward flux)

- High neutron dose in PHITS

- Higher dose from high-Z particles in OLTARIS2013

- Agreement of total dose within 10-20%

- MSL-RAD (Hassler et al. 2014)
  - $0.21\pm0.04 \text{ mGy/d}$
  - $0.64\pm0.12 \text{ mSv/d}$
### Comparison of calculated and measured dose rates

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

<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>
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<tbody>
<tr>
<td><strong>dose rate in tissue [mGy/d]</strong></td>
<td>0.21±0.04</td>
<td>0.19</td>
<td>0.20</td>
<td>0.16</td>
<td>0.18</td>
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<tr>
<td><strong>dose equivalent rate [mSv/d]</strong></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><strong>Quality factor</strong></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>
Comparison of calculated dose rate at Martian surface (20 g/cm² atmospheric shielding) from different G4 versions and G4 models: Dose from Z=1,2,26

- Differences below 5%-10% for absorbed dose rate
- High neutron production in the Bertini model (BERT)

→ 25% higher dose equivalent rate
Summary

• Output of DLR and BO-10 model very similar; 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

• Discrepancies in the high energy regime of some particles unresolved
## Overview of calculated dose rates at Martian surface

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<td>0.21±0.04</td>
<td>0.19 (0.021)</td>
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<td>[mGy/d]</td>
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<td><strong>dose equivalent</strong></td>
<td>0.64±0.12</td>
<td>0.52 (0.063)</td>
<td>0.51</td>
<td>0.61</td>
<td>0.60 (0.081)</td>
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### GEANT4 physics list setups

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| **[1]** Physics Lists: emstandard_opt3, G4HadronPhysicsINCLXX, G4IonINCLXX  
Models:  
Ions: INCL v5.1.14.2 (0 eV < E < 54 GeV); FTFP (53.9 GeV < E < 1 TeV)  
Neutrons/Protons: PRECO (0 eV < E < 2 MeV); INCL v5.1.14.2 (1 MeV < E < 3 GeV); Bertini (2.9 GeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) | | | |
| **[2]** Physics Lists: emstandard_opt3, user defined  
Models:  
Ions: INCL v5.1.14.2 (0 eV < E < 48 GeV); FTFP (47.999 GeV < E < 1 TeV)  
Protons: PRECO (0 eV < E < 2 MeV); INCL v5.1.14.2 (1 MeV < E < 3 GeV); Binary Cascade (2.9 GeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)  
Neutrons: NeutronHPinelastic (0 eV < E < 20 MeV); INCL v5.1.14.2 (19.9 MeV < E < 3 GeV); Binary Cascade (2.9 GeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) | | | |
| **[3]** Lists: emstandard_opt3, G4HadronPhysicsQGSP_BIC_HP, G4IonPhysics  
Models:  
Ions: Binary Light Ion Cascade (0 eV < E < 4 GeV); FTFP (2 GeV < E < 100 TeV)  
Protons: Binary Cascade (0 eV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)  
Neutrons: NeutronHPinelastic (0 eV < E < 20 MeV); Binary Cascade (19.9 MeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) | | | |
| **[4]** Physics Lists: emstandard_opt3, G4HadronPhysicsQGSP_BIC_HP, G4IonQMDPhysics  
Models:  
Ions: QMDModel (0 eV < E < 10 TeV)  
Protons: Binary Cascade (0 eV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)  
Neutrons: NeutronHPinelastic (0 eV < E < 20 MeV); Binary Cascade (19.9 MeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) | | | |
| **[5]** Physics Lists: emstandard_opt3, G4HadronPhysicsQGSP_BERT_HP, G4IonINCLXX  
Models:  
Ions: INCL v5.1.14.2 (0 eV < E < 54 GeV); FTFP (53.9 GeV < E < 1 TeV)  
Protons: BertiniCascade (0 eV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)  
Neutrons: NeutronHPinelastic (0 eV < E < 20 MeV); BertiniCascade (19.9 MeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) | | | |