The Solar Energetic Particle (SEP) Radiation Hazard

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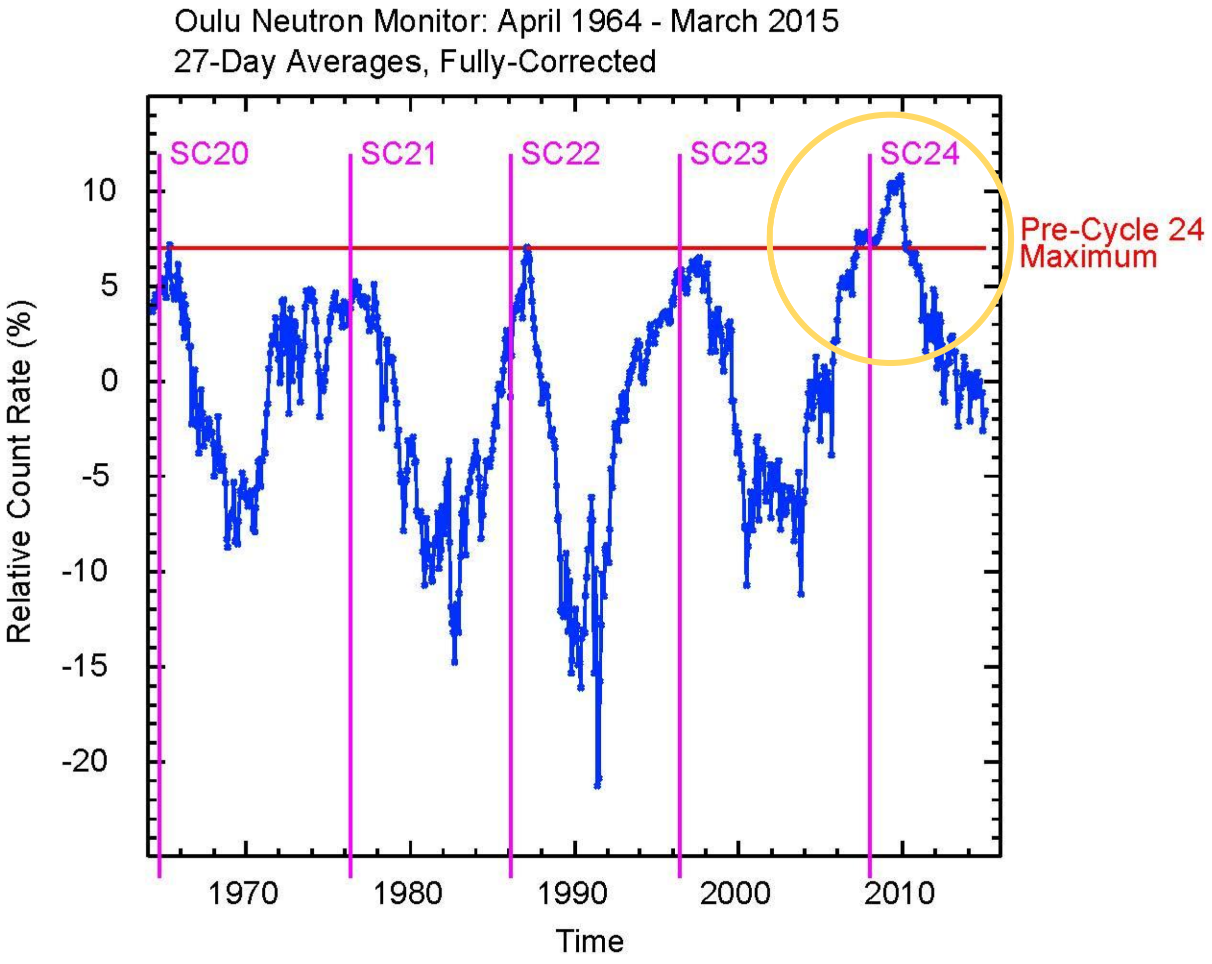
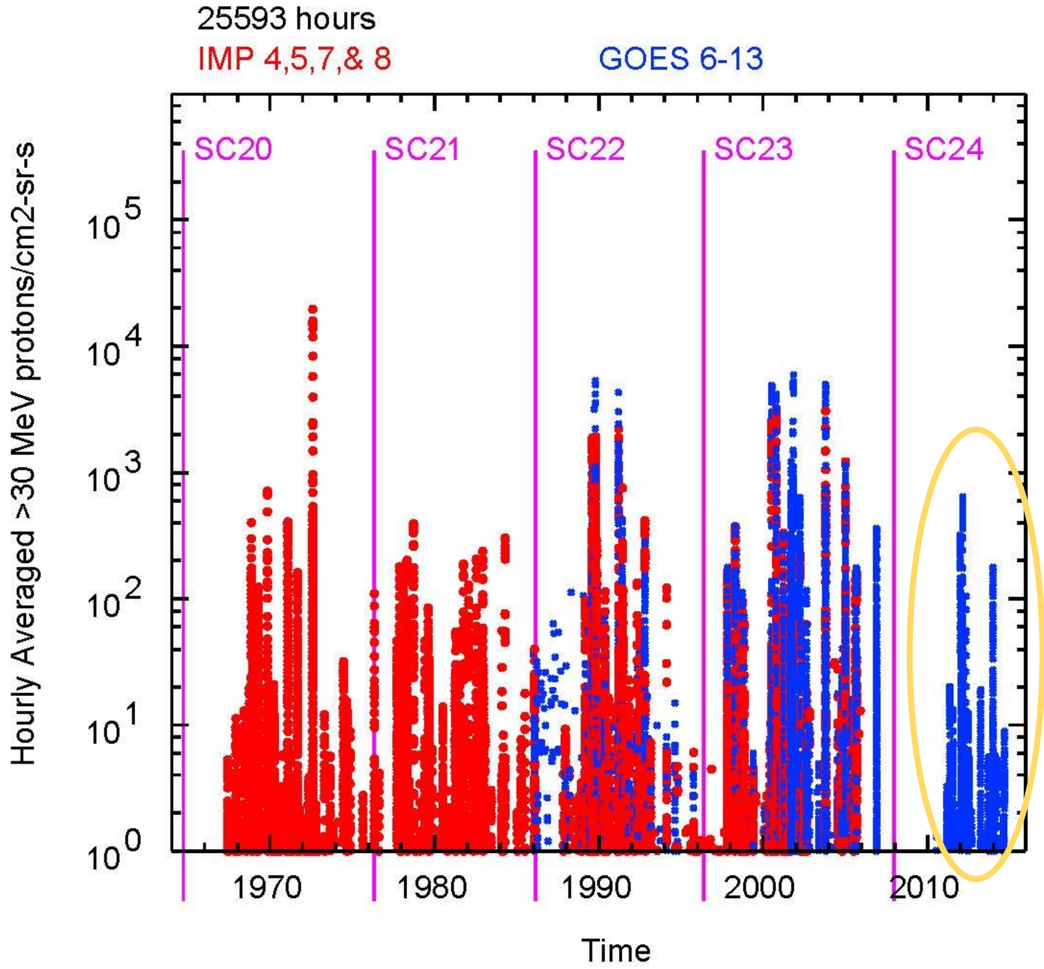
Motivation:

In the 2008-2010 minimum of solar activity, we saw a higher flux of Galactic Cosmic Rays (GCRs) at Earth than ever seen before in the Space Age.

How do the SEP Events of Solar Cycle (SC) 24 differ from those of earlier Solar Cycles?
Do the differences between SC 24 and earlier SCs have implications for a manned mission to Mars?

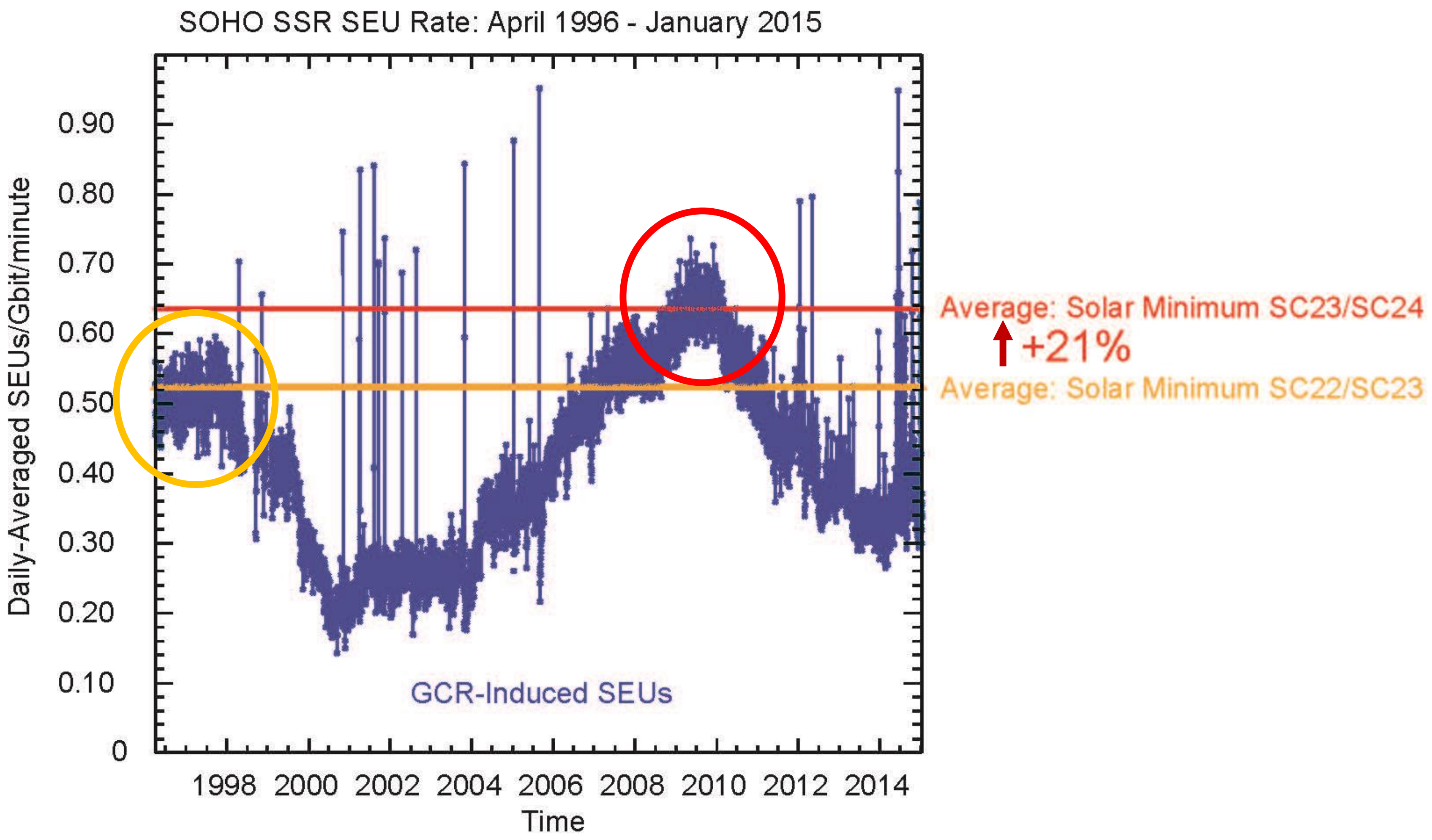




An Example: Effects of Ionizing-Radiation on Spacecraft Systems

SEUs in the SSR on SOHO at L1

(Single-Event Upsets in the Solid-State Recorder on the Solar and Heliospheric Observatory at the First Lagrangian Point)



But this is not the whole picture….

