Example Solar Proton Event Data

NASA JSC
August 30, 2006
Times of Occurrence of Large SPE's

Fig. 1. The times of occurrence of >30 MeV solar proton events with fluence exceeding $1.0 \times 10^8$/cm$^2$, and the annual international sunspot numbers.

Modern Era (1956-2005)

Recent Era (1550-2000)

McKracken et al.
Projections of Cycles and Mean Occurrence Frequency of SPE

Cycle 23
Population distribution level, percent

90
70
50
30
10

Smoothed sunspot number

Cycle 24
Projected smoothed sunspot number at level, percent

80
75
70

<ν(t)>:
Φ_{30} \geq 10^5
Φ_{30} \geq 10^6

M. Kim and F. Cucinotta
### Large Solar Proton Events during Solar Cycles 19-23 with $\Phi_{30} > 10^9$ protons/cm$^2$

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Onset Time</th>
<th>$\Phi_{30}$, protons/cm$^2$</th>
<th>Time to Peak Flux, hr</th>
<th>Comment</th>
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</thead>
<tbody>
<tr>
<td>19</td>
<td>11/12/1960</td>
<td>$9.00 \times 10^9$</td>
<td>14</td>
<td>(a), note 1</td>
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<tr>
<td>20</td>
<td>8/2/1972</td>
<td>$5.00 \times 10^9$</td>
<td>69</td>
<td>(a)</td>
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<tr>
<td>22</td>
<td>10/19/1989 13:05</td>
<td>$4.23 \times 10^9$</td>
<td>26.9</td>
<td>(b)</td>
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<tr>
<td>23</td>
<td>7/14/2000 10:45</td>
<td>$3.74 \times 10^9$</td>
<td>25.8</td>
<td>(b)</td>
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<tr>
<td>23</td>
<td><strong>10/26/2003 18:25</strong></td>
<td>$3.25 \times 10^9$</td>
<td>4.2</td>
<td>(b), note 2</td>
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<td>23</td>
<td>11/4/2001 17:05</td>
<td>$2.92 \times 10^9$</td>
<td>33.2</td>
<td>(b)</td>
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<td>19</td>
<td>7/10/1959</td>
<td>$2.30 \times 10^9$</td>
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<td>(a)</td>
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<td>23</td>
<td>11/8/2000 23:50</td>
<td>$2.27 \times 10^9$</td>
<td>16.1</td>
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<td>22</td>
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<td>$1.74 \times 10^9$</td>
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<td>22</td>
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<tr>
<td>22</td>
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<td>14.1</td>
<td>(b)</td>
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<td>23</td>
<td><strong>1/16/2005 2:10</strong></td>
<td>$1.04 \times 10^9$</td>
<td>39.7</td>
<td>(b)</td>
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<tr>
<td>19</td>
<td>2/23/1956</td>
<td>$1.00 \times 10^9$</td>
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<td>(a)</td>
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</tbody>
</table>

(a) $\Phi_{30}$ for solar cycle 19-21: data taken from Shea and Smart.
(b) $\Phi_{30}$ for solar cycle 22 and 23: calculated using corrected 5-min average proton flux of GOES measurements.

**Note 1:** There are large differences in the estimate of fluence in November 1960 SPE. Data given by others are significantly smaller than this value ($1.3 \times 10^9$ protons/cm$^2$ by Freier and Webber).

**Note 2:** $\Phi_{30}$ for the combined 3 major peaks occurred during 10/26-11/6/2003: $3.42 \times 10^9$ protons/cm$^2$.

**Note 3:** one day later on July 11, 1959

**Note 4:** in the same day on February 23, 1956

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BFO Cumulative Dose
August 2-11, 1972 SPE

Cumulative Dose Equivalent, cSv

- Current 30-day limit

Al thickness, g/cm²:
- 0
- 1
- 3
- 5
- 10
- 15
- 20
- 30

Time, h
82 BFO Locations

- 32 location set
- 50 location set
Hourly-Averaged Proton Integral Flux during Oct 26 - Nov 6, 2003 SPE

Flux, protons/cm²-s

E \geq 30 \text{ MeV}
E \geq 60 \text{ MeV}
E \geq 100 \text{ MeV}

Time, h
BFO Dose Rate during Oct 26 - Nov 6, 2003 SPE
Hourly-Averaged Proton Integral Flux
Oct 26 - Nov 6, 2003 SPE

