Impact of AMS-02 Measurements on Reducing GCR Model Uncertainties

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Solar Energetic Particles, Solar Modulation and Space Radiation: New Opportunities in the AMS-02 ERA
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Outline

• Radiation exposure analysis overview
• Initial sensitivity and uncertainty quantification results
• Galactic cosmic ray (GCR) models
• Impact of AMS-02 measurements on reducing uncertainties
Exposure Analysis Overview

- Shielding models
- Environment models
- Physics models

Radiation transport models

Exposure & Biological response
Impact of GCR Model Uncertainty

- GCR protons account for >50% of the total exposure behind shielding\(^{(1)}\)
- GCR alphas are the next largest contributor
- Ions with Z > 2 and energy below 500 MeV/n (ACE) account for less than 5% of the exposure

Relative contribution (%) of each boundary ion/energy group to effective dose behind 20 g/cm\(^2\) aluminum during solar minimum\(^{(1)}\).

<table>
<thead>
<tr>
<th>Boundary energy interval (GeV/n)</th>
<th>&lt; 0.25</th>
<th>[0.25, 0.5]</th>
<th>[0.5, 1.5]</th>
<th>[1.5, 4]</th>
<th>&gt; 4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z = 1</td>
<td>1.2</td>
<td>5.4</td>
<td>18.2</td>
<td>18.4</td>
<td>14.8</td>
<td>58.1</td>
</tr>
<tr>
<td>Z = 2</td>
<td>1.2</td>
<td>2.2</td>
<td>4.1</td>
<td>2.9</td>
<td>1.7</td>
<td>12.2</td>
</tr>
<tr>
<td>Z = 3-10</td>
<td>&lt; 0.1</td>
<td>3.3</td>
<td>3.8</td>
<td>1.3</td>
<td>0.8</td>
<td>9.1</td>
</tr>
<tr>
<td>Z = 11-20</td>
<td>&lt; 0.1</td>
<td>0.2</td>
<td>6.6</td>
<td>2.0</td>
<td>1.1</td>
<td>10.0</td>
</tr>
<tr>
<td>Z = 21-28</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>4.7</td>
<td>3.8</td>
<td>2.1</td>
<td>10.6</td>
</tr>
<tr>
<td>Totals</td>
<td>2.5</td>
<td>11.1</td>
<td>37.4</td>
<td>28.4</td>
<td>20.5</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Impact of GCR Model Uncertainty

- GCR model uncertainty induces roughly +20% error on effective dose$^{(2)}$
  - Results below for Badhwar-O’Neill (BON) 2014 GCR model$^{(3)}$

![Effective dose versus shield thickness during solar minimum](image)

- Error bars represent uncertainty associated with GCR model only
- For nominal vehicle shielding (>10 g/cm$^2$), relative errors are roughly +20%

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The Badhwar O’Neill (BON) galactic cosmic ray model is used at NASA as input into radiation transport codes for:
- vehicle design, mission analysis, astronaut risk analysis
- other models used as well (discussed in later slides)

BON model revisions are based on the same fundamental framework:
- Model equations are solved to describe particle transport through solar system
- Solar activity is described by a single parameter related to observed sunspot numbers
International Models and Comparisons

• GCR models tend to agree reasonably well at highest energies\(^{(2)}\)
  – Effects of solar modulation are less pronounced
  – Significant contributor to exposure behind shielding

GCR proton & alpha flux compared to measurements

• Matthia et al. (DLR) recently developed a simplified form of Nymmik’s model\(^{(6)}\)
  – Shown to be reasonably accurate\(^{(2,6)}\)

• Nymmik (MSU) has developed a semi-empirical model\(^{(4,5)}\) (not shown)
  – Used by Russian Space Agency & others (DLR, ESA)
  – Official update has not been provided recently

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International Models and Comparisons

- Exposures behind shielding are in good agreement if updated GCR models are used
  - BON2014 and Matthia are within 10% of each other, on average, over past 40 years
GCR Model Development

- GCR models are developed and validated using available measurements
  - Short duration, high energy, balloon and satellite measurements
  - Low energy, continuous measurements from ACE/CRIS (most of the available measurements)
  - Current gap in measurement database for continuous, high energy measurements