SOHO SEU data provided by Dr. Bernhard Fleck, ESA

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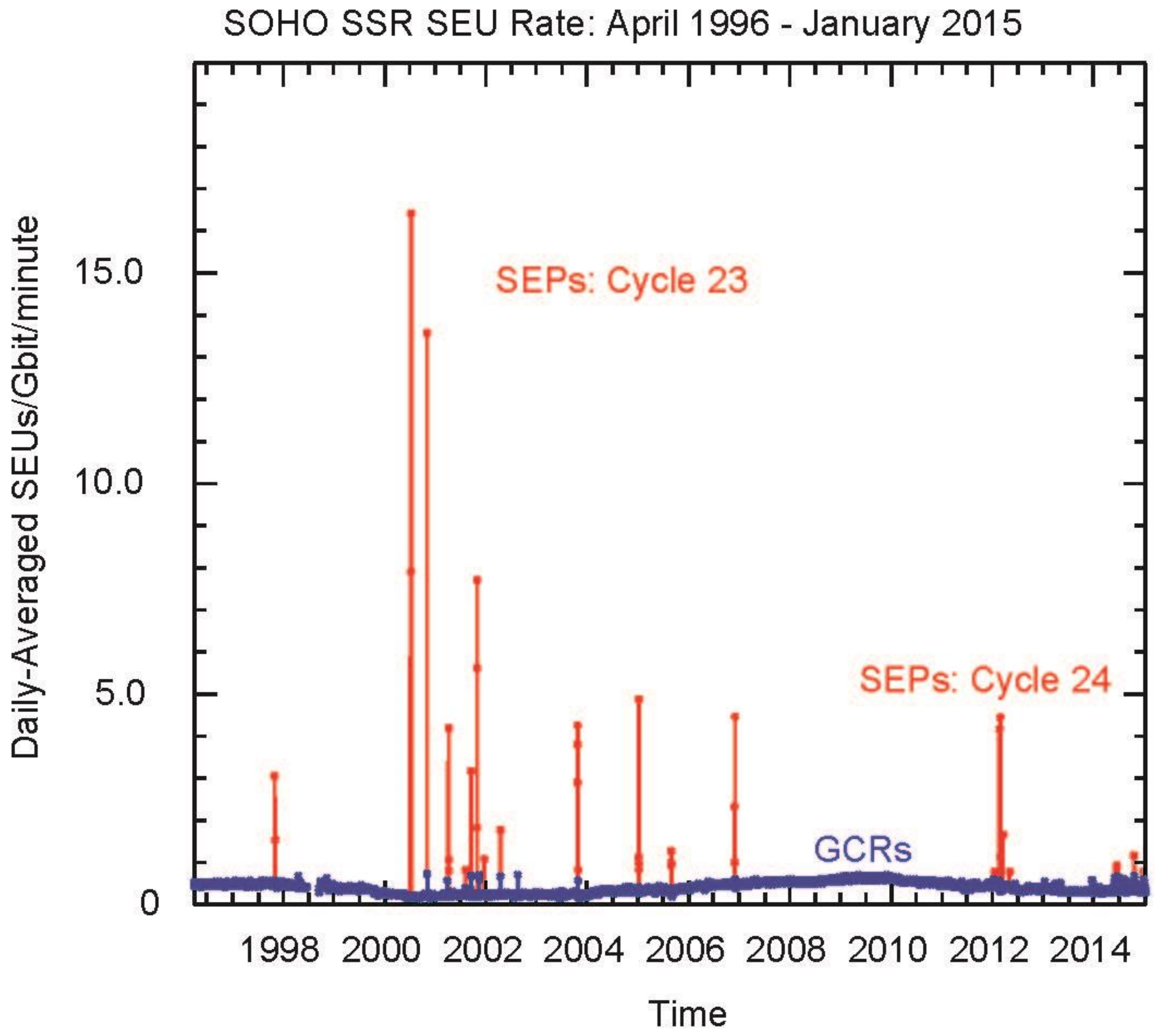


While the GCR-induced hazard has become more severe, the episodic SEP radiation hazard has become less severe and less frequent.

SOHO SEU data provided by Dr. Bernhard Fleck, ESA

Outline

- Brief Review of the SEP radiation hazard
- Comparison of SEP productivity Cycle 24 vs. Cycle 21, 22, and 23
- Speculation: What if Cycle 24 is the “new normal”?

Space Radiation Risk

NRC Panel convened at the request of NASA.

Chaired by J.D. van Hoften; Tylka was a Panel member.

Report published in 2007.

My comments below reflect both this report and progress since then.

A Brief Review of the SEP Radiation Hazard

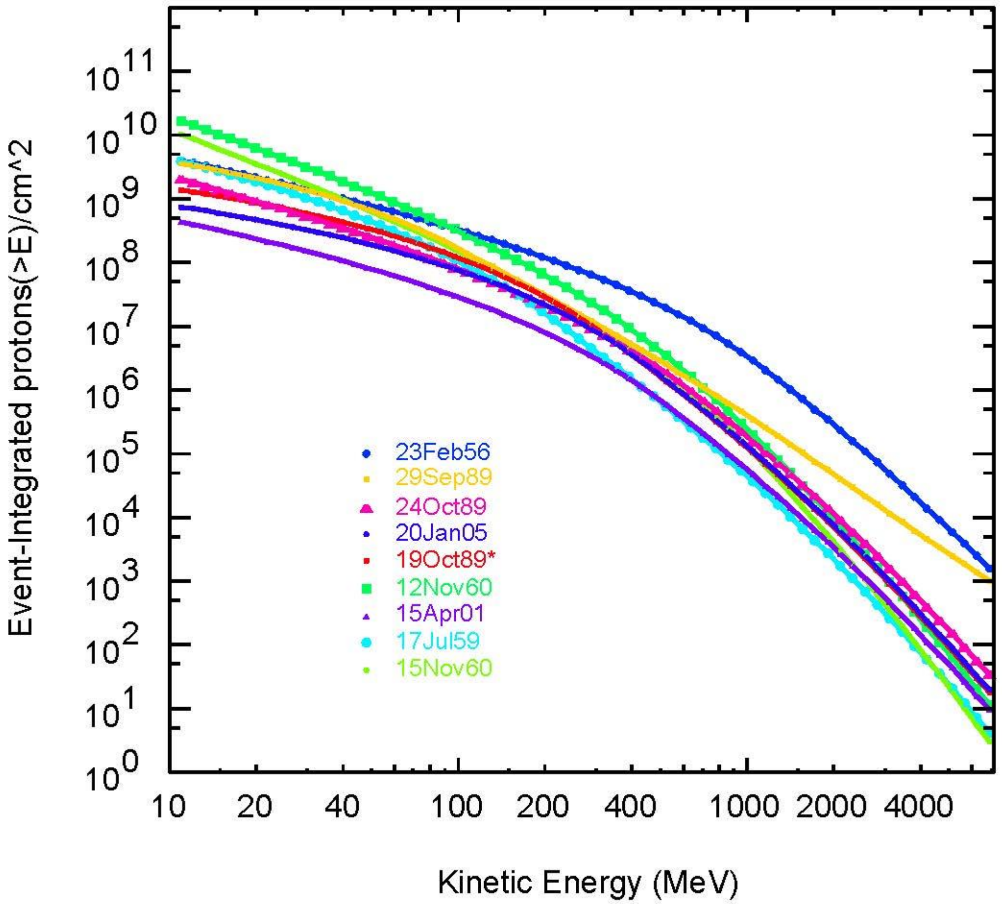
- The SEP radiation hazard is “out of phase” with the GCR radiation hazard.
  - SEP hazard is greatest when the GCR hazard is lowest, i.e., at solar maximum
  - However, very large SEP events (even Ground-Level Events [GLEs]) have been observed at solar minimum (sunspot number <20)

- The SEP radiation is due primarily to protons.
  - Unlike GCRs, where the primary rad-hazard concern comes from heavy-ions, which fragment in the shielding to produce neutrons.
  - SEPs also include ions heavier than protons:
    - SEP heavy-ions are unimportant in term of dose (<10%).
    - But heavy-ions may cause subtle biological effects whose risks are not adequately quantified by dose.
    - SEP heavy ions can be important for single-event effects in electronics.

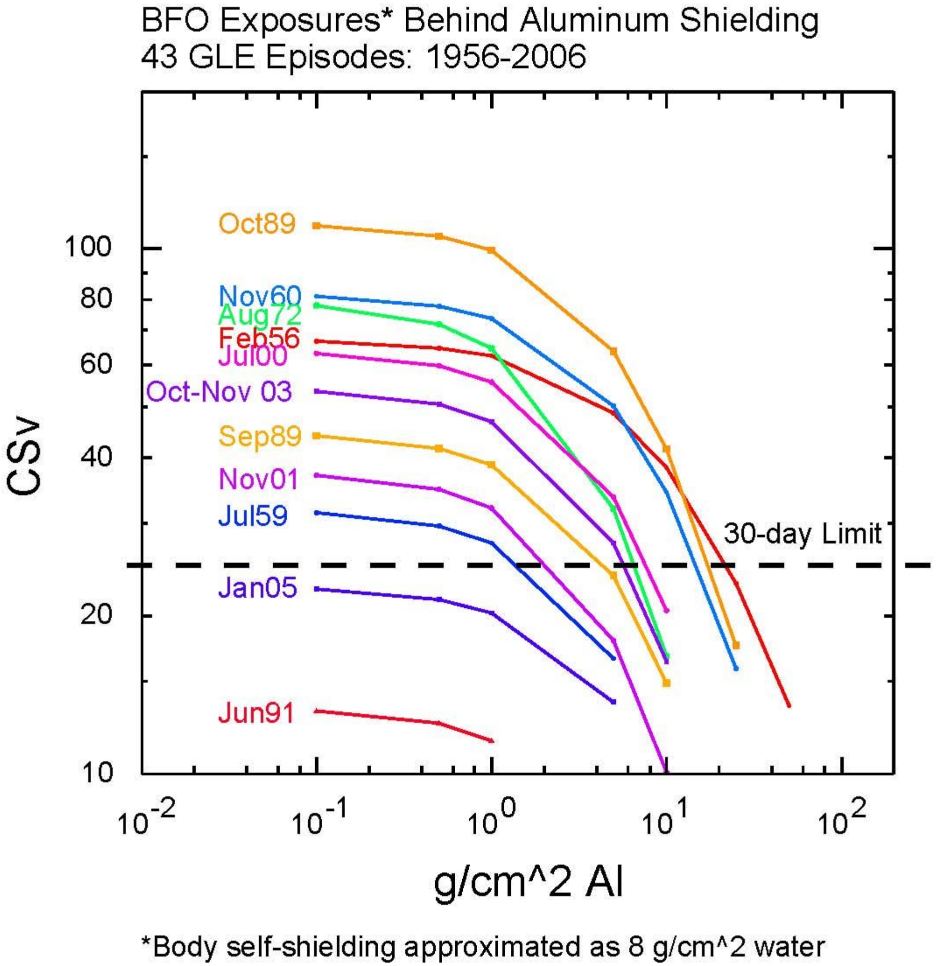
A Brief Review of the SEP Radiation Hazard (cont.)

- **Biology is the biggest uncertainty in assessing the SEP radiation hazard for astronauts:**
  - **rads → cancer risk?**
- **Astronauts can be shielded from the episodic SEP radiation hazard by a 'storm shelter' (Next slide)**
- **Early warning of the approaching SEP hazard is needed.**
  - **Time scale depends on the circumstance:**
    - **within the spacecraft but not the shelter**
    - **On EVA**
  - **Types of Early Warning 'Models'**
    - **Experience based: NOAA**
    - **Physics-based: Objective of NASA Heliophysics Research**
    - **Monitors: i.e., near-relativistic electrons: REleASE at iSWA.gsfc.nasa.gov**

Radiation Exposure from the Largest SEP Events of the Space Age



Band function fits to proton spectra from combined satellite+NM measurements, Tylka & Dietrich 2009; Cliver et al. 2013



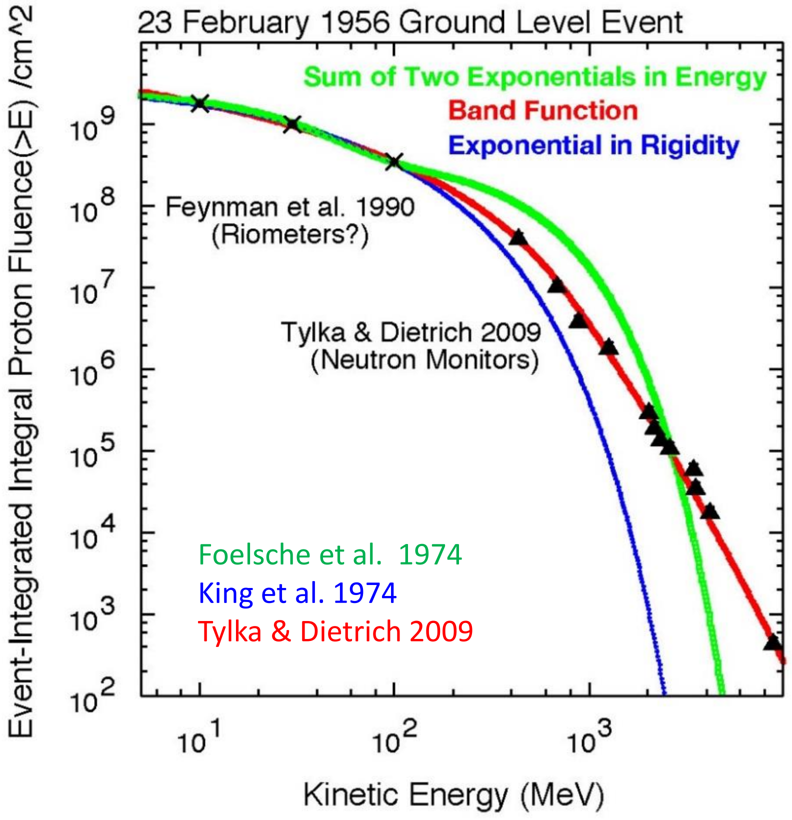
Dose-equivalent calculated by Bill Atwell (JSC/Boeing), using the NASA/Langley HZETRN code

