Why are there so few solar proton events in Solar Cycle 24?

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With thanks to Dick Mewaldt, Randy Jokipii, and Jozsef Kota
There have been few large SPEs this cycle; including only 1 (2?) GLEs this cycle compared to 13 at a similar stage of the previous cycle.
The largest SPEs are almost always associated with fast CMEs (usually halo CMEs)

At 1AU, at energies below several MeV, the peak proton intensity is almost always coincident with the passage of the CME shock.

The most widely accepted mechanism is diffusive shock acceleration (DSA) at CME-driven shocks.
Energy spectra at 2 different strong interplanetary shocks

The largest difference between the spectra at the shock in these two events is at high energies.
Acceleration time scale in DSA

For a planar shock, the time to accelerate particles from $E_0$ to $E$ is

$$\tau_{acc} = \frac{3/2}{U_1 - U_2} \int_{E_0}^{E} \left( \frac{\kappa_1(E')}{U_1} + \frac{\kappa_2(E')}{U_2} \right) \frac{dE'}{E'}$$

Where $\kappa$ is the diffusion coefficient normal to the shock front. The subscripts refer to upstream (1) and downstream (2) of the shock.

For a CME-driven, propagating shock, $E$ is the “spectral break energy”. Below this, the spectrum is power law, and above this it is steeper (sometimes to another power law).

The intensity at the highest energies depends critically on the spectral break energy, and, therefore, on the acceleration time scale (or rate).
Dependence of acceleration time on ...

**CME speed:**
- The acceleration time varies with $1/U_1^2$. Faster CMEs accelerate particles more rapidly, and the spectral break occurs at a higher energy, leading to more particles at high energies.
- For a slower CME, the spectrum will roll over from a power law at a lower energy, and ... **the intensity at the highest energies seen at 1 AU will be significantly reduced** compared to a faster CME shock.

**Magnetic field strength:**
- Generally, a weaker magnetic field will lead to a larger diffusion coefficient along the magnetic field, and a slower acceleration rate (longer acceleration time).
- Thus, the spectrum will roll over from a power law at a lower energy for a weak magnetic field, and ... **the intensity at the highest energies seen at 1 AU will be significantly reduced** compared to that of a stronger magnetic field.
• A slower CME shock does not create as many high-energy particles as a faster one.

• When the solar magnetic field is weaker, shocks do not create as many high-energy particles compared to when it is stronger.
There have been noticeably more CMEs this cycle compared to a similar stage of the previous cycle; but fewer fast ones (by over 50%).

<table>
<thead>
<tr>
<th>Cycle</th>
<th>ALL</th>
<th>&gt;500 km/s</th>
<th>&gt;1000 km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>8,382</td>
<td>3,137</td>
<td>408</td>
</tr>
<tr>
<td>24</td>
<td>13,328</td>
<td>2,193</td>
<td>188</td>
</tr>
</tbody>
</table>

The interplanetary magnetic field is significantly weaker during the rise to maximum of cycle 24 - a pattern that was also very evident during the extended solar minimum.

$\langle B \rangle = 7.04 \text{ nT}$

$\langle B \rangle = 5.24 \text{ nT}$

Adapted from slide provided by D. Mewaldt: averages include more-recent data
The r.m.s. value of the turbulent component of the IMF is also smaller in solar cycle 24 than it was in cycle 23.

But, the ratio is nearly unchanged $\rightarrow \frac{dB}{B}$ is not noticeably different (Mewaldt, 2015 fall AGU meeting).

Solar Cycle 23
$\sqrt{\langle B^2 \rangle} = 4.12$ nT
$\langle B \rangle = 7.04$ nT
ratio $= 0.584$

Solar Cycle 24
$\sqrt{\langle B^2 \rangle} = 3.11$ nT
$\langle B \rangle = 5.24$ nT
ratio $= 0.593$

data source: http://www.srl.caltech.edu/ACE/ASC/level2/index.html
The acceleration rate in DSA depends on the spatial diffusion coefficient, which depends on both $|B|$ and $dB/B$.

The (parallel) diffusion coefficient is given by:

$$\kappa(w) = \frac{w^2}{4} \int_0^1 \frac{(1 - \mu^2)^2 d\mu}{D_{\mu\mu}}$$

Where

$$D_{\mu\mu}(\mu) = \frac{\pi}{4} (1 - \mu^2) \Omega_0 \frac{f_r P(f_r)}{B_0^2}$$

Pitch-angle diffusion coefficient

$$f_r = \frac{\Omega_0 V_0}{w\mu}$$

Resonant frequency

$P(x)$ is the frequency power spectrum of the random component of the IMF, $B_0$ is the field strength, $V_0$ is the solar-wind speed, $\Omega_0$ is the cyclotron frequency, and $w$ is the particle speed.
Diffusion coefficients for 100-MeV protons as a function of time using ACE MAG & SWEPAM data.

$K$ is from the expression on the previous slide.

Power spectra of $B_n$ were computed using 6-hour time intervals of 16-s MAG data.

$B$ (to get $\Omega_0$) and $V$ were averaged over each 6-hour interval.
Diffusion coefficients for 100-MeV protons as a function of time using ACE MAG & SWEPAM data.

