Solar particle analyses: needs, data and analysis tools

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The Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment (SAPPHIRE) Model

- The SAPPHIRE SEP model is intended to provide outputs applicable for:
  - TID, TNID effects (including solar arrays and thin coatings)
  - SEEs: Upsets, Latch-up and Burnout
  - Sensor interference
  - Effects on astronauts

- To achieve this we have models for:
  - Severe environments (either peak flux or worst week equivalent)
  - Cumulative mission fluence environments
  - Extrapolations to low (0.1 MeV/nuc) and high (1 GeV/nuc) energies

- All models are probabilistic in nature with a basis of protons and helium and extensions to Heavy Ions (HIs)
The SAPPHIRE Model Outputs - Overview

## SEP species [protons (H); alphas (He)]

**Solar Maximum**
- 21 outputs
- Prediction periods (0.5 – 35 years)
- [5 cycles with 7 active years per cycle]

**Solar Minimum**
- 25 outputs
- Prediction periods (0.5 – 55 years)
- [5 full cycles for statistically sensible implementation]

### Particle Energies

**Core Model:** 5-300 MeV (11 logarithmically-spaced channels)

**Extrapolation/Interpolation:** 0.1 MeV – 1 GeV (81 Energies)

### Confidence Levels
- 53 outputs from 0.5 – 99.9%

### Model Outputs
- Cumulative Mission Fluence;
- Worst-case SPE Fluence; SEP Peak Flux

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### Particle Energies Table

<table>
<thead>
<tr>
<th>Ch.</th>
<th>Lower (MeV/nuc)</th>
<th>Upper (MeV/nuc)</th>
<th>Mean (MeV/nuc)</th>
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<td>6.01</td>
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<td>3</td>
<td>10.46</td>
<td>15.12</td>
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<tr>
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</table>
Model Data and Processing

- Newly processed data including solar protons and solar helium (1974-2015)
- GOES(SMS)/SEM/EPS/MEPAD data corrected in energy using IMP8/GME
- Difference of processed data w.r.t. (geo.) mean of bin upper/lower energies

Underlying Data, resulting from major clean-up, is available at: http://test.sepem.eu/help/SEPEM_RDS_v2-01.zip

<table>
<thead>
<tr>
<th>Ch.</th>
<th>Energy (MeV/nuc)</th>
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<tr>
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<td>38.02</td>
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<td>8</td>
<td>79.53</td>
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<tr>
<td>10</td>
<td>166.3</td>
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</tbody>
</table>
Model for Solar Energetic Helium

- Exponential cut-off power law probability distribution fit to SPEs at 11 energies
- Outputs of cumulative fluence/peak flux/worst-case SPE fluence vs confidence
- Extrapolations based on Band Fit and 4 benchmark cases

38 MeV/nuc
1-in-x-year Solar Particle Events

Pr_D(N = 0) = Pr(N = 0) \frac{D^x \times 11}{7} = 0.3679 \frac{D^x \times 11}{7} = 1 - p

<table>
<thead>
<tr>
<th>SPE Freq.</th>
<th>model Period (D)</th>
<th>Prediction Prob. (p)</th>
<th>Ideal p(D)</th>
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</tr>
</tbody>
</table>

Event Fluence (\# cm^{-2} sr^{-1} MeV/mc^-1)

Peak Flux (\# cm^{-2} sr^{-1} s^{-1} MeV/mc^-1)
Rare SPEs and Comparisons with CREME96/ESP

- Method to transform results from confidence-duration into SPEs that occur once in every $x$ years
- Protons (solid lines) and alphas (dashed)

- SAPPHIRE, CREME96 and ESP-PSYCHIC show different spectral shapes
- CREME96 Worst week more severe than Worst 5 minutes
Heavy Ion Abundances

- Update w.r.t. CREME96, agreement with Reames (1998) @ low Energy
- 7 ions (C, N, O, Ne, Mg, Si and Fe) with energy-dependent abundance ratios
- ACE/SIS data evaluated to determine abundances
- Example of iron (Fe; Z = 26) with fitted spectra summed and compared to helium
Single Event Effects Quantities (LET Spectra)

- Abundances to helium outputs allows derivation of flux/fluence spectra as a function of particle Linear Energy Transfer (LET)
- 1 g.cm\(^{-2}\): spectral differences to CREME96
Proton comparisons at high energy

- Heavily shielded environments place more emphasis on higher energy part of spectrum
- Building on work of Tylka & Dietrich and Raukunen et al., we’ll investigate this in more detail (starting 2018)
- 2-year and 7-year models at 95% confidence
- HSF might also care about forecasting for EVAs in deep space…
Proton comparisons to data at low energy

- ACE/EPAM data vs SAPHIRE confidence 50%, 60%, 70%, 80%, 90%, 95%, 99%
- Could be important for solar cell applications.
Yearly 35 MeV p+ Fluence from Cumulative Model
Solar Max – Solar Min combined Implementation
Next Generation of SEP Models

- **Motivation**
  - Combine SEP outputs with RB outputs
  - Produce flux time series not just cumulative fluence or SPE fluence or peak flux

- **Approaches**
  - Use a virtual timelines method but assign each event a flux profile
  - Requires seeding and modification of events from our RDS

- **End Game**
  - Transform both time series into an effect and sum
  - Find some parameter to drive both models (perhaps a dream?)

- Work by IASA & SPARC in Greece (I. Sandberg, Sigiava Giamini et al.)
The Statistical Basis

- Find a parameter related to flux to make a regression with duration (done)
- Sample waiting time
- Randomly sample duration or flux-type parameter
  - Find corresponding second parameter
  - Select random close by event to use as a seed
  - Build virtual event
- Repeat a gazillion times (>100,000 years)
Example modified SPE
System Logical Approach
Some Preliminary Comparisons

- Good agreement at low energy (especially with SAPPHIRE)
- Some apparent under-estimation of peak fluxes and higher energy fluences
Some Preliminary Comparisons

- Good agreement at low energy (especially with SAPPHIRE)
- Some apparent underestimation of peak fluxes and higher energy fluences
SEP Forecasting (for ESA SSA application)

- New Activity to develop SEP Advanced Warning System
- Evolution of FORSPEF, see:
  - Anastasiadis et al., Solar Phy. 2017
  - Papaioannou et al., Jour. SWSC, 2016)
- More system based, leveraging the RDS, a load more data.

Today’s SPE!
Concluding Remarks

- SAPPHIRE model development is complete
  - Updated solar proton model (JSWSC, submitted)
  - New solar helium model (IEEE, Jan 2018)
  - New abundance ratios for solar heavy ions
- Outputs/implementation instructions on request
  - On SPENVIS in 2017 & OMERE in 2018
- Underlying Data (RDS) is already available at:
  http://test.sepem.eu/help/SEPEM_RDS_v2-01.zip
- And now viewable at:
  https://spitfire.estec.esa.int/ODI/dplot_sepem.html
- Next-gen and forecasting on the horizon
Thank you for your attention!
Back-Up Slides
Data Processing – Cross-Calibration

GOES08,11_He#4: 39.323MeV/nuc

$Y = 0.0025 + 1.0453 \times X$

IMP8 flux [(cm$^2$ sec str MeV nuc)$^{-1}$]
Comparison of RDSv2.1 to PSYCHIC IDS
Example Probability Distribution Fit
Example Energy Extrapolation
Abundances for 7 elements
Cumulative Fluence as a function of LET
Solar Array Degradation

![Graph showing solar array degradation over time with different materials and thicknesses.](image-url)