The Ionizing Radiation Environment for Exploration

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This talk will focus on what is needed for lunar missions. It will address:

- What we need to know?
- When we need to know it?
- The current issues
- What we need to do and why
What do we need to know?

• **To predict, manage and assess crew exposures**
  – Solar Proton fluxes from 20 MeV to ~1000 MeV
  – GCR fluxes for \(0.1 \leq E \leq 10\) GeV/nuc for \(1 \leq Z \leq 26\)
  – Knowledge of the lunar neutron albedo

• **To predict the impact on electronics**
  – SEP fluxes for \(5 \leq E \leq 200\) MeV/nuc for \(1 \leq Z \leq 26\)
    • \(0.1 \leq E \leq 1000\) MeV/nuc in special cases
  – GCR fluxes for \(0.02 \leq E \leq 10\) GeV/nuc for \(1 \leq Z \leq 30\)
When do we need to know it?

• **To predict, manage and assess crew exposures:**
  
  – Reliable predictions during the largest SPEs of the solar proton spectrum versus time extending least a few hours into the future.
  
  – The predicted worst-case solar proton spectrum for the mission, years in advance.
  
  – Measurements of the solar proton spectrum in real-time and the measured proton fluence spectrum for the mission after the flight.
  
  – The measured mission-integrated elemental fluence spectra for GCRs after the flight as well as predictions of it years in advance.
When do we need to know it?

• To predict the impact on electronics in specific missions the following are needed for at design time for each mission:
  – The worst-case solar elemental flux spectra at selected confidence levels.
  – The worst-case solar proton fluence spectra at selected confidence levels.
  – The GCR elemental flux spectra
Current Issues
Unreliable Solar Particle Data

- Solar proton fluences from the IMP-8 and the GOES satellites are inconsistent
  - This has affected the accuracy of such widely used engineering models as the JPL proton fluence model (Feynman et al, 2002) and probably others as well.
- The ERNIE instrument on SOHO is known to saturate in large SPEs (ERNIE WWW site)
- There is known to be an over-correction of the CRNC instrument on IMP-8 for the deadtime in large SPEs (Tylka, 2007)
Examples of event-integrated proton fluences, $E>10$ MeV

(taken from Rosenqvist et al., 2005)
Another Example

(taken from Rosenqvist et al., 2005)
And Another

(taken from Rosenqvist et al., 2005)
Required Range for Solar Proton Measurements

• For Skin Dose
  – Behind 0.5 to 40 g/cm² of Al shielding
  – For six large SPEs
  – ≥80% of the dose comes from protons with energies $20 \leq E \leq 600$ MeV

• For dose to the blood forming organs
  – The dose comes from protons with energies
    $\sim 50 \leq E \leq \sim 1000$ MeV
Proton energy range to account for 80% of the skin dose

