What Caused the Large Deficit of High-Energy Solar particles in Solar Cycle 24?

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Outline

Compare SEP Fluences & Spectral Breaks in 3 Cycles

Discuss Possible Interpretations

- Spectral breaks
- Weaker magnetic field
- Shock acceleration limits?
- Suprathermal seed particle densities
- Injection efficiencies, and non-linear effects
- Simulations with the Path and iPath codes

Summary
The weak Cycle 24 is very evident if we look at >100 MeV Protons
Table 1: Cycle 23 & 24 Comparison - 11/1/16

<table>
<thead>
<tr>
<th>Property</th>
<th>Cycle 23</th>
<th>Cycle 24</th>
<th>Ratio 24/23</th>
<th>Comments/References</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Flares</td>
<td>88</td>
<td>28</td>
<td>0.32</td>
<td>Solar Soft Catalog</td>
</tr>
<tr>
<td>CMEs &gt;1000 km/s</td>
<td>296</td>
<td>168</td>
<td>0.57</td>
<td>SOHO CME Catalog</td>
</tr>
<tr>
<td>GOES SEPs</td>
<td>78</td>
<td>39</td>
<td>0.50</td>
<td>NOAA GOES Data</td>
</tr>
<tr>
<td>Number of GLEs</td>
<td>11</td>
<td>1-2</td>
<td>0.1-0.2</td>
<td>5/1/12; 1/6/14?,</td>
</tr>
<tr>
<td>&lt;B&gt; IMF</td>
<td>6.8</td>
<td>5.2</td>
<td>0.76</td>
<td>ACE/MAG @ L1</td>
</tr>
<tr>
<td>Suprathermal Seed Density</td>
<td>0.3/m³</td>
<td>0.080/m³</td>
<td>0.27</td>
<td>ACE/ULEIS</td>
</tr>
<tr>
<td>H Fluence &gt;10 MeV</td>
<td>6.3 x 10^8</td>
<td>9.7 x 10^7</td>
<td>0.15</td>
<td>NOAA /GOES</td>
</tr>
</tbody>
</table>
The interplanetary magnetic field has been significantly weaker during the first 8 years of cycle 24. This lowers the acceleration rate and maximum energy of SEP shock acceleration (dE/dT is proportional to B).

The Interplanetary Magnetic Field has been considerably weaker in Cycle 24 than in Cycle 23.

- Cycle 23 $\langle B \rangle = 6.66$ nT
- Cycle 24 $\langle B \rangle = 5.41$ nT

(First 99 27-day cycles)
Spectral Breaks Indicate the Energy/Rigidity above which particles are no longer trapped at the shock

Mean “Break Energy” for the 10 Largest Proton Events

H: SC23 > 31.5 ± 3.8 MeV
O: 18.9
Fe: 8.6

Evidently SEP Acceleration is less Efficient in Cycle 24
Several lines of evidence indicate that CME-driven shocks accelerate suprathermal ions rather than bulk solar wind.

- SW and SEP composition differ.
- SEP $^3$He and He$^+$ common.
- FIP fractionation differs.
- Suprathermals pre-injected.

So, the intensity of SEP events should depend on the suprathermal ion density close to the Sun.

Mewaldt et al. 2001
Suprathermal Seed Particle Densities are much lower this cycle (densities scaled by x1000)

- Mean lower by ~X3.6
- Mean lower by ~X3.2
- Mean lower by ~X7
In the Li, Zank & Rice (2005) model, the wave intensity $I$ is proportional $N/u_{up}^2$, where $N$ is the proton injection rate and $u_{up}$ is the background fluid speed in the shock frame.

However, the diffusion coefficient $K$ is proportional to $1/I$. Thus, reducing $N$ allows ions to escape from the shock more easily and the maximum momentum $P_{max}$ is decreased.

Reducing the proton injection rate also causes heavier ion spectral breaks to occur at lower rigidity. We suggest that this is a key factor in reducing SEP fluences and maximum energies in cycle 24.
Simulations Using the PATH Model (1D)

\( V_{\text{cme}} = 2200 \text{ km/s} \)
\( \theta_{\text{BN}} = 5^\circ \)

Seed particle spectrum
\( f(E) = f(E_0)(E/E_0)^{-3.5} \)

- \( E_{\text{Brk}} = 1.4 \text{ MeV}; E_{\text{Max}} = 24 \text{ MeV} \)
- \( E_{\text{Brk}} = 2.2 \text{ MeV}; E_{\text{Max}} = 52 \text{ MeV} \)

Injection Rate
\( \varepsilon N = 5 \times 10^{-5} \)

\( \varepsilon n = 1 \times 10^{-4} \)
Simulated Proton Spectra using the PATH Code