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Hourly-Averaged Proton Integral Flux
January 16-22, 2005 SPE

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BFO Dose Rate
January 16-22, 2005 SPE

Time, h

Dose Rate, cGy-Eq/h

Al thickness, g/cm²

0 20 40 60 80 100 120 140 160 180

1 E-05 1 E-04 1 E-03 1 E-02 1 E-01

1 cGy/h

0 1 3 5 10 15 20 30

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BFO Cumulative Dose
January 16-22, 2005 SPE

Cumulative Dose Equivalent, cSv

Current 30-day limit

Time, h

AL(0)
AL(1)
AL(3)
AL(5)
AL(10)
AL(15)
AL(20)
AL(30)
Role of Dose-Rate and Shielding

- Shielding mitigates most SPE events
  - High-energy component (>100 MeV) often poorly known
- Proton biological damage is dependent on dose-rate
  - Effects increase above ~5 rad/hr

EVA Today (Y/N?)
IVA (time to storm shelter)

FIG. 9. Predicted BFO dose-rate variation and cumulative dose during the October 1989 event with 0.5, 2.0, 5.0, and 10.0 cm thickness. (a) BFO dose equivalent rate; (b) cumulative BFO dose equivalent.
Large SPE Integral Fluence Spectra at 1AU

- Feb 1956 SPE
- Aug 1972 SPE
- Nov 1960 SPE
- Oct 2003 SPE

$\Phi_p(p>E)$, protons/cm²

Kinetic energy, MeV
From Nymik - COSPAR

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The Average BFO Doses of the Regions at 6 DLOCs from 1972 SPE

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Was Carrington Event (1859) Lethal?

1859 event has largest F>30 Flux known

Blood Forming Organ Dose, cGy-Eq

- % Probability in 2-Week Missions
- Proton Fluence >30 MeV per cm²

Mission disruption-days lost?
Increased fatal cancer risk and other late effects

3 missions/year for 5-yr Program
Single Mission
Modern data (1956-2005)

Conditions under Apollo Spacecraft -type shielding

Ice-Core data
-F>30MeV flux from 1450-1990

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Large SPE’s

Fig. 4. Cumulative probabilities of the SPEs observed by satellite, and derived from the nitrate data. The diamond shaped symbols refer to the nitrate data; the histogram and lines to the satellite data and fluence limits derived from cosmogenic isotopes in moon rocks.
Long-Term Forecasting

Climax Neutron Monitor and Deceleration Potential ($\Phi$)

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SPE Probability in 1-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space

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Frequency of SPE Occurrence in 3-Month Periods

\( \Phi_{30} > 10^8 \text{ protons/cm}^2 \) for Solar Cycle 21.

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Frequency of SPE Occurrence in 3-Month Periods

$\Phi_{30} > 10^9$ protons/cm$^2$ for Solar Cycle 22.

![Graph showing frequency of SPE occurrence over time.](image)
Frequency of SPE Occurrence in 3-Month Periods

\( \Phi_{30} > 10^9 \text{ protons/cm}^2 \) for Solar Cycle 23.
GCR and SPE Dose: Materials & Tissue
GCR higher energy >> secondary radiation

No Tissue Shielding

With Tissue Shielding

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Risk and Uncertainties increase with Linear Energy Transfer (LET)

Dose = Flux x LET
Biological Dose \( H = Dose \times Q(L) \)
REID = Risk of exposure induced death = \( H \times R_0(\text{sex, age}) \)

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## Accuracy of Space Radiation Transport Models

### Absolute Predictions from HZETRN and Flight Measurements

<table>
<thead>
<tr>
<th>Mission</th>
<th>DATE</th>
<th>Inclination</th>
<th>Altitude</th>
<th>Shielding</th>
<th>Dose, mGy/d</th>
<th>Dose Eq., mSv/d</th>
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<td></td>
<td></td>
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<td>Measured</td>
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<td>51.6</td>
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<td>0-sphere</td>
<td>0.147</td>
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<td>1997</td>
<td>51.6</td>
<td>400</td>
<td>Poly 3-in</td>
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<td>1997</td>
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<td>400</td>
<td>Poly 8-in</td>
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<td>51.6</td>
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<td>Poly 12-in</td>
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<td>Al 7-in</td>
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<td>STS-89</td>
<td>1998</td>
<td>51.6</td>
<td>393</td>
<td>Al 9-in</td>
<td>0.171</td>
<td>0.162</td>
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</tbody>
</table>