Total time interval in both sets are the same, and the start is at the same phase of the cycle

(Start of Cycle 23 occurred before ACE launch, and Cycle 24 had not ended at the time of the most-recent data available.)
Distribution of diffusion coefficients of 100-MeV protons computed from ACE data and quasi-linear theory (QLT)

Solar Cycle 23
\[ \langle K \rangle = 2.6 \times 10^{20} \text{ cm}^2/\text{s} \]

Solar Cycle 24
\[ \langle K \rangle = 2.5 \times 10^{20} \text{ cm}^2/\text{s} \]

The mean is very nearly the same in the two cycles

For \( \kappa < 4 \times 10^{20} \text{ cm}^2/\text{s} \), the distributions differ significantly
The peak in the distribution for cycle 23 is shifted towards a lower $\kappa$ compared to that of cycle 24.

The location of the maximum in cycle 24 occurs at a $\sim$30% larger $\kappa$ than that of cycle 23.

$k_{\text{at peak}}$ (cycle 23) = $5.8 \times 10^{19}$ cm$^2$/s

$k_{\text{at peak}}$ (cycle 24) = $7.3 \times 10^{19}$ cm$^2$/s

$\approx 1.3 \ k_{\text{at peak}}$ (cycle 23)
Would a 30% increase in the diffusion coefficient, and a reduction in the number of fast CMEs, lead to the observed decrease in the number of SPE events?

To quantify this, we consider a model that solves the acceleration of particles at a shock and uses the observed CME speeds to estimate the cumulative number of protons > 10MeV at 1 AU.
A quantitative model:

• We solve the Parker transport equation using a spherically-symmetric geometry, for a shock moving radially outward from the Sun.

\[ \frac{\partial f}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \kappa_{rr} \frac{\partial f}{\partial r} \right) - U \frac{\partial f}{\partial r} + \frac{1}{3r^2} \frac{\partial (r^2 U)}{\partial r} \frac{\partial f}{\partial \ln p} + Q = 0 \]

• Solved using a standard finite-difference approach.

• The plasma speed is determined kinematically (consistent with that expected for a radially propagating interplanetary shock).

• The diffusion coefficient is assumed as follows:

\[ \kappa_{rr} = \kappa_0 \left( \frac{E}{1 \text{ MeV}} \right)^\gamma \left( \frac{r}{1 \text{ AU}} \right)^2 \]

• Where \( K_0 \) and \( \gamma \) are input parameters. The dependence on \( r \) given above is simply an assumption. It is not well constrained, but reasonably, one would expect \( K_{rr} \) to scale roughly inversely with the mag. field strength \( B \).
Normalization provided by comparison of simulation with observations of the large SEP event seen on DOY 302, 2003 (Halloween event)

- Shock speed is that at 1AU
- \( n_{ep} = 10^{-4} \) used to determine the source function (injection at the shock with \( E_{inj} = 250 \) keV).
- \( K_0 \) and \( \gamma \) determined from 1 AU observations by fitting energetic particle intensities ahead of shock to exponential
SEP intensities vs. time at 1 AU

Event Onset
(r=5R_\odot)

Shock

DOY of 2003

j(E) (particles/cm^2 \cdot sec \cdot MeV-sr)

1 MeV

10 MeV

100 MeV

1 GeV
Integrated spectra, at the time of passage of the shock at 1AU

$V_{\text{sh}} = 1900 \text{ km/s}$
$V_{\text{sw}} = 780 \text{ km/s}$

$$I(E) = \int_{E}^{\infty} \frac{dJ(E')}{dE} dE'$$
• Total integrated intensity above 10 MeV, as a function of the shock velocity for two different values of $K_0$

• The difference is very significant at lower shock speeds (nearly an order of magnitude)
Combined Modeling with CDAW/CME list to estimate TOTAL protons

- We run this model for a wide range of CME (shock) speeds, based on the SoHO/LASCO CME catalog from CDAW for cycles 23 and 24.

- Each CME is treated separately in our calculation and we sum all the events vs. time since start of cycle.

- The greatest contribution comes from CMEs with speeds $\sim 1000$ km/s.
Results: Progression of SPEs during solar cycle

Cycle 24: (10% larger $K_0$)
Cycle 24: (30% larger $K_0$)
Conclusions

There have been fewer SPE events in the current solar cycle (cycle 24) compared to previous ones

(A) There have been \(~ 50\%\) fewer fast (>1000 km/s) CMEs during cycle 24 compared to cycle 23

(B) The diffusion coefficients, computed from ACE data using quasi-linear theory, have a peak occurrence at a value that is \(~30\%\) larger in cycle 24 compared to cycle 23.

According to the DSA theory, the combination of (A) and (B) will lead to fewer SPE events because the acceleration rate is slower, resulting in fewer particles at very high energies.

A quantitative model for particle acceleration at individual CME shocks, and using the observed CME speeds during the previous 2 solar cycles, gives a cumulative amount of \(>10\) MeV protons at 1 AU in solar cycle 24 that is smaller than that of cycle 23 by an amount that is roughly consistent with observations.