Radiation Dose Assessments of Solar Particle Events with Spectral Representation at High Energies for the Improvement of Radiation Protection

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Solar Proton Spectra for Radiation Analysis

Functional Forms with Measurements up to 100 MeV

- Exponential in Rigidity\(^1\) : \( \Phi(>R)=J_0 \exp(-R/R_0) \)
- Exponential in Energy\(^2\) : \( \Phi(>E)=J_0 \exp(-E/E_0) \)
- Sum of Two Exponentials\(^3,4\) : \( \Phi(>E)=J_1 \exp(-E/E_1) + J_2 \exp(-E/E_2) \)
- Weibull Fuction in Energy\(^5,6\) : \( \Phi(>E)=J_0 \exp(-\kappa E^\alpha) \)

These spectral representations are also correct for high energies?

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Fit to Proton Fluence Measurements up to 100 MeV for Continuous Energy Spectrum

\[ \Phi(> E) = 1.91 \times 10^{12} e^{-2.5677 E^{0.256}} \]

\[ \Phi(> E) = 5.644 \times 10^{10} e^{-\sqrt{E \times (E+1876)}/92.469} \]
Solar Proton Spectra for Radiation Analysis of SPE

Ground-Level Enhanced (GLE) events observed from worldwide neutron monitor (NM) network for proton spectra above ~430 MeV (1 GV): 66 GLEs have been observed since 1956.

→ Functional form of *Band function fit (a double power law in rigidity) based on the combined measurements from ~10 MeV to ~10 GeV for accurate solar proton spectra.

Converting NM Data to Absolute Normalized Fluence Measurements:

- Each station at a geographical position implies a characterization of the flux of charged particles arriving at the magnetosphere (arrival direction and rigidity/energy).
- The combination of NM stations with the Earth's atmosphere and magnetosphere forms a unique instrument with directional and energy resolution.
- Advantage of using all stations as a unified multidirectional detector: substantially higher (less than 0.1% for hourly data) accuracy than for a single instrument.

New Technique (Tylka and Dietrich, 2009) for Analyzing GLE NM Data:

- Pressure-corrected data from the world-wide NM network
- Yield functions (Clem and Dorman, 2000)
- Cutoff code “RcUT3” (Smart et al., 2006)
- Altitude correction (McCracken, 1962)

→ Absolute Normalization and Spectral Index

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Functional Form of Event-Integrated GLE Proton Spectra for Radiation Analysis of Large SPEs

Band Function with 4 Parameters ($J_0$, $\gamma_1$, $\gamma_2$, $R_0$): Double Power Law in Rigidity

$$\Phi(> R) = J_0 R^{-\gamma_1} e^{-R/R_0}$$

for $R \leq (\gamma_2 - \gamma_1)R_0$

$$\Phi(> R) = J_0 R^{-\gamma_2} \left\{ \left[ (\gamma_2 - \gamma_1)R_0 \right]^{(\gamma_2 - \gamma_1)} e^{(\gamma_1 - \gamma_2)} \right\}$$

for $R \geq (\gamma_2 - \gamma_1)R_0$

Differential Energy Spectra of Band Function

$$\frac{d\Phi}{dE} = \frac{d\Phi}{dR} \frac{dR}{dE} = \left( J_0(\gamma_1)R^{-\gamma_1-1} e^{-R/R_0} + J_0(\gamma_1)R^{-\gamma_1} \left( -\frac{1}{R_0} \right) e^{-R/R_0} \right) \frac{dR}{dE}$$

$$= J_0 e^{-R/R_0} \left( \frac{\gamma_1}{R} + \frac{1}{R_0} \right) R^{-\gamma_1} \frac{dR}{dE}$$

for $R \leq (\gamma_2 - \gamma_1)R_0$

$$\frac{d\Phi}{dE} = \frac{d\Phi}{dR} \frac{dR}{dE} = J_0(\gamma_2)R^{-\gamma_2-1} \left\{ \left[ (\gamma_2 - \gamma_1)R_0 \right]^{(\gamma_2 - \gamma_1)} e^{(\gamma_1 - \gamma_2)} \right\} \frac{dR}{dE}$$

for $R \geq (\gamma_2 - \gamma_1)R_0$

$$\frac{dR}{dE} = 10^{-3} \frac{A}{Z \times \beta(E)}$$

Where,

$R$ in GV, $E$ in MeV, and $\beta(E)$ is the proton velocity relative to the speed of light.
GLE SPE Spectrum Comparison:
Exponential, Weibull, & Band Functions