Comment on SEP Proton-Energy Thresholds

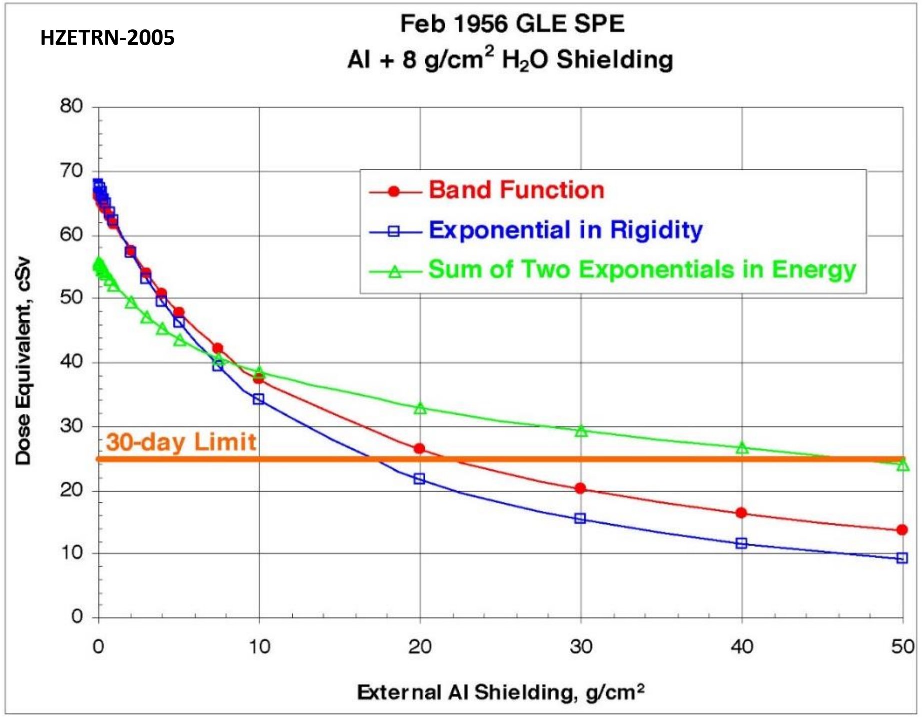
- **Evaluating the SEP radiation hazard requires both the absolute normalization of the proton flux as well as its energy spectrum.**
- **Historically, certain energy thresholds have been used to *roughly* characterize the severity of the SEP hazard:**
  - **>10 MeV: relevant to solar panels and sensors; NOAA uses this threshold to identify 'events'.**
  - **>30 MeV: relevant to biological effects and electronics (single-event effects (SEEs))**
  - **>100 MeV: relevant to storm-shelter design**
    - **But for shelter-design calculations, the spectrum is needed up to ~1000 MeV (Next slide)**

Designing a "Storm Shelter" for Astronauts

Solar-Proton Energy Spectrum

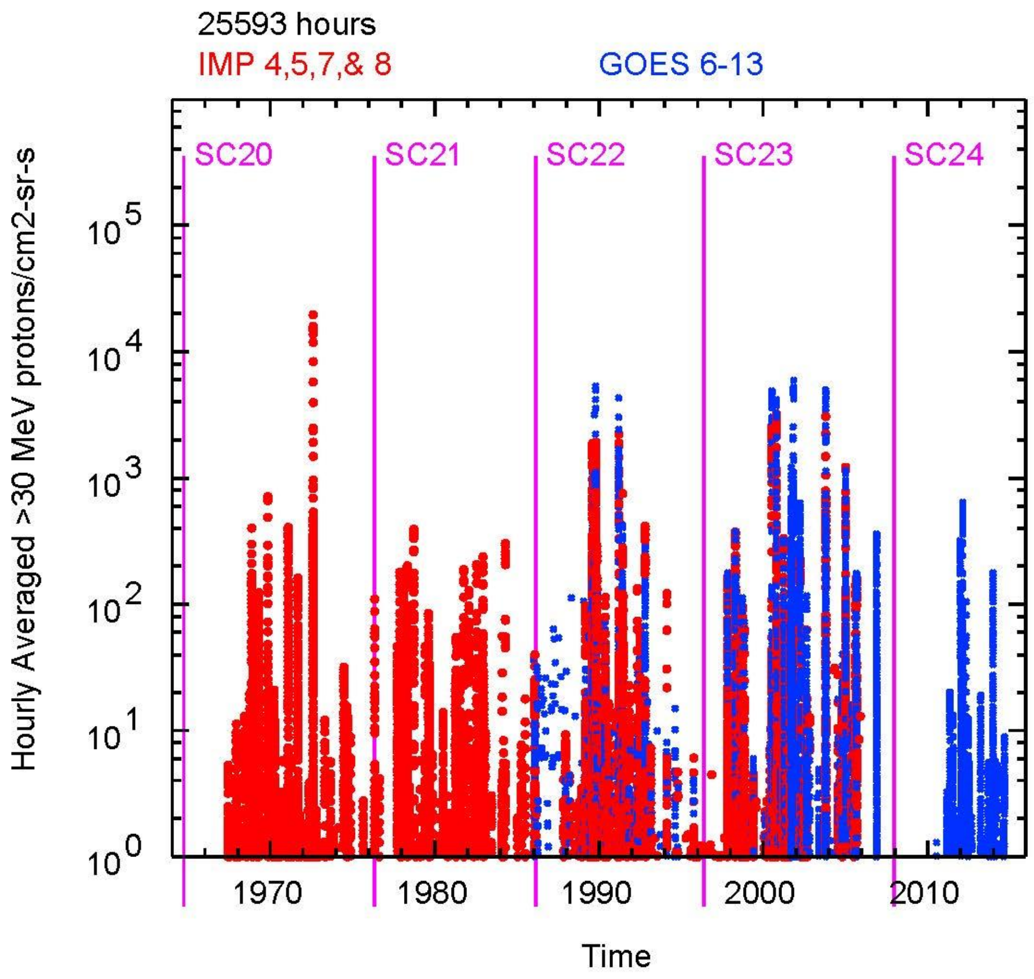


Dose-Depth Curves

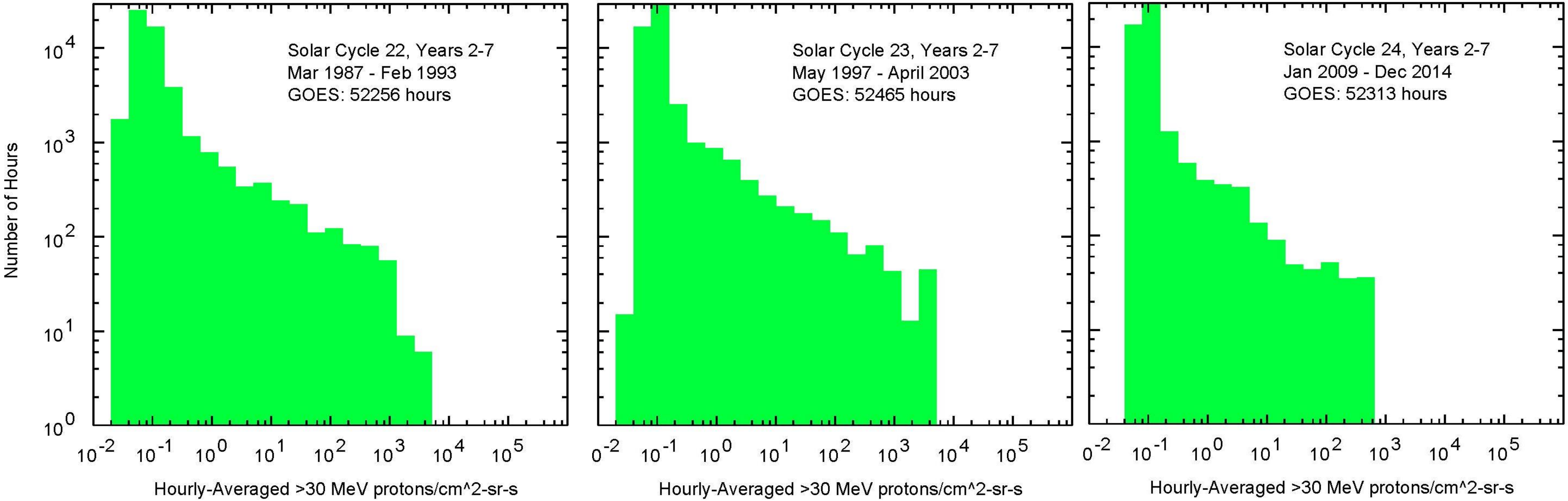


The correct spectral form above ~100 MeV is needed for shelter-design.

Comparison of SEP productivity Cycle 24 vs. Cycles 20, 21, 22 and 23



>30 MeV SEP Production in the Years 2-7 of the Solar Cycle
(Hourly-averaged fluxes in p/cm^2-sr-s)



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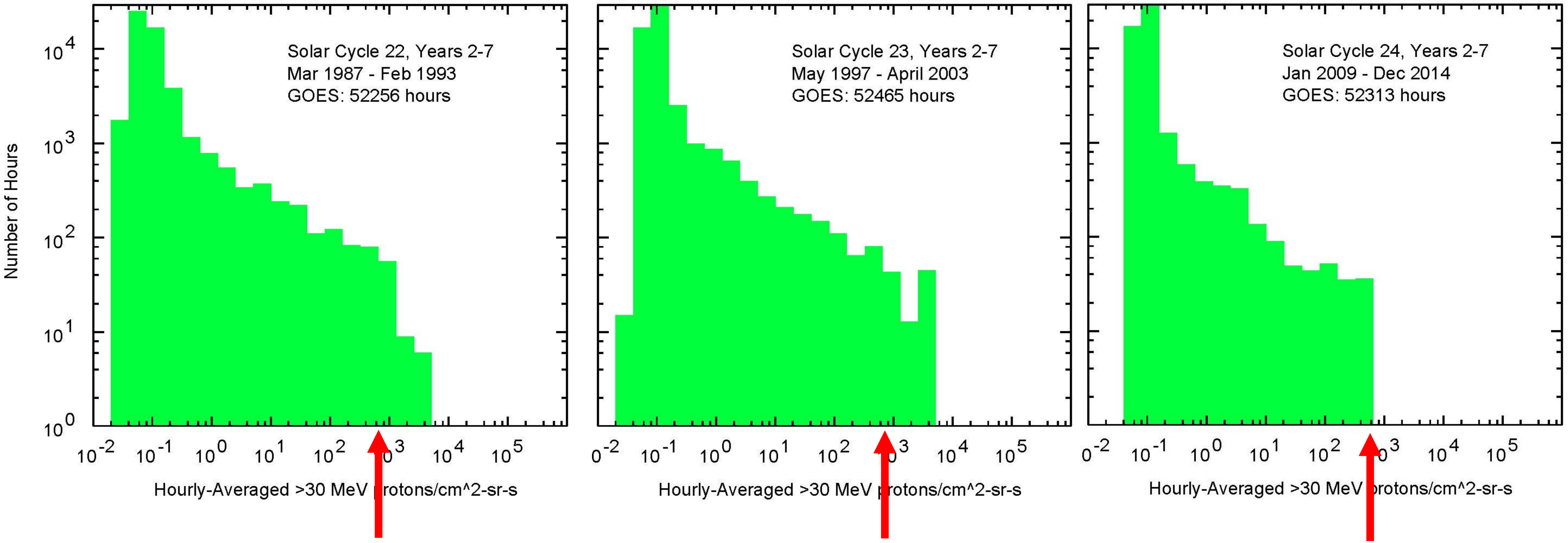

In Cycle 22, the Cycle 24 Max is exceeded in 73 hrs

In Cycle 23, the Cycle 24 Max is exceeded in 112 hrs

Max Flux in Cycle 24: 643 p/cm^2-sr-s

An interesting question: when, in the course of an event, do these hours with big fluxes occur? See back-up slides.

And what about the 2012 July 23 event observed by STEREO-A? See back-up slides.

