Introduction to SEPs

Christina Cohen

Caltech
Outline

• What are SEPs?
  › And why do we care?

• How are the measured?
  › on the ground
  › in space

• What is the SEP history?
  › pre-1997
  › post 1997

• What is new and exciting about SEPs?
  › in my humble opinion.....
What are SEPs?

- Solar Energetic Particles
  - Solar = assumed to originate at the Sun
  - Energetic = historically above a few hundred keV/nuc
  - Particles = ions (mostly H, He like the Sun) + electrons

- Seen as increases in counting rates of ions (and/or electrons) of energies usually above 0.1 MeV/nucleon
Why do we care about SEPs?

- A sample of the Sun
  - one of the most accurately measured solar samples
  - if we can just figure out the details of creating them and getting them here
- Earth effects
  - energetic particles hitting the Earth’s atmosphere excite atoms and create aurora
Aurora Examples

- energetic particles hitting the Earth’s atmosphere excite atoms and create auroras.
Earth Radiation Belts

- Energetic particles are trapped in belts around the Earth
- Radiation hazard for Earth-orbiting spacecraft
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- Earth effects
  - energetic particles hitting the Earth’s atmosphere excite atoms and create aurora
  - energetic particles contribute to the radiation belts
  - part of geomagnetic storms which can cause black outs
    - change in Earth’s magnetic field induces strong currents in power system
    - Hydro Quebec lost power grid for 9 hours in March 1989
Why do we care about SEPs?

• **Spacecraft Effects**
  › Loss of data
  › Spurious signals
    • False alarms, noise strobes, erroneous telemetry values
  › Phantom commands
    • For example gain changes and attitude sensor errors
  › Mission or sensor degradation
  › Solar array degradation
  › Safeholds
  › Latchups
  › Subsystem failure
    • Loss of a redundant system
  › Mission Loss
How are SEPs Measured?

- On the ground
  - neutron monitors (indirect measurement)

- In space (since early 1960s)
  - first measurements (scintillation and Geiger counters)
  - \( \frac{dE}{dx} \) vs \( E \) technique
    - Proportional counters
    - Solid state detectors
  - Time of flight
  - \( \frac{E}{q} + \frac{dE}{dx} \) vs \( E \) (SEPICA)

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  › E/q + dE/dx vs E
How are SEPs Measured?

\[
\frac{dE}{dx} \propto (Z/V)^2 \propto (MZ^2/E)
\]

\[
E \frac{dE}{dx} \propto Z^2M
\]

\[
\frac{dE}{dx} \sim \frac{\Delta E}{L} = \frac{\Delta E}{(L_0 \text{ sec } \theta)}
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What is the History of SEPs? (pre-1997)

- First detection with connection to solar flare observation - Forbush 1946 in neutron monitor
- Timing related to gamma ray flare 1956 (most well studied)
- Better in space because can see them directly
  - space age
    - intensity
    - energy spectra
    - composition

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**FIGURE 2.** Chicago neutron monitor record of the ground level event of 23 February 1956 (adapted from 5).
What is the History of SEPs? (pre-1997)

- At the same time...
  - flares are being categorized by size, duration, emission wavelength
  - radio emission is being categorized
  - flares and radio emission combined to create...

- Two classes of flares
  - Impulsive
  - Gradual
What is the History of SEPs? (pre-1997)

- Correlations with SEP characteristics results in a 2 class SEP system:

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<tr>
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<th>Gradual</th>
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<td>Flare Characteristics</td>
<td>Short duration Compact/Point Source</td>
<td>Long duration Large Source</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio Characteristics</td>
<td>Type III/V</td>
<td>Type II/IV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Particle Characteristics</td>
<td>(^3)He, e(^-), heavy ion rich short duration, small, limited longitude</td>
<td>SW like composition long duration, large, wide longitude</td>
</tr>
</tbody>
</table>

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What is the History of SEPs? (pre-1997)

Gradual

Impulsive

*Figure 2.2. Intensity-time profiles of electrons and protons in ‘pure’ (a) gradual and (b) impulsive SEP events. The gradual event is a disappearing-filament event with a CME but no impulsive flare. The impulsive events come from a series of flares with no CMEs.*
What is the History of SEPs?
(pre-1997)

• All SEPs created by flares
  › slight problem with longitude distribution of gradual events
  › ideas of storage, cross-field transport, lots of scattering in the interplanetary medium (not happy about this)
  › Not a good correlation between interacting protons and SEP protons (SMM allowed gamma-ray measurements in space 1980)

