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

Myung-Hee Y. Kim¹, William Atwell², Allan J. Tylka³, William F. Dietrich³,⁴, and Francis A. Cucinotta⁵

¹DSLS, Universities Space Research Association, Houston, TX 77058, USA
²The Boeing Company, Houston, TX 77059, USA
³Space Science Div., Naval Research Laboratory, Washington, DC 20375, USA
⁴Consultant
⁵NASA Johnson Space Center, Houston, TX 77058, USA

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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 Function 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

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

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

Ground-Level Enhanced (GLE) events observed from the 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.

World-Wide Neutron Monitor (NM) Network Map

Source: Neutron Monitor Program, Bartol Research Institute, U. of Delaware
World-Wide Neutron Monitor (NM) Network

Converting NM Data to Absolute Normalized Fluence Measurements:

- Each station at a geographical position → 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 → a unique instrument with directional and energy resolution.
- Advantage of the use of all stations as a unified multidirectional detector → Substantially higher (< 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

\[
\Phi(> R) = J_0 R^{-\gamma_1} e^{-R/R_0} \quad \text{for } R \leq (\gamma_2 - \gamma_1) R_0
\]

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

Differential Energy Spectra of Band Function

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

\[
= J_0 e^{-R/R_0} \left( \frac{\gamma_1}{R} + \frac{1}{R_0} \right) R^{-\gamma_1} \frac{dR}{dE} \quad \text{for } R \leq (\gamma_2 - \gamma_1) R_0
\]

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

\[
\frac{dR}{dE} = 10^{-3} \frac{A}{Z \times \beta(E)} \quad \text{Where,}
\]

\(R\) 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

$\Phi(>E)$, p/cm²

E, 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

Exponential
Weibull
Band

Data by King 1974
Event-Integrated Differential Energy Spectra

February 23, 1956

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

$E, \text{MeV}$

Graph showing different models of energy spectra:
- Exponential
- Weibull
- Band

$10^0$, $10^1$, $10^2$, $10^3$, $10^4$, $10^5$, $10^6$, $10^7$, $10^8$ on the Y-axis.

$10$, $100$, $1000$, $10000$ on the X-axis.
Event-Integrated Differential Energy Spectra

- **November 12-15, 1960**
- **August 4-7, 1972**
- **9/29-10/2, 1989**
- **October 19-24, 1989**
## Tissue Weighting Factors (ICRP 2007)

The equation for calculating the effective dose ($E$) is given by:

$$E = \sum_T w_T H_T$$

<table>
<thead>
<tr>
<th>Tissue/organ</th>
<th>$w_T$</th>
<th>$\sum w_T$</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

Exponential
Weibull
Band

12-15 Nov. 1960

1-7 Aug. 1972 SPE
Effective dose (mSv) for male crew members on the Lunar Surface

**Sept. 29-Oct. 2, 1989 SPE**

- Exponential
- Weibull
- Band

**19-24 Oct. 1989 SPE**

- Exponential
- Weibull
- Band
Proton Spectra with Spectral Representation at High Energies: Band Function Fit

$\Phi > E$, protons/cm²

$E$, MeV

- 23 Feb. 1956
- 12-15 Nov. 1960
- 4-7 Aug. 1972
- 9/29-10/2/89
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

BFO dose, mGy

$X_{Al} \ g/cm^2$

20 30 40 50

0 10 20 30 40 50
Simulated Distribution of $\Phi_{30}$ for Mission Period

The Carrington Event on 1 September 1859
Proton Spectra at the Median Fluence of 180-d with Various Band Function Fits

- Spec_Feb56
- Spec_Nov60
- Spec_Oct89
- Spec_Sep89
- Spec_Aug72

$\Phi > E$, protons/cm²

$E$, MeV
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

\[ \Phi > E, \text{protons/cm}^2 \]

- Spec_Feb56
- Spec_Nov60
- Spec_Oct89
- Spec_Sep89
- Spec_Aug72

E, MeV

\(10, 100, 1000, 10000, 100000, 1000000, 10000000, 100000000, 1000000000, 10000000000, 100000000000\)
Proton Spectra of the Carrington Event with Various Band Function Fits

\[ \Phi(E, \text{protons/cm}^2) \]

\[ E, \text{MeV} \]

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

BFO dose, mGy-Eq

$X_{Al}$, g/cm$^2$

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

NASA 30-d limit
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
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.

- **9/29-10/2 1989 SPE and 19-24 Oct. 1989 SPE:**
  - 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.
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>