Numerical estimation of Galactic Cosmic Ray (GCR) exposure in space - An Investigation of GCR models and shielding effects

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Space Radiation – A concern for human spaceflight

- GCR radiation is highly penetrating and densely ionizing and has the potential to cause biological damage
  - Assessment of radiation related health risk

- Future manned mission beyond LEO to encounter higher GCR intensity
  - Prediction of radiation exposure

- How reliable are these predictions?
  - Discrepancies found between measured and calculated dose rates for LEO

Sources of radiation in space

Credit: NASA
Contents

1. Assessment of GCR models
   Since radiation models are a necessary prerequisite for dose calculations

2. Numerical estimation of GCR exposure
   – How the differences in the GCR model spectra affect the dose rates
   – Effect of shielding
   – Exposure during the deep solar minimum in 2009 in comparison with previous solar minima

3. Summary
Assessment of GCR Models
GCR Models

- Must be able to describe the temporal variation of GCR intensity for particle range \(1 \leq Z \leq 26\) with energies between \(10^{-10} \text{ MeV/nuc}\)

- Models:
  - CREME96 (based on Nymmik et al., 1992)
  - CREME2009 (based on ISO15390, 2004)
  - Burger-Usoskin: H, He (Usoskin et al., 2005; Burger et al., 2000)
  - SPENVIS (ISO15390)

- Model spectra compared with measurements from various high altitude balloon flights and space-borne experiments

Temporal variation of GCR flux
Temporal variation of GCR flux – H nuclei

Energy range: 210 MeV/nuc - 24GeV/nuc
Temporal variation of GCR flux – H nuclei

Energy range: 210 MeV/nuc - 24GeV/nuc
A new GCR model

- GCR model developed at DLR based on ISO model for particles ranging from $1 \leq Z \leq 28$ and for periods from 1964 onwards

- based ISO model

- Solar modulation derived by fitting carbon measurements from ACE (Matthiä/ACE) and Oulu neutron monitor count rates (Matthiä/OULU)

Temporal Variation in GCR flux

- **Hydrogen nuclei**
  - (210 MeV/nuc – 20 GeV/nuc)

- **Helium nuclei**
  - (210 MeV/nuc – 20 GeV/nuc)

- **Oxygen nuclei**
  - (80-231 MeV/nuc)

- **Iron nuclei**
  - (150-460 MeV/nuc)
Temporal Variation in GCR flux

Hydrogen nuclei
(210 MeV/nuc – 20 GeV/nuc)

Helium nuclei
(210 MeV/nuc – 20 GeV/nuc)

Oxygen nuclei
(80-231 MeV/nuc)

Iron nuclei
(150-460 MeV/nuc)
Numerical estimation of GCR exposure
Monte-Carlo simulation with GEANT4

Simulation Setup

- Isotropic irradiation of a spherical water phantom of 25 cm radius either unshielded or shielded by aluminium of 0.3, 10 and 40 g/cm²
- QGSP_BERT_HP and JAM/JQMD physics models for hadronic interactions and emstandard_opt3 for electromagnetic interactions


Mrigakshi et al., Estimation of Galactic Cosmic Ray exposure inside and outside the Earth’s magnetosphere during the recent solar minimum between solar cycles 23 and 24, Adv. Space Res., 2013
GCR dose estimation (no shielding): Near-Earth interplanetary space

\[ \frac{dH}{dt} : 0.28 \text{ – } 1.43 \text{ mSv/d} \]

\[ \frac{dD}{dt} : 0.14 \text{ – } 0.47 \text{ mGy/d} \]
GCR dose estimation (no shielding): ISS orbit

\[ dH/dt: \quad \text{0.09} \text{ – 0.24 mSv/d} \]

\[ dD/dt: \quad \text{0.03} \text{ – 0.08 mGy/d} \]
Dose rates using different GCR models (no shielding)

Near-Earth Interplanetary Space

Dose equivalent rate [mSv/d]

Absorbed dose rate [mGy/d]

+100%

+55%

-25%

+45%

+30%

-20%


Year

ISS Orbit

Matthäi/ACE
CREME96
CREME2009
Badhwar-O’Neill 2010


Year

Matthäi/ACE
CREME96
CREME2009
Badhwar-O’Neill 2010
Variation of dose with shielding: Near-Earth interplanetary space

- **$dH/dt$:** Variable behaviour with increasing shielding depending on the solar activity.
- **$dD/dt$:** Increases with increasing shielding.

Peak dose rate in November 2009

<table>
<thead>
<tr>
<th>Shielding (g/cm²)</th>
<th>$dD/dt$ (mGy/d)</th>
<th>$dH/dt$ (mSv/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.47</td>
<td>1.43</td>
</tr>
<tr>
<td>0.3</td>
<td>0.47</td>
<td>1.41</td>
</tr>
<tr>
<td>10</td>
<td>0.48</td>
<td>1.19</td>
</tr>
<tr>
<td>40</td>
<td>0.53</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Highest dose rates in November 2009. Relative to the peak exposure in 1997 solar minimum, the doses are higher by 6%-10%.
Variation of dose with shielding: ISS orbit

\[ \frac{dD}{dt} \] (mGy/d):
- Increases with increasing shielding

\[ \frac{dH}{dt} \] (mSv/d):
- Increased exposure at higher shielding
- Dependence on solar activity at lower shieldings