• Enter Skylab and CME observations (1978)
  › high correlation (96%) between gradual flares and CMEs
  › CMEs can drive shocks and shocks can accelerate...
What is the History of SEPs? (pre-1997)

• Nice things about CME-shock acceleration for gradual SEP events
  › CME angular size close to longitude distribution of gradual SEP events
  › Solves the cross-field transport ‘problem’
  › Correlation between CME size/speed and SEP size
  › Found a gradual SEP event with no flare but with CME
  › Found CMEs did not occur with impulsive SEP events
  › Long acceleration in the IPM explained long duration of gradual SEP events (compared to
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What is the History of SEPs? (pre-1997)

- ‘Paradigm Shift’
  - Had 1 acceleration mechanism for all SEP events
  - Now have two independent acceleration mechanisms
    - CME-driven shock acceleration => Gradual SEP events
    - Impulsive flare acceleration => Impulsive SEP events

Reames 1999
What is the History of SEPs? (pre-1997)

- Flurry of activity in SEP studies to define characteristics of two classes (1980s)
- Impulsive
  - Klecker et al. 1984 finds charge state difference
  - Mason et al. 1986 finds systematic composition difference
  - Reames explains charge and composition characteristics in terms of low altitude

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  - All flare material is like impulsive SEP material but gradual SEP material looks like the solar wind
    - composition
    - charge states
  - Roll offs of spectra consistent with diffusion from shock region
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What measure history (old/new) excitement
What is the History of SEPs? (pre-1997)

- The 1990s standard 2 class system table

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Big Point to remember:
» the two classes are *exclusive*

Flare particles in gradual events do not escape into the IPM because of closed field lines behind the CME.
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What is the History of SEPs? (post-1997)

• ACE launches August 1997
  › Suite of high-tech instruments to study heavy ions in SEP events over 3 orders of magnitude in energy (.1-100 MeV/n)
    • Elemental Composition (ULEIS+SIS)
    • Isotopic Composition (ULEIS+SIS)
    • Charge State Composition (SEPICA)
  › In November 1997, ACE observes first gradual SEP events
    • Composition does not look as it should...

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• Within the first year, ACE observes many more of these enriched-Fe events
  › Composition from C-Ni looks impulsive (12-60 MeV/n)
  › Enhancements of $^3$He (not at impulsive levels)

• SAMPEX measures charge states with geomagnetic cutoff technique
  › At 30 MeV/n $Q_{Fe}$ is ~20 (like impulsive)
  › $Q_{Fe}$ is *energy dependent*
What is the History of SEPs?

- Within the first year, ACE observed many more of these enriched Fe events:
  - Composition from C-Ni looks impulsive (12-60 MeV/n)
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  - \( Q_{Fe} \) is \( \sim 20 \) (like impulsive)
  - \( Q_{Fe} \) is energy dependent

Cohen et al. 1999
Leske et al.
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Moebius et al., 1999

Mazur et al., 1999 Energy (MeV/nuc)
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• What happens when new results challenge old beliefs?
  › Q/M effect
  › Velocity dispersion effect

• Grudging acceptance into existing framework (shock acceleration)
  › Diffusion from shock region
  › Suprathermal flare material (small amounts from preceding flares)
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Mewaldt et al. 2000
What is New and Exciting About SEPs?

• Back to the big questions
  › Are there 2 distinct classes of SEP events??
  › What is being accelerated?
  › How is it being accelerated?
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Probably not 2 separate classes of events
But 2 acceleration mechanisms (the hard part is distinguishing them in SEP observations)

What measure history (old/new) excitement
What is New and Exciting About SEPs?

• Two competing theories
  › Shock orientation
    • flare suprathermals present → energy-dependent composition of the seed population
    • perpendicular vs parallel shock difference
  › Direct flare contribution
    • flare particles can escape
    • observation depends on
      » connection to flare
      » strength of shock
      » size of flare
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Tylka et al. 2005
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What measure history (old/new) excitement

Cane et al. 2003
What is New and Exciting About SEPs?

• Two competing theories - How to decide?
  › Measurements at different longitudes at the same time

STEREO
What is New and Exciting About SEPs?

• Two competing theories - How to decide?
  › Measurements at different longitudes at the same time
  › Measurements closer to the Sun (and/or at different distances at the same time)