Feb 1956
Nov 1960
Aug 1972
Sept 1989
Oct 1989
Event-Integrated Integral Energy Spectra

February 23, 1956

\( \Phi(>E), \text{p/cm}^2 \)

\( E, \text{MeV} \)

Exponential

Weibull

Band
Event-Integrated Integral Energy Spectra

November 12-15, 1960

August 4-7, 1972

9/29-10/2, 1989

October 19-24, 1989

$\Phi (>E), \text{p/cm}^2$

$E, \text{MeV}$

King Weibull Band Data by King 1974
Event-Integrated Differential Energy Spectra

February 23, 1956

$\phi(E), \frac{1}{(cm^2\cdot MeV)}$

$E, \text{MeV}$

- Exponential
- Weibull
- Band
Event-Integrated Differential Energy Spectra

November 12-15, 1960

August 4-7, 1972

9/29-10/2, 1989

October 19-24, 1989

\( \phi(E), \text{1/(cm}^2-\text{MeV)} \)
Tissue Weighting Factors (ICRP 2007)

\[ E = \sum_{T} w_{T} H_{T} \]

<table>
<thead>
<tr>
<th>Tissue/organ</th>
<th>( w_{T} )</th>
<th>( \Sigma w_{T} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone-marrow, Lung, Stomach, Breast, Remainder Tissues*</td>
<td>0.12</td>
<td>0.72</td>
</tr>
<tr>
<td>Gonads</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Bladder, Esophagus, Liver, Thyroid</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>Bone surface, Brain, Salivary glands, Skin</td>
<td>0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>

*Remainder Tissues: Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate, Small intestine, Spleen, Thymus, Uterus/cervix.
Effective dose (mSv) for male crew members on the Lunar Surface

- 23 Feb. 1956
- 12-15 Nov. 1960
- 4-7 Aug. 1972 SPE
Effective dose (mSv) for male crew members on the Lunar Surface

- Sept. 29-Oct. 2, 1989 SPE

Graphs showing the effective dose (E, mSv) versus average air composition weight (X_{Air}, g/cm²) for two different periods.
Proton Spectra with Spectral Representation at High Energies: Band Function Fit

![Graph showing proton spectra with spectral representation at high energies. The graph plots the flux, Φ(E), in protons/cm² as a function of energy, E, in MeV. Different data sets are represented with lines and markers for specific dates: 23 Feb. 1956, 12-15 Nov. 1960, 4-7 Aug. 1972, 9/29-10/2/89, and 19-24 Oct. 1989. The x-axis represents energy in MeV, ranging from 10 to 1000, and the y-axis represents flux in protons/cm², ranging from 10² to 10¹¹. The graph highlights the spectral distribution and variability over time.]
BFO dose for Males on the Lunar Surface
SPEs with Spectral Representations at High Energies

- 23 Feb. 1956
- 12-15 Nov. 1960
- 29 Sept. 1989
- 4-7 Aug. 1972

NASA 30-d limit
The Carrington Event on 1 September 1859

Simulated Distribution of $\Phi_{30}$ for Mission Period
Proton Spectra at the Median Fluence of 180-d with Various Band Function Fits

Φ > E, protons/cm² vs. E, MeV

- Spec_Feb56
- Spec_Nov60
- Spec_Oct89
- Spec_Sep89
- Spec_Aug72
BFO dose for Males for 180-d Interplanetary Space with the Median Fluence of GLE SPE Spectra
Proton Spectra at the Upper 95% Fluence of 180-d with Various Band Function Fits
Proton Spectra of the Carrington Event with Various Band Function Fits

$\Phi > E$, protons/cm$^2$

$E$, MeV

Spec_Feb56
Spec_Nov60
Spec_Oct89
Spec_Sep89
Spec_Aug72
BFO dose of Male for 180-d Interplanetary Space the Upper 95% Fluence with GLE SPE Spectra