Peak dose rate in November 2009

<table>
<thead>
<tr>
<th>Shielding (g/cm²)</th>
<th>dD/dt (mGy/d)</th>
<th>dH/dt (mSv/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.08</td>
<td>0.24</td>
</tr>
<tr>
<td>0.3</td>
<td>0.08</td>
<td>0.24</td>
</tr>
<tr>
<td>10</td>
<td>0.09</td>
<td>0.23</td>
</tr>
<tr>
<td>40</td>
<td>0.13</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Dose rates in November 2009 higher by 3%-4% relative to the peak exposure during the 1997 solar minimum.
What about SPENVIS/ISO15390?

\[
\frac{Dose_{SPENVIS/ISO15390}}{Dose_{Matthiä/ACE}} = 1.45 \quad \text{(No shielding)}
\]
What about SPENVIS/ISO15390?

\[
\frac{\text{Dose}_{\text{SPENVIS/ISO15390}}}{\text{Dose}_{\text{Matthiä/ACE}}} = 0.87 \quad \text{(No shielding)}
\]
Trapped Protons: SPENVIS and CREME

- Trapped proton spectra for ISS orbit:
  51.6°, 350km altitude

- Discrepancies between SPENVIS AP8 and CREME AP8
Summary

- Intercomparison of GCR models for dosimetry purposes and measurements:
  - Large discrepancies for various epochs during the last decade

- GCR model by Matthiä et. al 2012 shows best agreement with the measurements

- It was quantitatively shown that the choice of GCR model affects the dose estimations

- Absorbed dose and dose equivalent rates for unshielded and shielded (aluminium) water phantom were calculated

- GCR exposure during late 2009 was estimated to be the highest since 1970: possible worst-case GCR scenario
Summary

- SPENVIS/ISO15390 GCR model investigated for August 2000 (solar maximum) and November 2009 (solar minimum)
  
  - Produces higher fluxes for the year 2000 in comparison with measurements and vice-versa for the year 2009
  
  - Relative to Matthiä/ACE, the SPENVIS model yields higher dose rates by ≈45% for the year 2000 and lower by ≈13% for 2009

- Discrepancies observed for different implementations of AP8

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Thank you for your attention!
Inter-comparison of dose using different models:

- No shielding
- Large differences (up to 100%)
- Least difference between Badhwar-O’Neill2010 and Matthiä/ACE
- Dose using DLR model relative to Badhwar-O’Neill2010 in November 2009:

<table>
<thead>
<tr>
<th></th>
<th>Outside Magnetosphere</th>
<th>ISS Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>dD/dt</td>
<td>~ +28 %</td>
<td>~ +19 %</td>
</tr>
<tr>
<td>dH/dt</td>
<td>~ +25 %</td>
<td>~ +20 %</td>
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Variation of Dose Rates with Shielding

- Dose measurements Vs calculations:

  32 – 47 g/cm² in Zvezda Module, ISS (Jardrnickova et al. 2009)

<table>
<thead>
<tr>
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<th>Absorbed dose rate (µGy/d)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Measurement</td>
</tr>
<tr>
<td>May-August 2009</td>
<td>125</td>
</tr>
<tr>
<td>(Semones et al. 2009)</td>
<td></td>
</tr>
<tr>
<td>December 2009</td>
<td>100-110</td>
</tr>
<tr>
<td>(Lishnevskii et al. 2012)</td>
<td></td>
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<tr>
<td></td>
<td>Calculation (40 g/cm²)</td>
</tr>
<tr>
<td></td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>131</td>
</tr>
</tbody>
</table>

- Estimated absorbed dose rates from 0 - 40 g/cm² range from 77 - 131 µGy/d during the periods of measurements shown above

- Absorbed dose rates of about 160 µGy/d was measured in the Columbus module by Semones et al. 2010 during August-September 2009. Higher mean shielding of about 100 g/cm² was calculated by Stoffle et. al, 2012 for the module

→ Large variations in dose rates with shielding, therefore an accurate information about the amount and the distribution of shielding is essential for reasonable prediction of dose
What about SPENVIS/ISO15390?

Difference in dose rates using SPENVIS and the Matthia models (No shielding)

<table>
<thead>
<tr>
<th></th>
<th>$\frac{dD}{dt}$ ($\mu$Gy/d)</th>
<th>$\frac{dH}{dt}$ ($\mu$Sv/d)</th>
<th>$\frac{Dose_{SPENVIS/ISO15390}}{Dose_{Matthia/ACE}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPENVIS/ISO15390</td>
<td>273</td>
<td>861</td>
<td>~1.45</td>
</tr>
<tr>
<td>Matthia/ACE</td>
<td>187</td>
<td>599</td>
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What about SPENVIS/ISO15390?

Difference in dose rates using SPENVIS and the Matthia models (No shielding)

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</tr>
</thead>
<tbody>
<tr>
<td>SPENVIS/ISO15390</td>
<td>405</td>
<td>1247</td>
<td>~0.87</td>
</tr>
<tr>
<td>Matthia/ACE</td>
<td>472</td>
<td>1427</td>
<td></td>
</tr>
</tbody>
</table>
Dose rates using different GCR models (No shielding)
A new GCR model

- GCR model developed at DLR based on ISO model for particles ranging from 1≤Z≤28 and for periods from 1964 onwards

- ISO model:

\[
\phi_i(R,t) = \frac{C_i \beta^{\alpha_i}}{R^{\gamma_i}} \left[ \frac{R}{R + R_0(R,t)} \right]^{\Delta_i(R,t)}
\]

- Solar modulation derived by fitting carbon measurements from ACE (Matthiä/ACE) and Oulu neutron monitor count rates (Matthiä/OU卢)