- $E_{\text{BRK}} = 6.0$
- $E_{\text{BRK}} = 1.4$
- $E_{\text{BRK}} = 2.2$

Injection Rates

- $E_{\text{max}} = 24, 53, 350 \text{ MeV}$

Energy (MeV/nucleon)

Fluence (arbitrary unit)
A schematic view of the iPATH 2D shell model. At each time $t_k$, the $k$-th shell is generated with the leading edge located at the shock location $R(t_k)$. All shells convect with the solar wind and expand adiabatically. Each shell is divided longitudinally into parcels with 5° angular separation. Energetic particles diffuse between parcels both radially and longitudinally.
Model two SEP Events with the mean interplanetary properties of cycles 23 & 24

\[ \langle B \rangle = 6.82 \text{ nT} \]
\[ V_{SW} = 426 \text{ km/s} \]
Supratherm. H Density (m\(^{-3}\)): 0.30
Inject. Eff.: 1.8e\(^{-4}\)

\[ \langle B \rangle = 5.2 \text{ nT} \]
\[ V_{SW} = 401 \text{ km/s} \]
Supratherm. H Density (m\(^{-3}\)): 0.080
Inject. Eff.: 5e\(^{-5}\)
Modeled Fluences as a Function of Property

<table>
<thead>
<tr>
<th>IMF &lt;B&gt;</th>
<th>ST Density</th>
<th>E-Break MeV</th>
<th>Emax MeV</th>
<th>&gt;10 MeV Fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC23</td>
<td>SC23</td>
<td>48.7</td>
<td>389</td>
<td>1.46e7</td>
</tr>
<tr>
<td>SC24</td>
<td>SC24</td>
<td>12.8</td>
<td>119</td>
<td>1.43e6</td>
</tr>
<tr>
<td>SC24</td>
<td>SC23</td>
<td>49.4</td>
<td>152</td>
<td>1.63e7</td>
</tr>
<tr>
<td>SC23</td>
<td>SC24</td>
<td>12</td>
<td>119</td>
<td>1.50e6</td>
</tr>
</tbody>
</table>

The reduced seed particle density in Cycle 24 has a greater effect than reducing <B>
Summary

Although the number of SEP events in the first ~8 years of cycle 24 is only lower by 50%,
- The fluence of >10 MeV protons is down by factors from 4 to 6, depending on energy
- Heavy ions are down by factors of ~4 to ~10 (Q/M dependent)
- The number of GLEs is reduced from 11 to 1 or 2

- The Factor of 2 reduction in the number of “GOES” SEP events is mainly because of a
  - 43% reduction in number of fast CMEs

- In Cycle 24 spectral breaks of all species are occurring 2-4 times lower in energy than in
  - large events of cycle 23.

- The 23% weaker magnetic field this cycle is important, especially if $\delta B/B$ has declined.
  The first iPATH runs suggest $\langle B\rangle$ affects the maximum energy, but it is harder to
discern the effect since it changed much less than the seed particle density.

- A key cause of lower SEP fluences is a reduced density of suprathermal seed particles.
  - The reduced wave activity from a lower injection rate of suprathermal protons
  - reduces the acceleration rate and maximum energy to which all particles are

- We suggest that shock acceleration is a more non-linear process than is generally
  - realized. If only solar wind is accelerated, density & spectral changes are not great.
  But suprathermal ions are the main seed population and they are >10x more variable.
A Dramatic Example of Cycle to Cycle Differences in the Sun’s Ability to Celebrate Bastille Day
Survey of Turbulence Levels 1998-2015 by Chuck Smith
[16 minute samples of dB/B (excluding ICMEs) averaged over a year]

Sampling period corresponds to the gyro period of a ~20 MeV proton at ~0.2 AU

The cycle 24 solar maximum average of δB/B is actually 7% greater than the SC23 solar maximum period.
The Cycle-24 fluences of 10-30 MeV/nuc heavy ions are reduced even more than protons by factors that depend on charge-to-mass ratio.
Solar-Cycle Dependent Fluences and Spectral Breaks

A comparison of fits to the O and Fe spectra for the 5 largest events of the first 5.8 years of cycle 23, and the 10 largest events in cycle 24 shows that spectral breaks do occur at lower energies in Cycle 24.

Mean break energies based on double power-law fits

<table>
<thead>
<tr>
<th>Cycle</th>
<th>O Break Energy</th>
<th>Fe Break Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>24.3 MeV/n</td>
<td>4.8 MeV/n</td>
</tr>
<tr>
<td>24</td>
<td>5.3 MeV/n</td>
<td>2.0 MeV/n</td>
</tr>
</tbody>
</table>
Integrated >10 MeV Proton Fluences at Three Locations
Cycle 24 has fallen very far behind in SEP Production

As of Oct 20, 2016, the cycle 24 proton fluence trailed cycles 22 and 23 by factors of 3.9 and 5.8.