Oct 1989 Solar Particle Event

August 1972 Solar Particle Event
## Proton Energy Ranges

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Instrument</th>
<th>Z range</th>
<th>Proton Energy Range in MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAMPEX</td>
<td>PET</td>
<td>$1 \leq Z \leq 2$</td>
<td>$20 \leq E \leq 300$</td>
</tr>
<tr>
<td>IMP-8</td>
<td>CPME</td>
<td>$1 \leq Z \leq 28$</td>
<td>$0.3 \leq E \leq 440$</td>
</tr>
<tr>
<td>IMP-8</td>
<td>CRNC</td>
<td>$1 \leq Z \leq 28$</td>
<td>$4 \leq E \leq 95$</td>
</tr>
<tr>
<td>IMP-8</td>
<td>GME</td>
<td>$1 \leq Z \leq 28$</td>
<td>$0.5 \leq E \leq 500$</td>
</tr>
<tr>
<td>Wind</td>
<td>EPACT</td>
<td>$1 \leq Z \leq 30+$</td>
<td>$0.04 \leq E \leq 110$</td>
</tr>
<tr>
<td>Ulysses</td>
<td>COSPIN</td>
<td>$1 \leq Z \leq 28$</td>
<td>$5.4 \leq E \leq 92$</td>
</tr>
<tr>
<td>SOHO</td>
<td>ERNIE</td>
<td>$1 \leq Z \leq 28$</td>
<td>$1 \leq E \leq 100$</td>
</tr>
<tr>
<td>Stereo</td>
<td>HET</td>
<td>$1 \leq Z \leq 2$</td>
<td>$13 \leq E \leq 100$</td>
</tr>
<tr>
<td>Helios A&amp;B</td>
<td>E7</td>
<td>$1 \leq Z \leq 2$</td>
<td>$0.6 \leq E \leq 56$</td>
</tr>
<tr>
<td>ACE</td>
<td>SIS</td>
<td>$1 \leq Z \leq 28$</td>
<td>$\geq 10, \geq 30$</td>
</tr>
<tr>
<td>PAMELA</td>
<td>PAMELA</td>
<td>$1 \leq Z \leq 6$</td>
<td>$40 \leq E$</td>
</tr>
<tr>
<td>GOES</td>
<td>HEPAD</td>
<td>$1 \leq Z \leq 2$</td>
<td>$0.8 \leq E \leq 700$</td>
</tr>
<tr>
<td>RBSP</td>
<td>RPS</td>
<td>$Z=1$</td>
<td>$50 \leq E \leq 2000$</td>
</tr>
</tbody>
</table>
Are Lunar Albedo Neutrons a Hazard?

• The effective dose has been estimated from
  – Monte Carlo simulations of lunar neutron albedo
  – Fluence to effective dose conversion (Bozkurt et al, 2000 and 2001)

• The results have been compared to the ionizing particle doses and the results are:

<table>
<thead>
<tr>
<th></th>
<th>1970 GCRs in cSv/yr</th>
<th>1977 GCRs in cSv/yr</th>
<th>October 89 SPE in cSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons</td>
<td>2.63</td>
<td>3.84</td>
<td>1.43</td>
</tr>
<tr>
<td>Charged Particles</td>
<td>8.95</td>
<td>24.40</td>
<td>96.40</td>
</tr>
<tr>
<td>% from Neutrons</td>
<td>13.6</td>
<td>23.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>
So how good is the simulation?
But the effective dose comes mostly from higher energies.
SPE Prediction

• **In Advance**
  – This requires a detailed understanding of:
    • The free energy available in active regions
    • The mechanisms for its release
    • When the release will occur
    • How much energy will be released
  – Prediction of “All Clear” periods seems possible.
SPE Prediction

• **After the outburst on the Sun**
  – This requires knowledge of:
    • The pre-existing state of the IPM
      – To predict the Cobpoint location
    • Detailed diagnostics of the event
      – Will it be a gradual event?
      – What are the characteristics of the IP shock
    • A model for shock acceleration that
      – Is driven by real-time data
      – To produce detailed spectra injected at the Cobpoint
    • A reliable shock propagation model
      – That accurately predicts storm-time
      – And the proton spectra at storm-time
Forecast Models

• Proton Prediction System (Shea and Smart)
• SEC Proton Prediction Model (Balch, 1999)
  – Flux predictions from these codes are uncertain by a factor $\sim 10 \Rightarrow$ they do not provide actionable info.
• SOLPENCO Model (Aran et al., 2005)
  – This model is in the early stages of development
  – Only 10 events have been modeled so far
• Improved HAF model (Frye and Wu)
  – This model shows promise of accurate shock arrival time predictions
What is Needed and Why?

• An evaluated data base of the SEP event measurements over the space age
  – To accurately plan missions and reduce cost

• Solar proton measurements on future missions for energies up to ~1000 MeV that are reliable in the largest events
  – For the planning and management of crew exposures

• Measurements of lunar neutrons to \( \geq 100 \text{ MeV} \)
  – To be sure we understand the radiation hazard

• SPE predictions hours to days in advance
  – To minimize the radiation exposure of the crew
The End
Gyroradii of Solar Energetic Protons
All protons have pitch angles of 90°