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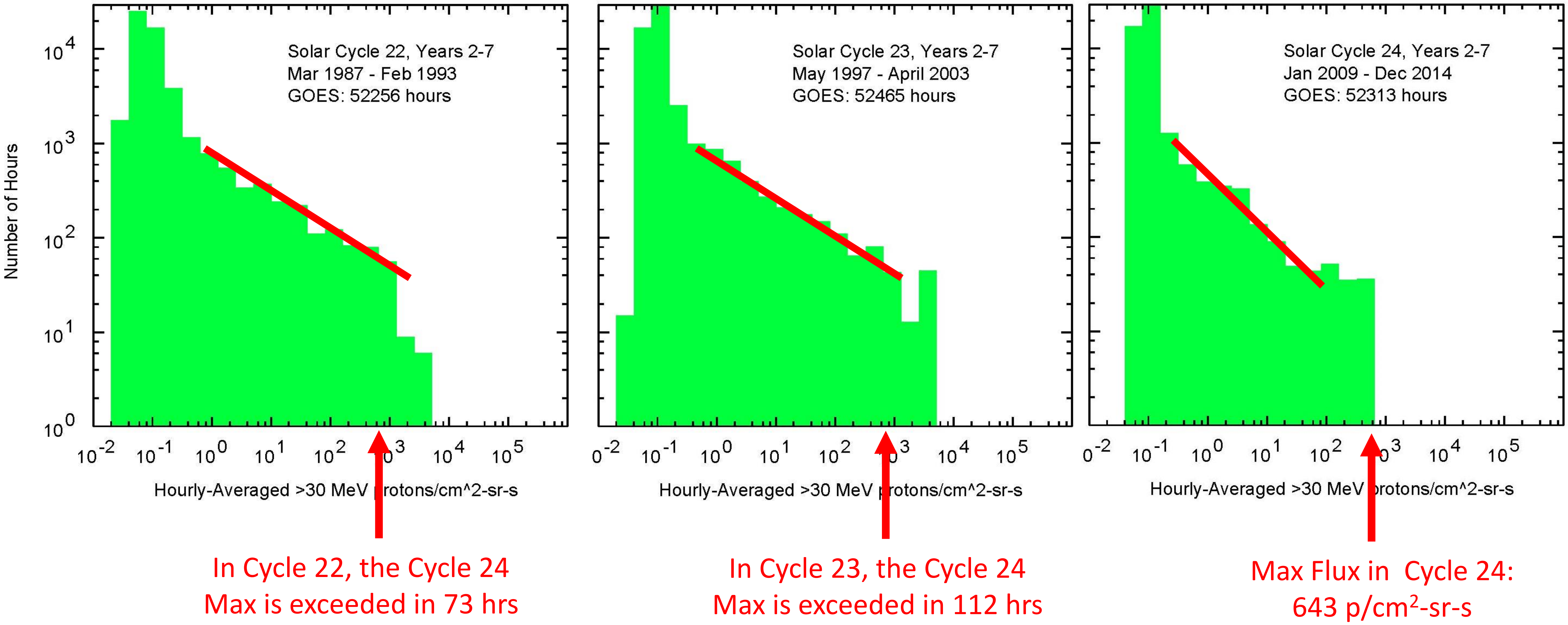
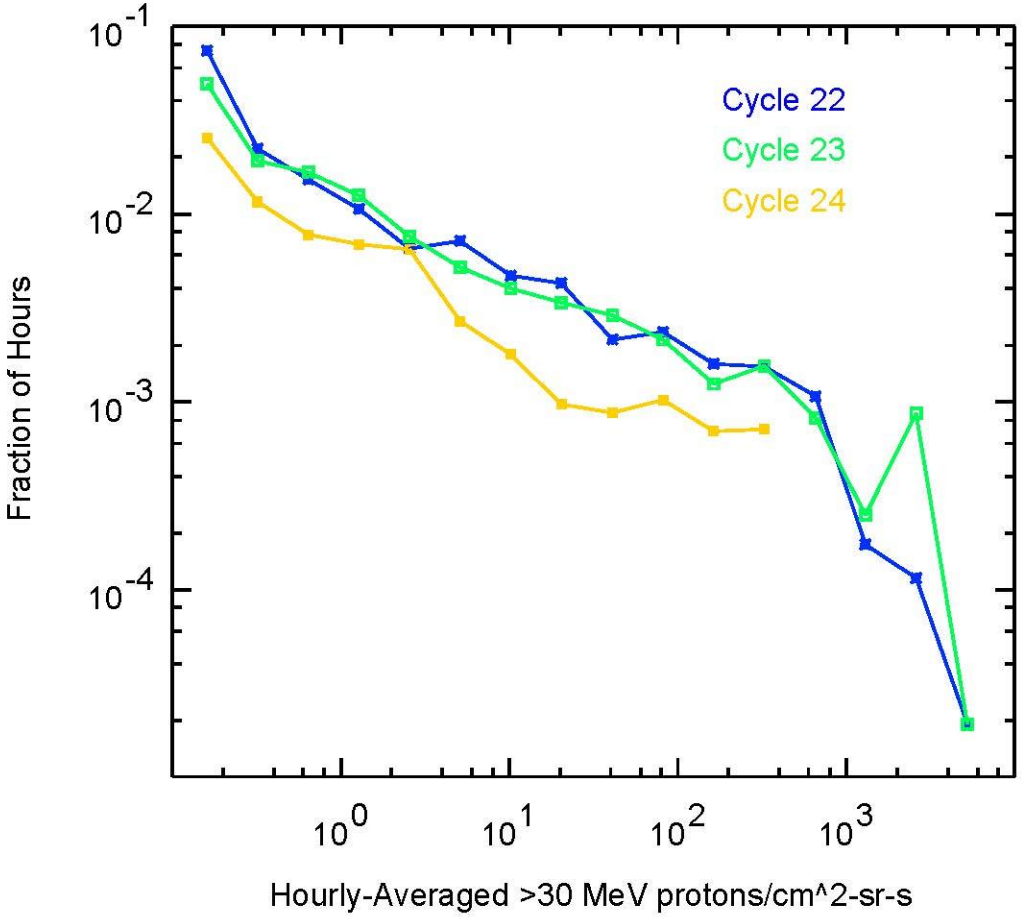
(Hourly-averaged fluxes in p/cm^2-sr-s)



In Cycle 24, the slope of the flux distribution is also steeper than in Cycles 22 & 23.

Let's look at this more quantitatively…

>30 MeV SEP Production in the Years 2-7 of the Solar Cycle
(Hourly-averaged fluxes in p/cm^2-sr-s)



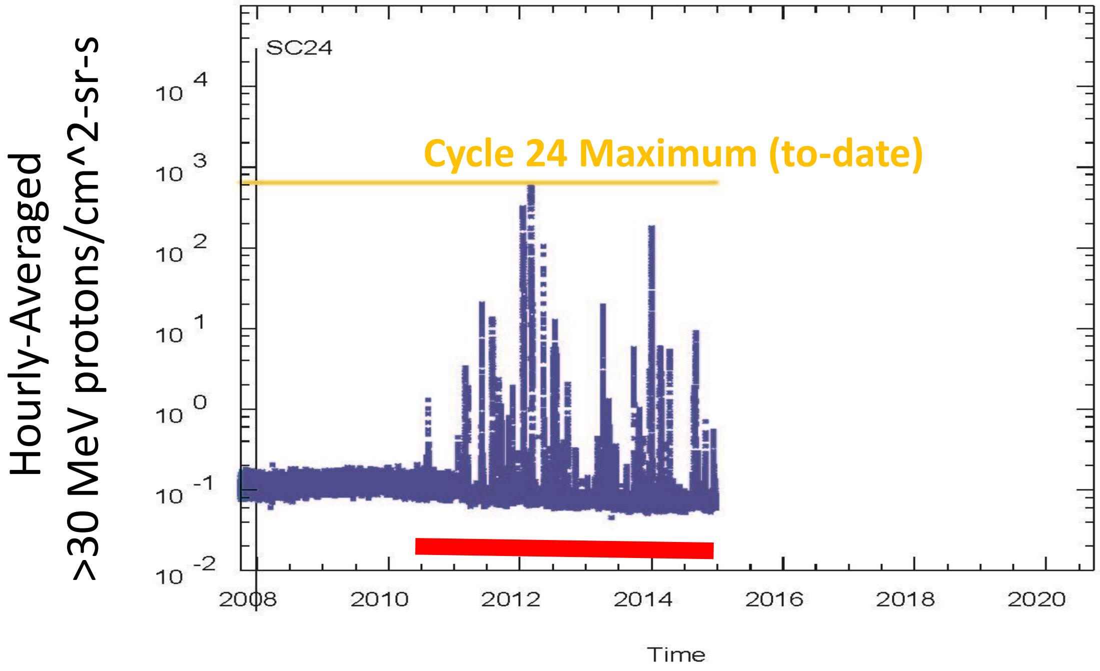
At every flux level, SC 24 has fewer hours at that level than either SC 22 or 23 by a factor of 2-4.

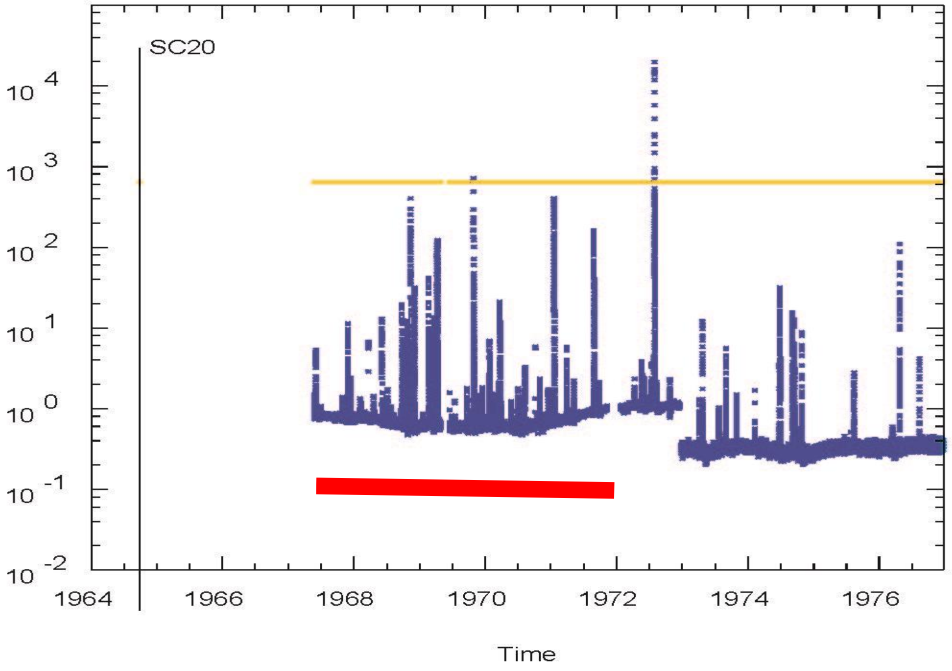
In SC 24, the highest SEP fluxes (top ~0.2%) are completely missing.

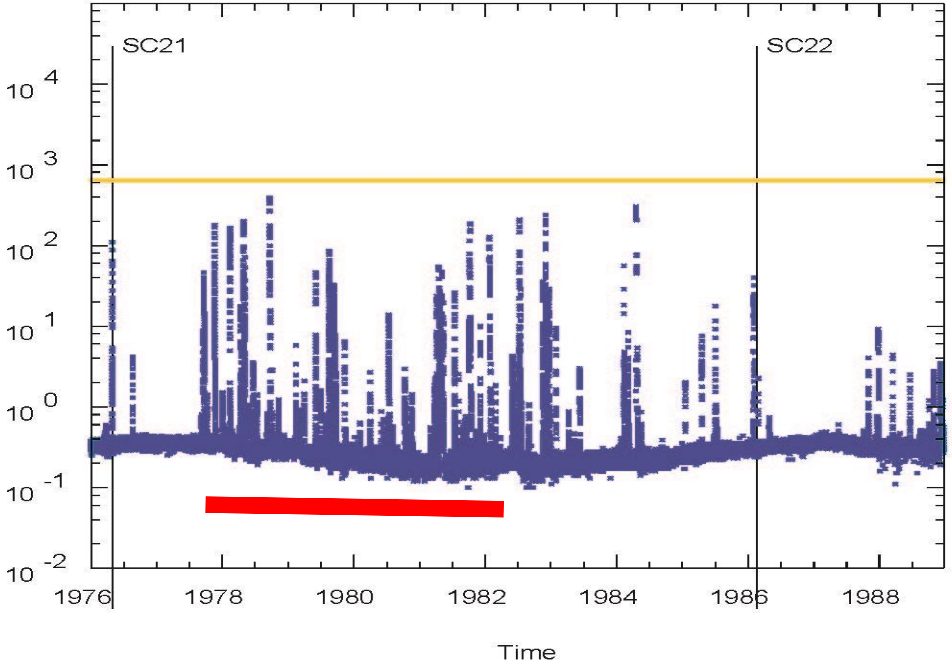
The same behavior is seen at other energies:
See backup slides at>10 and >100 MeV

In terms of the SEP radiation, SC 24 (at least so far) has been much less severe than SCs 22 & 23.