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Model vs. Phantom Expt. (STS and ISS)

### Phantom Data on STS-91 for Trapped + GCR (51.6 x 390 km)

<table>
<thead>
<tr>
<th>Organ</th>
<th>Measured (mGy)</th>
<th>Theory (mGy)</th>
<th>Theory* (mGy)</th>
<th>% Difference</th>
<th>% Difference*</th>
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<tbody>
<tr>
<td>Brain</td>
<td>2.23</td>
<td>2.42</td>
<td>2.26</td>
<td>-8.5</td>
<td>-1.4</td>
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<tr>
<td>Bone Surface</td>
<td>2.16</td>
<td>2.36</td>
<td>2.21</td>
<td>-9.3</td>
<td>-2.1</td>
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<td>Esophagus</td>
<td>1.71</td>
<td>1.79</td>
<td>1.67</td>
<td>-4.7</td>
<td>2.2</td>
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<tr>
<td>Lung</td>
<td>1.92</td>
<td>1.81</td>
<td>1.69</td>
<td>5.7</td>
<td>11.9</td>
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<tr>
<td>Stomach</td>
<td>2.05</td>
<td>2.08</td>
<td>1.94</td>
<td>-1.5</td>
<td>5.2</td>
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<tr>
<td>Liver</td>
<td>1.88</td>
<td>2.15</td>
<td>2.01</td>
<td>-14.4</td>
<td>-6.9</td>
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<td>Spinal Column</td>
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<td>1.98</td>
<td>1.85</td>
<td>-20.0</td>
<td>-12.1</td>
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<td>Bone Marrow</td>
<td>1.75</td>
<td>1.98</td>
<td>1.85</td>
<td>-13.1</td>
<td>-5.7</td>
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<td>Colon</td>
<td>1.71</td>
<td>1.9</td>
<td>1.78</td>
<td>-11.1</td>
<td>-3.8</td>
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<td>Bladder</td>
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<td>1.87</td>
<td>1.75</td>
<td>-18.4</td>
<td>-10.6</td>
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<td>Gonad</td>
<td>1.75</td>
<td>1.85</td>
<td>1.73</td>
<td>-5.7</td>
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<td>Skin/Breast</td>
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<td>2.58</td>
<td>2.41</td>
<td>-4.9</td>
<td>2.0</td>
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<td>Skin/Abdomen</td>
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<td>2.58</td>
<td>2.41</td>
<td>-9.8</td>
<td>-2.6</td>
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*Includes a correction to TLD efficiency vs. LET.

### CALCULATIONS & % DIFFERENCES

<table>
<thead>
<tr>
<th></th>
<th>TRAPPED (mGy/day)</th>
<th>GCR (mGy/day)</th>
<th>TOTAL (mGy/day)</th>
<th>DIFF. (C-M)/M</th>
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<tbody>
<tr>
<td>BRAIN</td>
<td>0.066</td>
<td>0.077</td>
<td>0.143</td>
<td>13.3</td>
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<td>THYROID</td>
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<td>0.148</td>
<td>9.4</td>
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<td>HEART</td>
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<td>0.138</td>
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<td>STOMACH</td>
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<td>0.056</td>
<td>0.076</td>
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<td>LIVER</td>
<td>0.053</td>
<td>0.077</td>
<td>0.130</td>
<td>-4.0</td>
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HZETRN Comparisons to GCR Secondary Energy Spectra on STS 48
- Because of Earth Magnetic Cutoff predominantly secondary protons and deuterons are measured (Stringent test of HZETRN Code)

Figure 5. Comparison of observed and calculated secondary proton energy spectra.

Figure 6. Comparison of observed and calculated secondary deuteron energy spectra.
Phantom Torso TEPC Trapped + GCR Differential Flux
June 25 - July 3, 2001
LET vs TEPC

TEPC model
Vs TEPC (no TF)
Figure 3. An example of the energy transfer points produced by the passage of a high-energy Ne ion through a walled proportional-counter chamber (left) and of the two-dimensional spatial distribution of two long-range ħ-rays (electrons) originating from the primary track (right).