<table>
<thead>
<tr>
<th>Name</th>
<th>Flight</th>
<th>Time</th>
<th>Ions (Z)</th>
<th>Energy (GeV/n)</th>
<th>Data pts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE/CRIS</td>
<td>Satellite</td>
<td>1998-present</td>
<td>5-28</td>
<td>0.05 – 0.5</td>
<td>8288</td>
</tr>
<tr>
<td>AMS</td>
<td>STS-91</td>
<td>1998</td>
<td>1, 2</td>
<td>0.1 – 200</td>
<td>58</td>
</tr>
<tr>
<td>ATIC-2</td>
<td>Balloon</td>
<td>2002</td>
<td>1, 2, 6, 8, 10,…, 14, 26</td>
<td>4.6 – 10^3</td>
<td>55</td>
</tr>
<tr>
<td>BESS</td>
<td>Balloon</td>
<td>1997-2000, 2002</td>
<td>1, 2</td>
<td>0.2 – 22</td>
<td>300</td>
</tr>
<tr>
<td>CAPRICE</td>
<td>Balloon</td>
<td>1994, 1998</td>
<td>1, 2</td>
<td>0.15 – 350</td>
<td>93</td>
</tr>
<tr>
<td>CREAM-II</td>
<td>Balloon</td>
<td>2005</td>
<td>6-8, 10, 12, 14, 26</td>
<td>18 – 10^3</td>
<td>42</td>
</tr>
<tr>
<td>HEAO-3</td>
<td>Satellite</td>
<td>1979</td>
<td>4-28</td>
<td>0.62 – 35</td>
<td>331</td>
</tr>
<tr>
<td>IMAX</td>
<td>Balloon</td>
<td>1992</td>
<td>1, 2</td>
<td>0.18 – 208</td>
<td>56</td>
</tr>
<tr>
<td>IMP-8</td>
<td>Satellite</td>
<td>1974</td>
<td>6, 8, 10, 12, 14</td>
<td>0.05 – 1</td>
<td>53</td>
</tr>
<tr>
<td>LEAP</td>
<td>Balloon</td>
<td>1987</td>
<td>1, 2</td>
<td>0.18 – 80</td>
<td>41</td>
</tr>
<tr>
<td>MASS</td>
<td>Balloon</td>
<td>1991</td>
<td>1, 2</td>
<td>1.6 – 100</td>
<td>41</td>
</tr>
<tr>
<td>PAMELA</td>
<td>Satellite</td>
<td>2006-2009</td>
<td>1, 2</td>
<td>0.08 – 10^3</td>
<td>472</td>
</tr>
<tr>
<td>TRACER</td>
<td>Balloon</td>
<td>2003</td>
<td>8, 10, 12,…, 20, 26</td>
<td>0.8 – 10^3</td>
<td>55</td>
</tr>
<tr>
<td>Lezniak</td>
<td>Balloon</td>
<td>1974</td>
<td>4-14, 16, 20, 26</td>
<td>0.35 – 52</td>
<td>131</td>
</tr>
<tr>
<td>Minagawa</td>
<td>Balloon</td>
<td>1975</td>
<td>26, 28</td>
<td>1.3 – 10</td>
<td>16</td>
</tr>
<tr>
<td>Muller</td>
<td>STS-51</td>
<td>1985</td>
<td>6, 8, 10, 12, 14</td>
<td>50 – 10^3</td>
<td>16</td>
</tr>
<tr>
<td>Simon</td>
<td>Balloon</td>
<td>1976</td>
<td>5-8</td>
<td>2.5 – 10^3</td>
<td>46</td>
</tr>
</tbody>
</table>

82% of available data
Recent work has significantly reduced model uncertainties (3)

- More rigorous approach to model calibration and validation – resulted in BON2014
- Determined measurements (energies) most important for exposure quantities behind shielding
- Model parameters calibrated using optimization methods with an emphasis on higher energies
- Comprehensive validation metrics applied to quantify model uncertainty
- Process can include new measurements and is repeatable

Impact of AMS-02 Data

• Widely used GCR models are mainly semi-empirical
  – Data is needed to refine free parameters in models

• AMS-02 data will serve two important functions
  – Provide substantial data for independent validation
    (i.e. data not used to tune model)
  – Fill important data gaps to enable improved parameter calibration

• Current schedule for using AMS-02 for GCR measurements is mainly driven by impact on exposure
  – Monthly GCR proton measurements for energies greater than 500 MeV
  – Next step is to analyze GCR alphas
  – Specific heavy ions will be emphasized later
Impact of AMS-02 Data

- If GCR proton and alpha uncertainty is cut in half
  - Uncertainty estimate drops from roughly $\pm 20\%$ to $\pm 15\%$

**Graph: Effective dose versus shield thickness during solar minimum**

- Error bars represent uncertainty associated with GCR model only
- Blue error bars represent current model uncertainties
- Red error bars represent assumed modified uncertainties with AMS-02 measurements
Impact of AMS-02 Data

- If GCR proton and alpha uncertainty is entirely removed
  - Uncertainty estimate drops from roughly $+20\%$ to $+5\%$

**Effective dose versus shield thickness during solar minimum**

- Error bars represent uncertainty associated with GCR model only
- Blue error bars represent current model uncertainties
- Red error bars represent assumed modified uncertainties with AMS-02 measurements
Summary

• Widely used GCR models rely on available measurements
  – Measurements used directly for development and validation
  – Updated models are in reasonable agreement
  – GCR models induce roughly ±20% uncertainty on effective dose behind shielding

• AMS-02 will fill an important gap in the measurement database
  – Significant need for high energy, time-resolved proton and alpha measurements
  – Current measurement database is dominated by ACE/CRIS
  – ACE/CRIS measurement domain induces less than 5% of exposure behind shielding

• Proton and alpha measurements from AMS-02 will reduce model uncertainties
  – Possibility exists to have a significant impact on reducing overall exposure uncertainties