Cycle 24 compared to Cycles 20 & 21



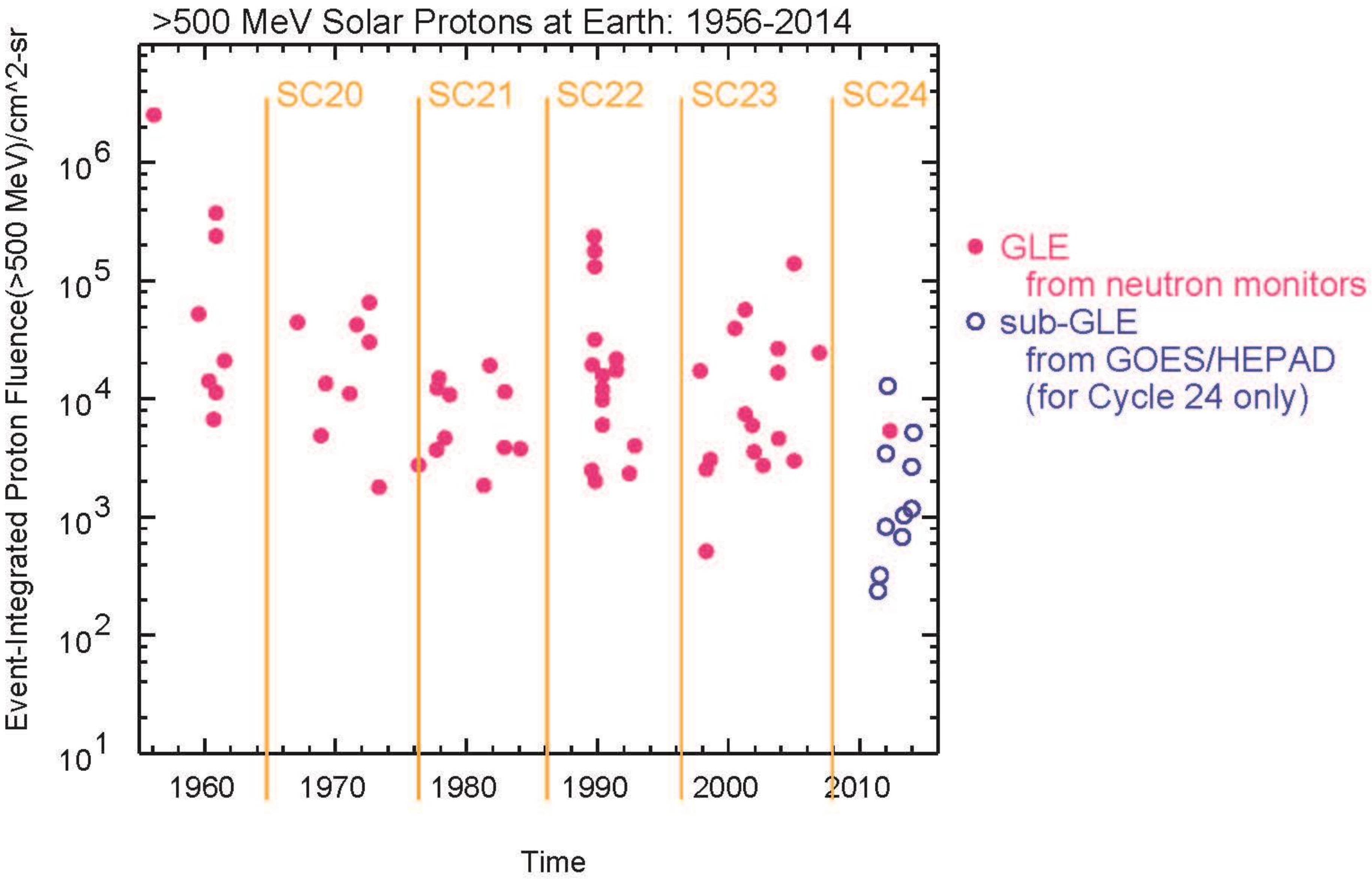




At >30 MeV, the differences between Cycle 24 and Cycles 20 and 21 are less impressive than the differences with Cycles 22 and 23.

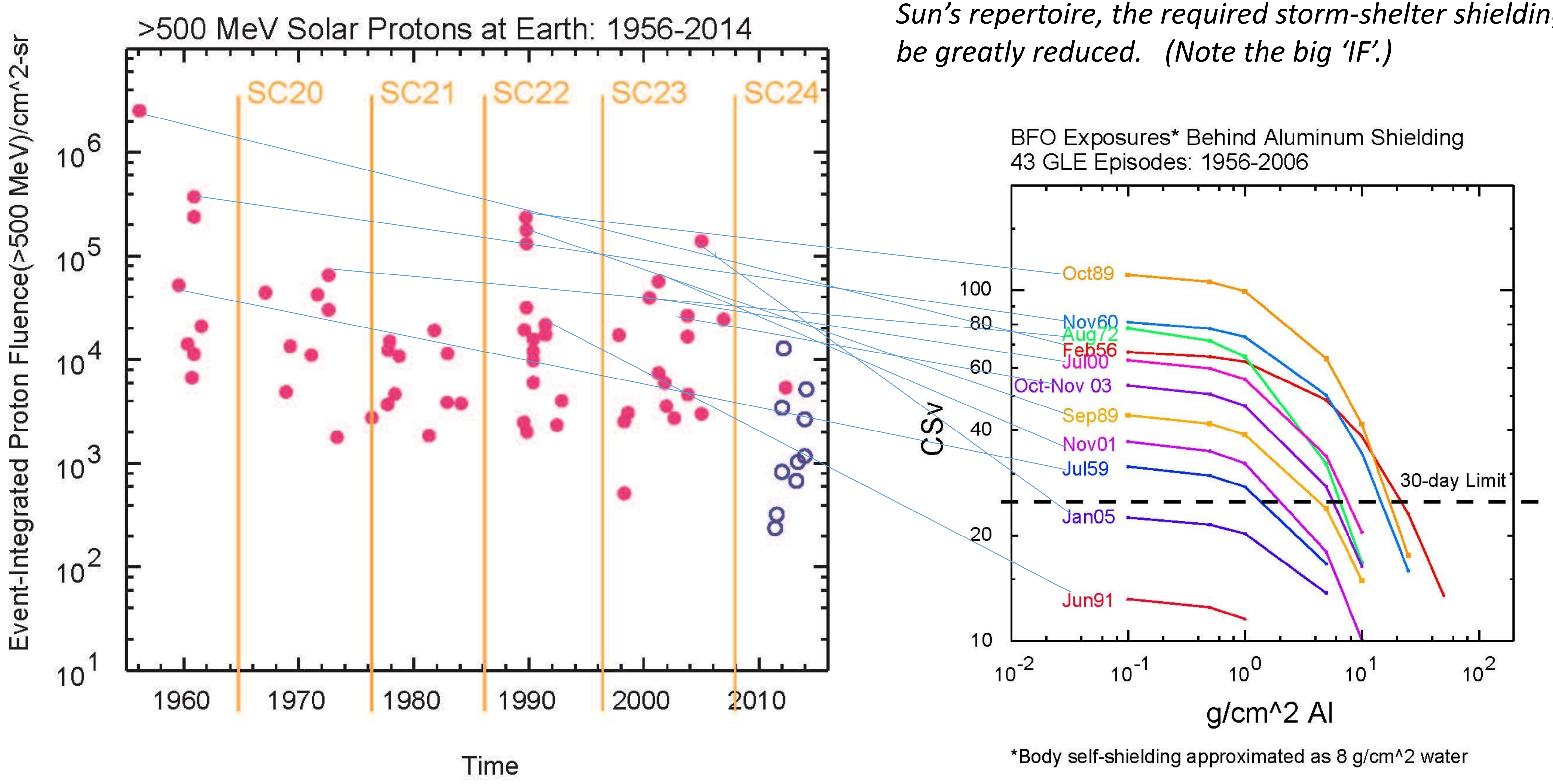
It will be important to see how the SEP events continue in the next two years.

But what about higher energies?



>500 MeV Solar Protons at Earth: 1956-2014
Event-Integrated Proton Fluence(>500 MeV)/cm^2-sr
SC20
SC21
SC22
SC23
SC24
10^1
10^2
10^3
10^4
10^5
10^6
1960
1970
1980
1990
2000
2010
Time
GLE
from neutron monitors
sub-GLE
from GOES/HEPAD
(for Cycle 24 only)

- IF *these very big GLEs have disappeared from the Sun's repertoire, the required storm-shelter shielding will be greatly reduced. (Note the big 'IF'.)*



Speculation: What if Cycle 24 is the “new normal”?

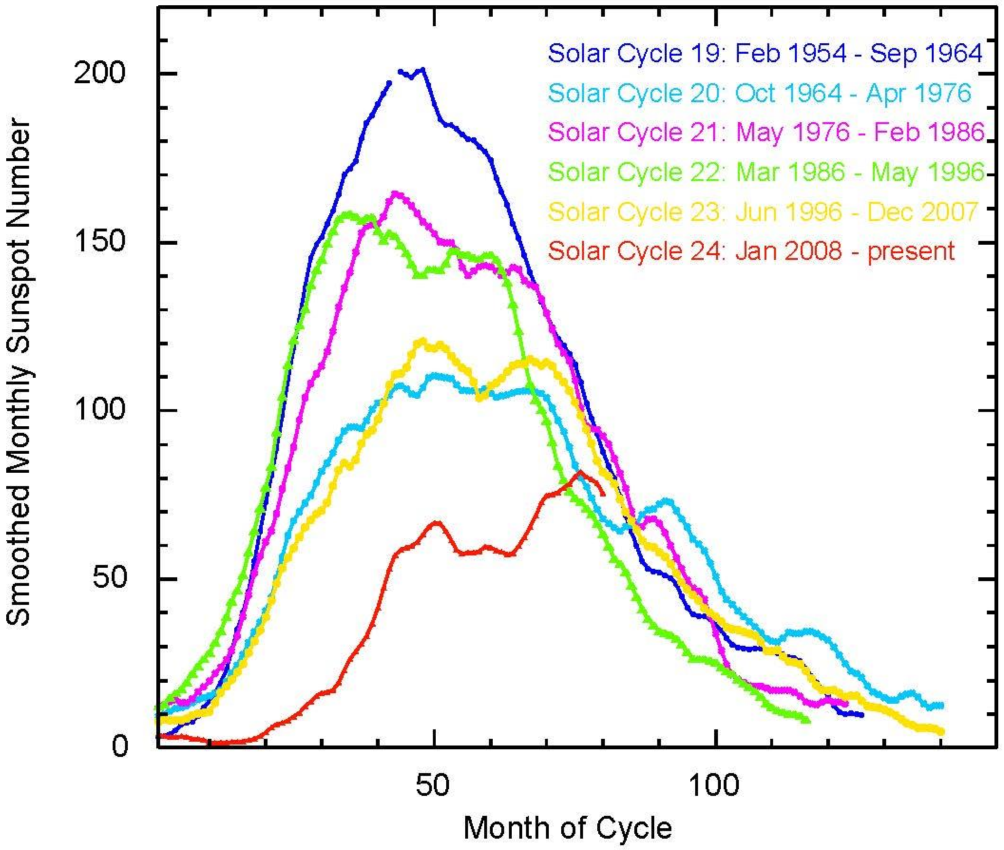
***Prediction is very difficult, especially if it’s about the future*.**

Neils Bohr

It’s tough to make predictions, especially about the future.

Yogi Berra

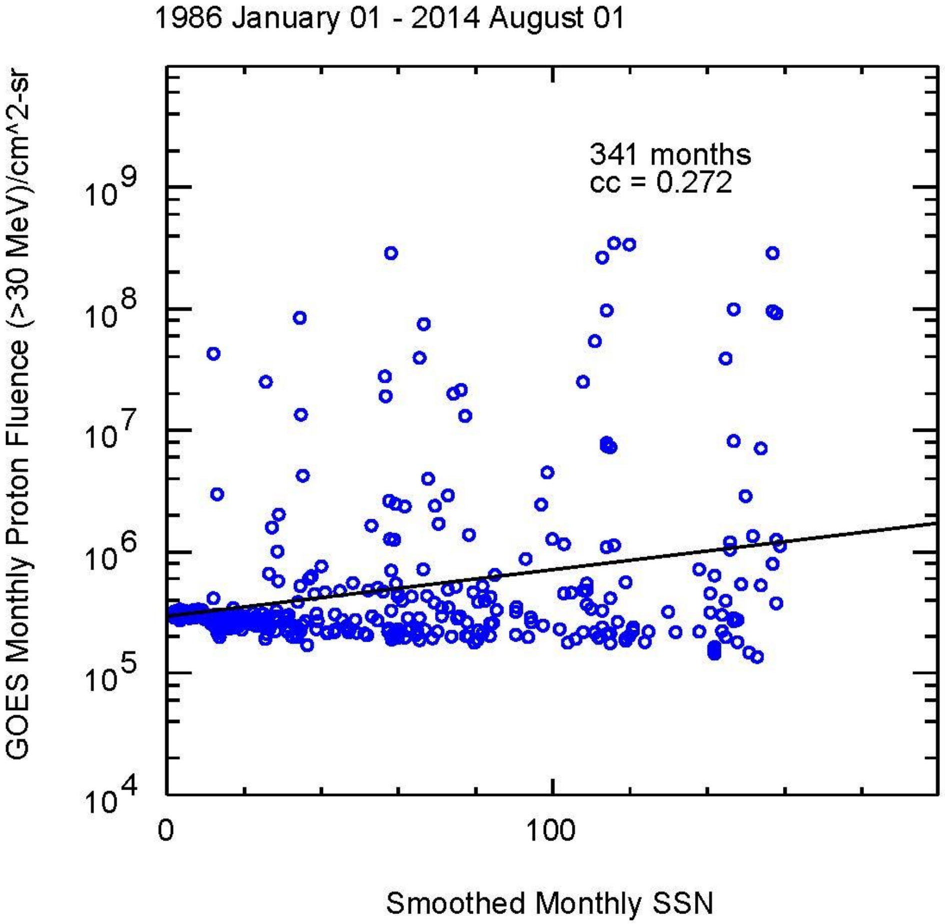
Sunspot Number (SSN) serves as a general measure of solar activity, for which we have a long historical record.