**Graph Details:**
- **X-axis:** $X_{Al}$, g/cm²
- **Y-axis:** BFO dose, mGy-Eq
- **Colors:**
  - Blue: 23 Feb. 1956
  - Red: 12-15 Nov. 1960
  - Green: 4-7 Aug. 1972
  - Purple: 29 Sept. 1989
- **Lines:**
  - Black: NASA 30-d limit
  - Dashed Black: ARR_threshold
BFO dose for Males during a 180-d Lunar Mission
Upper 95% Fluence with GLE SPE Spectra

August 1972 SPE: the design standard
~70% spectral hardness

BFO dose, mGy-Eq

$X_{\text{Al}}$, g/cm²

23 Feb. 1956
12-15 Nov. 1960
29 Sept. 1989
4-7 Aug. 1972

ABR threshold
NASA 30-d limit
Concluding Remarks

• Band Function Fit for Ground-Level Enhanced (GLE) SPEs:
  - Smoothly rolled one to the other power-law functions:
    - Spectral index at low energies from satellite data
    - Spectral index at high energies from NM data
  - Accurate spectral representation of event-integrated integral fluence:
    - Band function fit based on the combined data from ~10 MeV to ~10 GeV
    - Conventional representations made using on-board satellite detectors up to ~100 MeV

Accurate knowledge of the proton fluences and event-integrated differential energy spectra is applied for the radiation analysis of 5 GLE SPEs.
Comparison of spectrum and effective dose with 3 Functional forms for 5 GLE SPEs: The spectral determination by exponential/Weibull extrapolation in proton energy underestimates the actual proton spectrum above 100 MeV.

- 23 Feb. 1956 SPE:
  - Overestimated proton fluence and the resultant higher effective dose in exponential spectrum.
  - Weibull and Band functions agree well with each other.

- 12-15 Nov. 1960 SPE:
  - Higher effective dose at thin shielding by overestimated low energy proton fluence in Weibull function decreases faster at thick shielding by underestimated high energy proton fluence.

- 4-7 Aug. 1972 SPE:
  - Overestimated King spectrum at 60-200 MeV (IMP series of spacecraft: systematically higher rate of an instrument of > 60 MeV channel on IMP8).
  - Lower effective dose in Band function spectrum, because the decrease in fluence at 60-200 MeV outweighs the increase above ~300 MeV.

  - Qualitatively the same effective dose with three spectral forms, because small decrease in fluence at 60-200 MeV compensates the increase above ~300 MeV in Band function spectrum.
• Radiation dose assessments with spectral representation at high energies

- **Proton spectra** with spectral representation at high energies:
  - Exposure attenuation: Feb. 1956 is the most and Aug. 1972 is the least in the spectral hardness among 5 GLE SPEs studied in the current study.

- **BFO dose during a 180-d mission in interplanetary space:**
  - Fluence at median with various GLE spectra: BFO dose within NASA 30-d limit, with no ARR symptom.
  - Fluence at upper 95% (near the Carrington event) with various GLE spectra: More than 15 g/cm² shielding required for the Carrington-like event size with 4 spectral hardness of GLE SPEs except the Aug 1972.

- Exposure to upper 95% fluence with various GLE spectra during **180-d lunar mission**: Radiation dose is dependent on total fluence and spectral hardness.
  - No threat to astronauts from large fluence at the upper 95% level with a relatively soft spectrum of Aug. 1972 SPE.
  - Threat to astronauts from the same fluence with harder spectra, such as Feb. 1956 SPE.
### Result

**Shielding Requirement during 180-d Lunar Mission Against the Upper 95% Fluence with Various GLE SPE Spectra**

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Aluminum shielding requirement, g/cm²</th>
<th>NASA 30-d limit</th>
<th>ARR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb. 1956 SPE</td>
<td>50</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>Nov. 1960 SPE</td>
<td>28</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Oct. 1989 SPE</td>
<td>17</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Sept. 1989 SPE</td>
<td>17</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Aug. 1972 SPE</td>
<td>4</td>
<td></td>
<td>EVA suit</td>
</tr>
</tbody>
</table>