(Sunspot data provided by WDC-SILSO, Royal Observatory of Belgium)

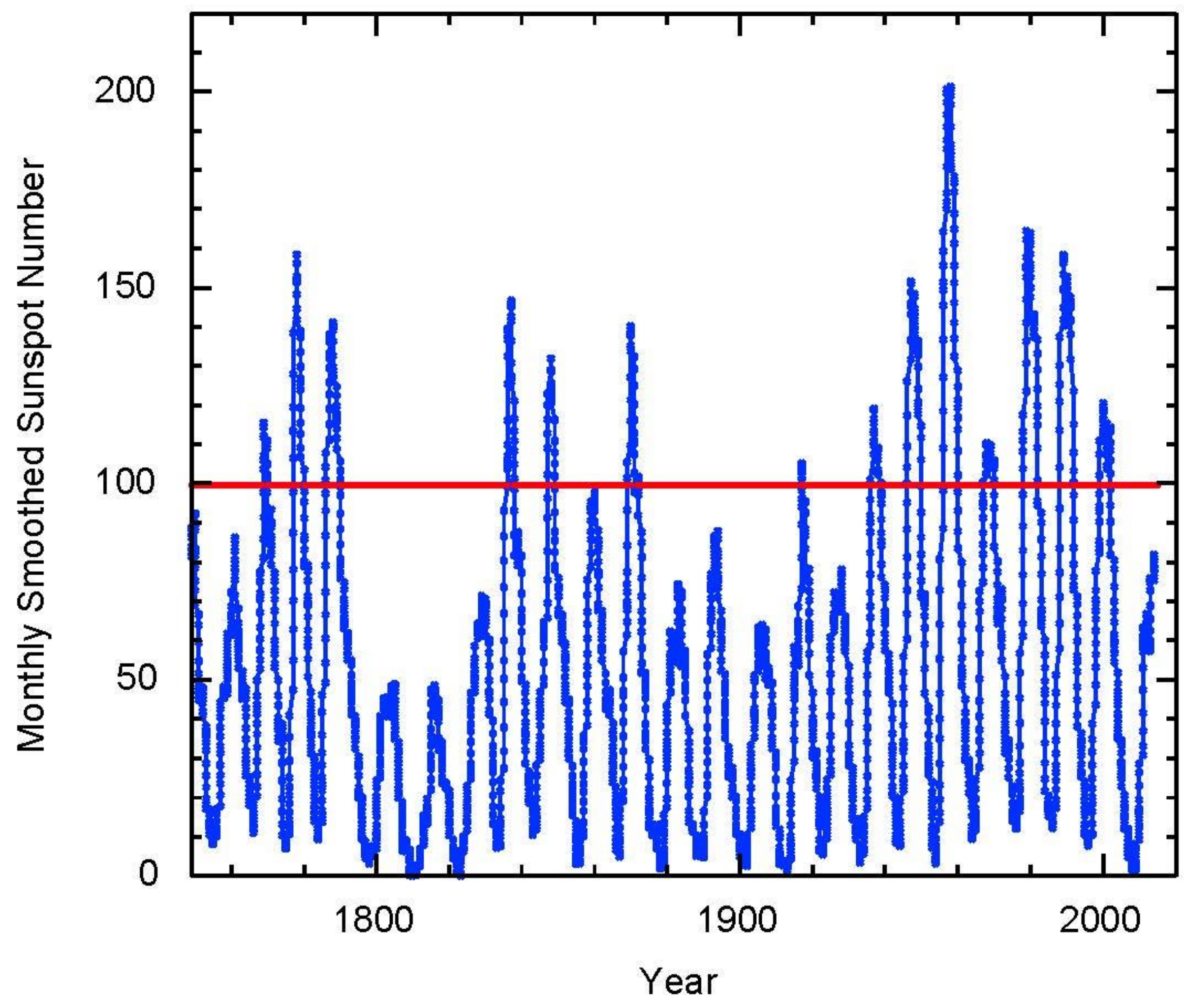
- **Sunspot Numbers in the Space Age, 1954-present**
  - **Cycles 24 is smaller – and unique**

But a **BIG CAVEAT**:
SSN is **not** a good predictor of SEP production



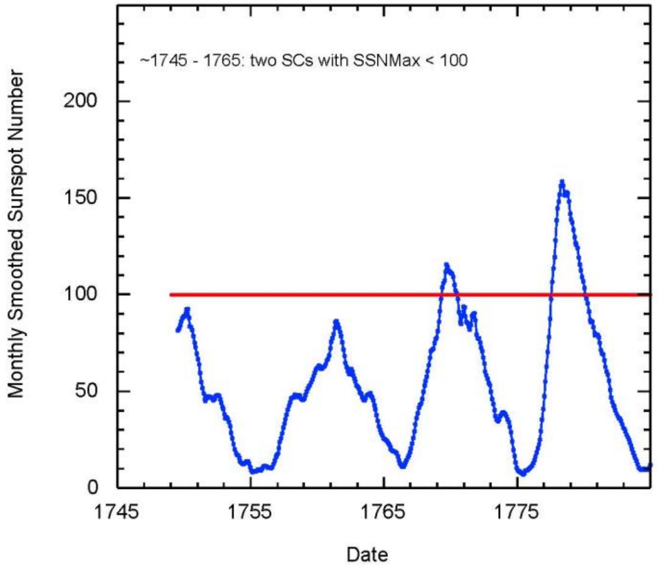
- **Nevertheless, let us boldly speculate where no one has ever speculated before…**

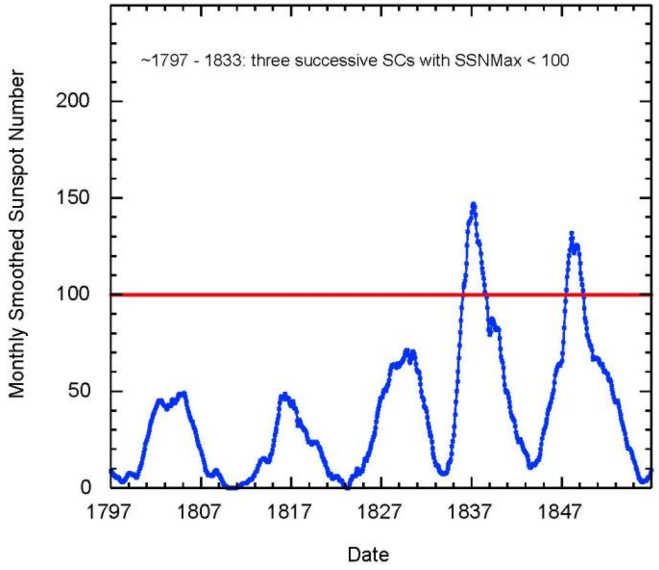
- **Cycle 24 is not yet over, but SSN is declining from a maximum of 82 in April 2014.**
- **Let’s examine previous Cycles with maximum SSN < 100.**

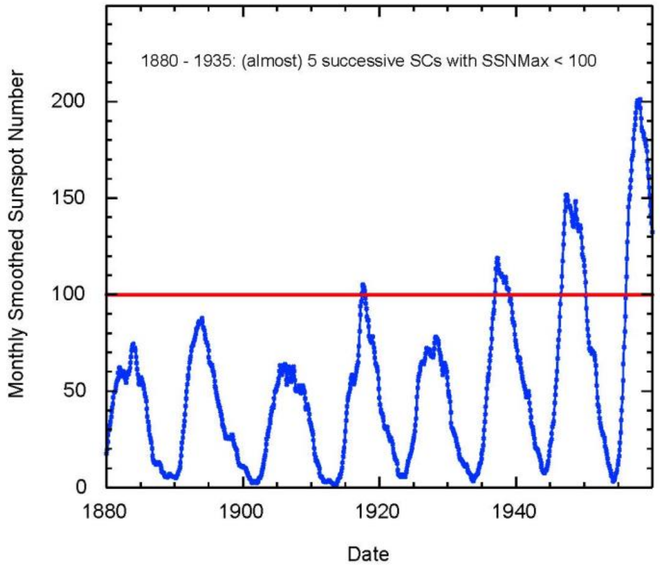


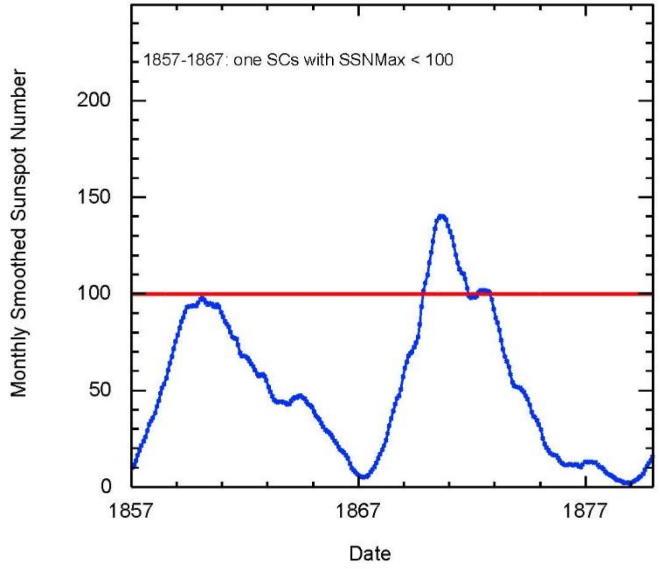
Sunspot numbers provided by WDC-SILSO, Royal Observatory of Belgium, Brussels

- **Cycle 24 is not over yet, but SSN is declining from a maximum of ~82 in April 2014.**
- **Let’s examine previous Cycles with maximum SSN < 100.**









- In three cases (above), the appearance of an SC with SSNMax < 100 presaged an extended period of time (20-50 years) with comparably low sunspot numbers.
- However, there is also an example (left) of a single, isolated SC with SSNmax <100; after that, sunspot numbers returned to higher values.
- And, of course, there’s also the Maunder Minimum: No sunspots: 1645-1715

Summary

- SEP radiation hazard is important for both human and robotic explorers.
  - Astronauts will need: (1) early warning and (2) an adequate storm-shelter.
  - The largest uncertainty in the long-term cancer risk is due to biology.
- Compared to Solar Cycles 22 & 23, the SEP radiation hazard is reduced in Solar Cycle 24, at least over the first 7 years of the cycles:
  - The probability of encountering any given flux level is less.
  - The largest fluxes of previous Solar Cycles (top ~0.2%) are absent.
  - These statements are true at all energies relevant to space-system design.
- Differences with Solar Cycles 20 and 21 are most apparent at very high-energies (>500 MeV), as evidenced by Solar Cycle 24's relative dearth of GLEs.

Summary (continued)

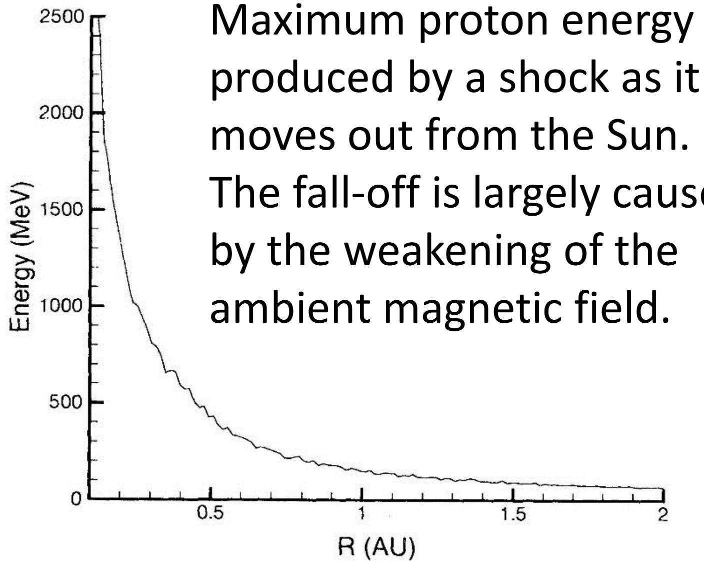
- IF Cycle 24 presages a new type of solar behavior, not seen before in the Space Age and that will continue for decades, the relative importance of the SEP radiation hazard will be reduced. (Note the 'big IF'.)

- IF the Sun is no longer producing the very large Ground-Level Events (GLEs) seen in 1956-2006, the required storm-shelter shielding will be greatly reduced.

- These reductions in the SEP-radiation hazard, combined with the ***increase*** in the GCR-radiation hazard, might make solar maximum a better time-frame for long-duration human missions.

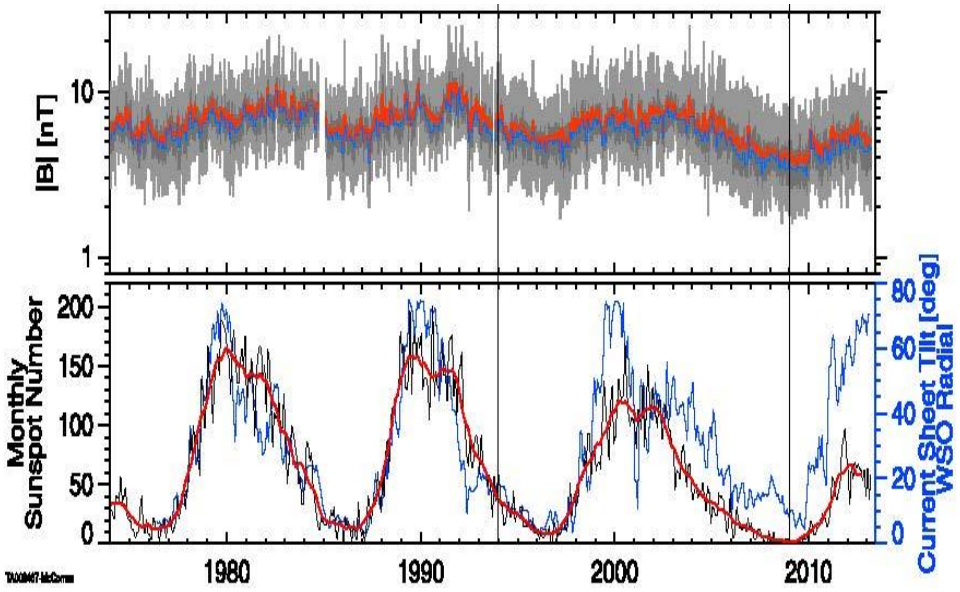
Backups

What's the physics behind the reduced SEP productivity? *We can speculate…*



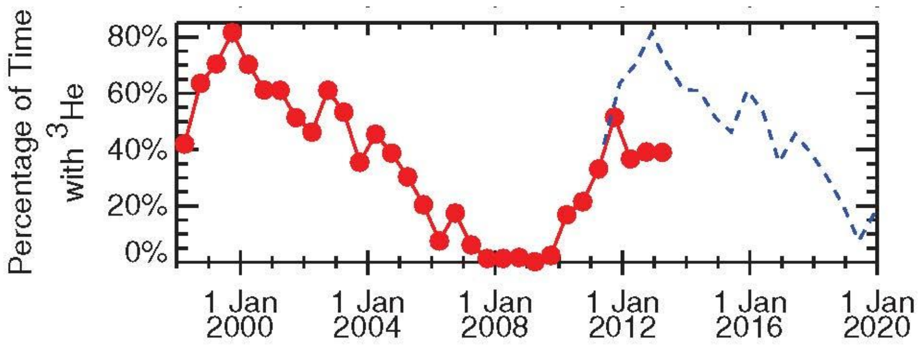
Maximum proton energy produced by a shock as it moves out from the Sun. The fall-off is largely caused by the weakening of the ambient magnetic field.

Zank et al., JGR 105, 25709 (2000)



McComas et al., ApJ 779:2 (2013)

Compared to previous solar maxima, the mean magnetic in the ecliptic at 1 AU has fallen by ~30%.



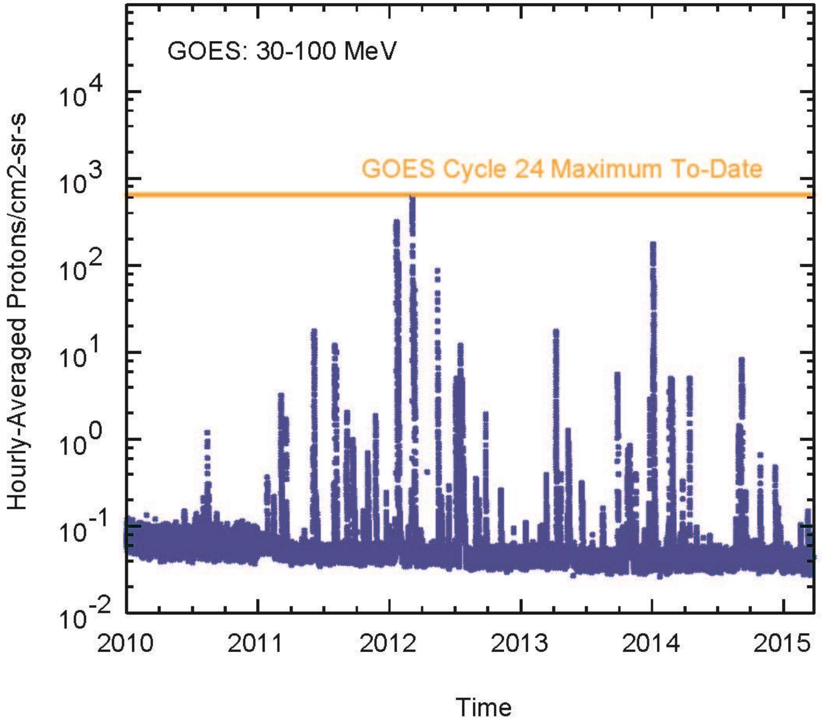
Wiedenbeck & Mason, ASP Conf 484 (2014)

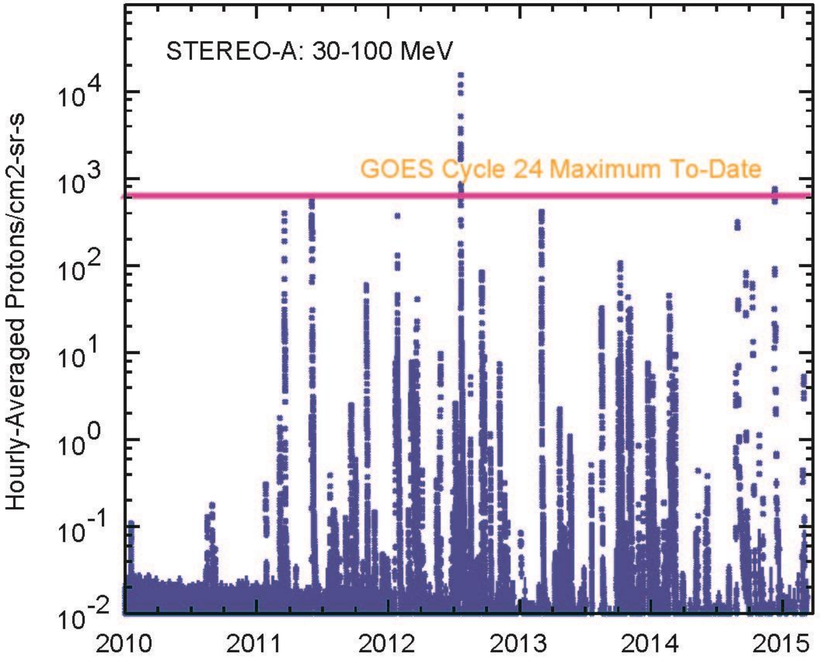
Compared to SC 23, there are fewer potential suprathermal seed particles available in SC 24.

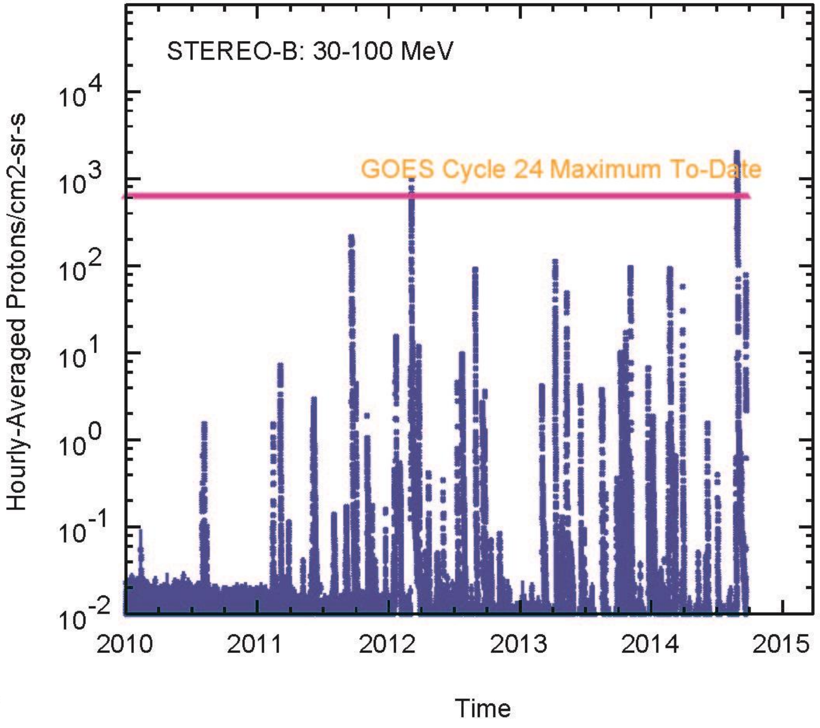
These factors – weakened magnetic field and fewer suprathermals – together may explain why SEP production is down.

Other ideas: Gopalswamy et al. *Earth, Planets and Space* 66:104 (2014)

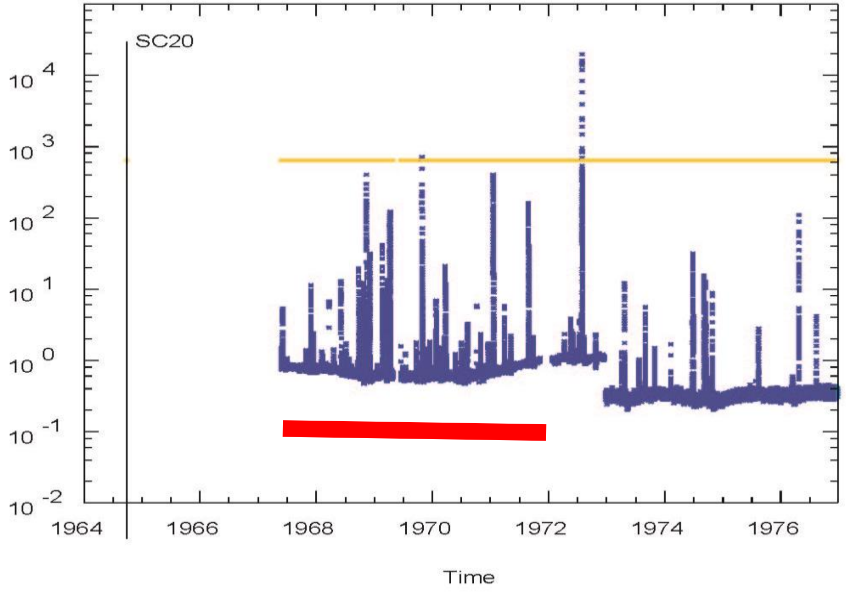
STEREO-A Observations of the 23 July 2012 Shock Event





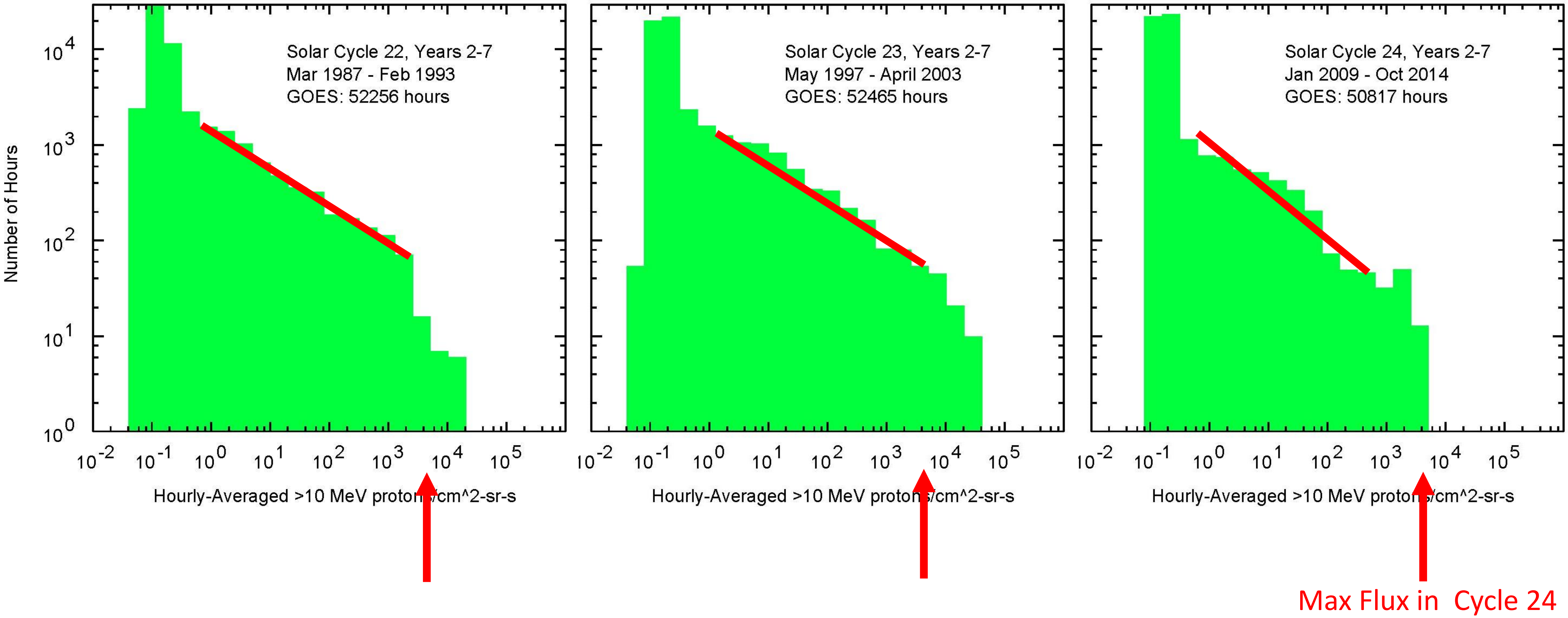


Russell, et al., *ApJ* **770**:38, 2013)

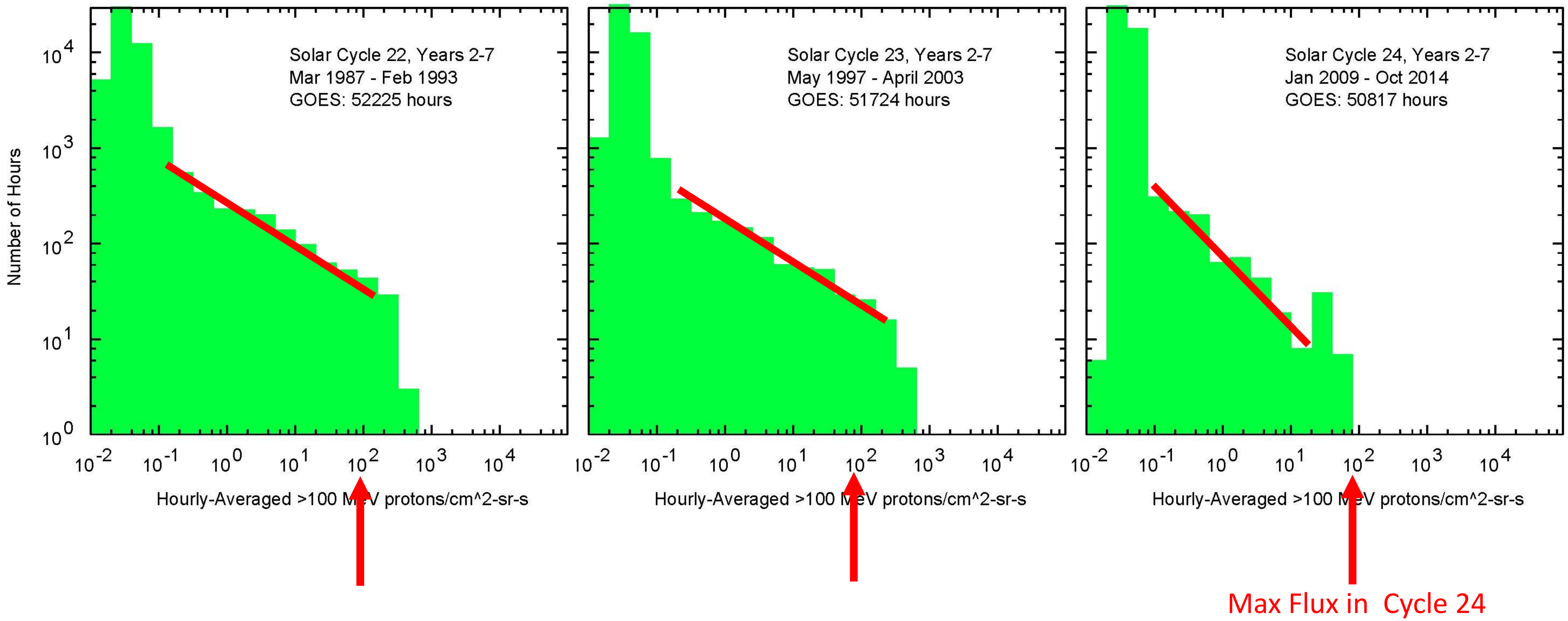


The July 2012 event is similar the August 1972 events of Cycle 20.

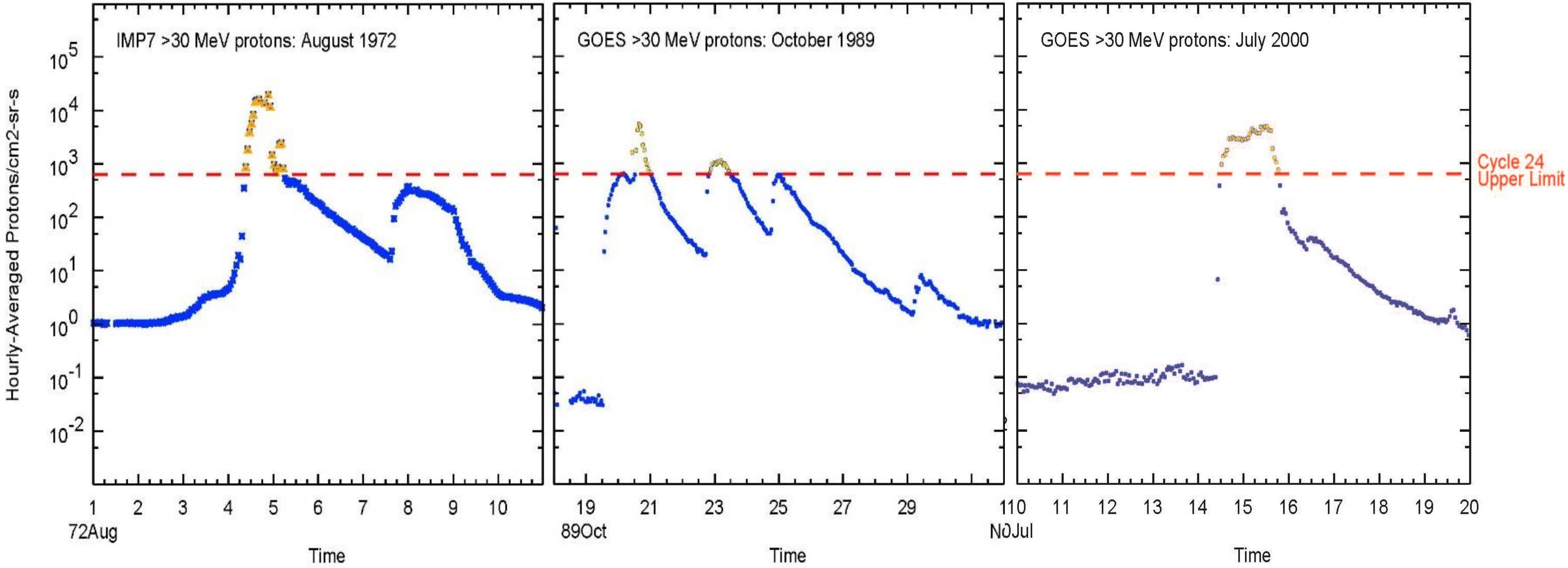
>10 MeV SEP Production in the Years 2-7 of the Solar Cycle
(Hourly-averaged fluxes in p/cm2-sr-s)



>100 MeV SEP Production in the Years 2-7 of the Solar Cycle
(Hourly-averaged fluxes in p/cm2-sr-s)

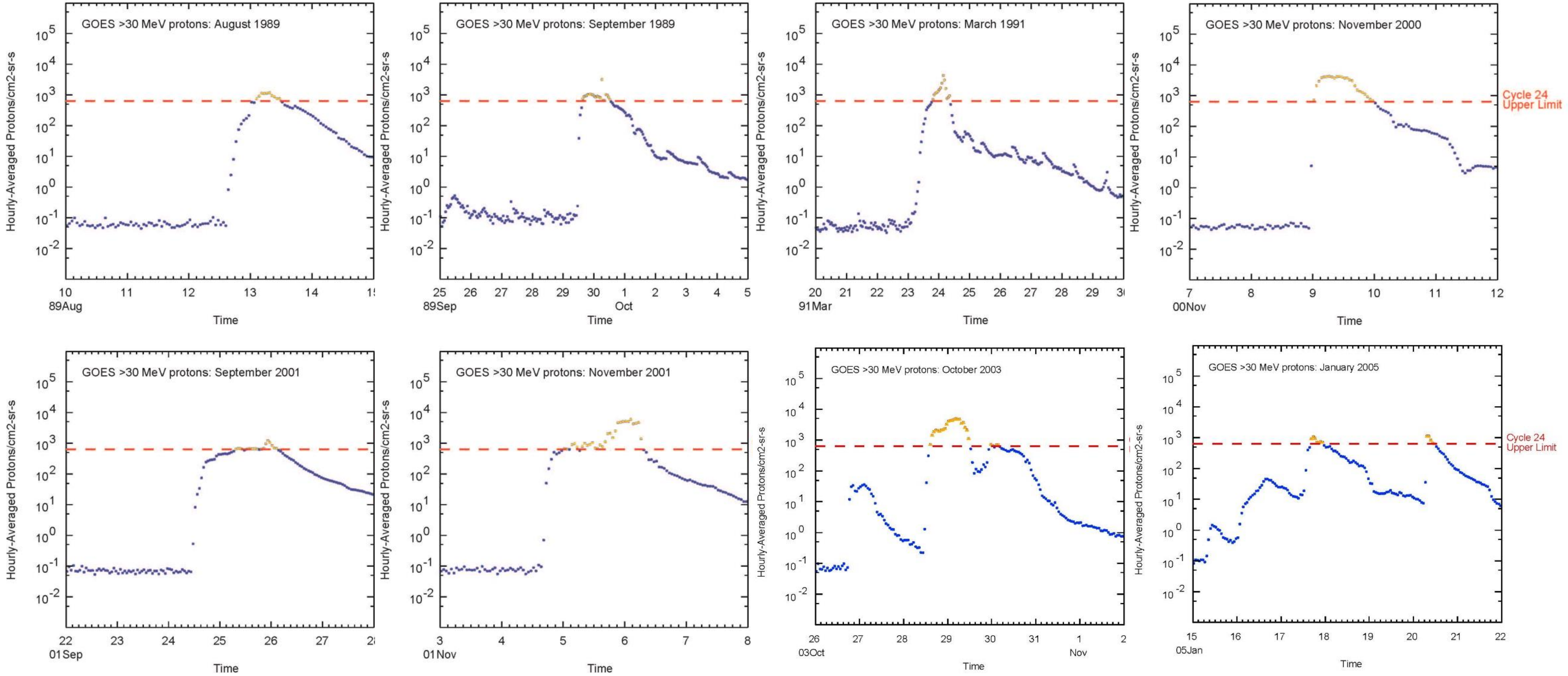


Examples of "Big Hours": >30 MeV Intensity exceeds Cycle 24 Upper Limit

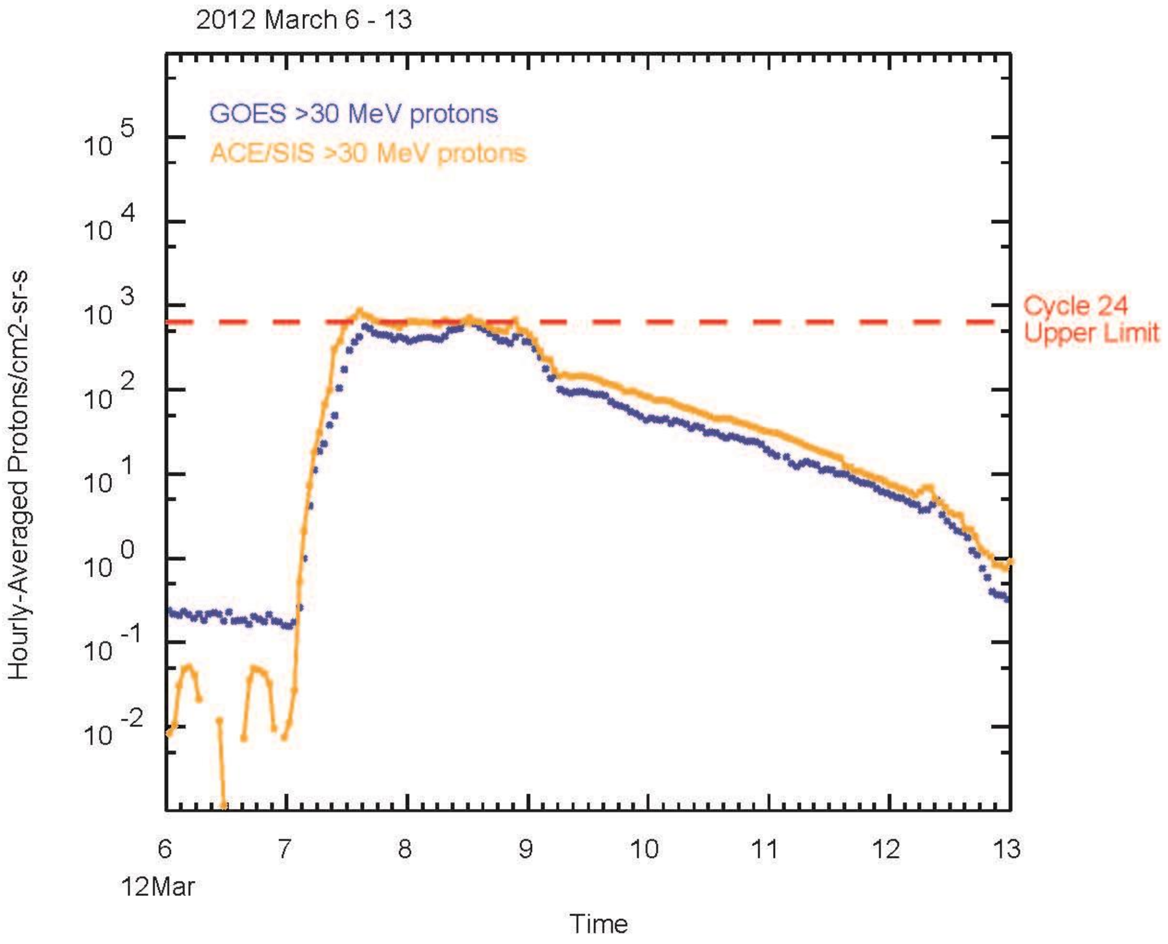


1. GOES can measure fluxes that are more than 10x greater than the maximum seen in Cycle 24. The Cycle 24 maximum is unlikely to be an instrumental artifact.
2. These 'severe hours' occur during events which are often used as "worst-case" SEP environments for design studies.
3. In some cases (like July 2000), the Cycle 24 upper limit is exceeded in less than 3 hours.

More Examples of "Big Hours": >30 MeV Intensity exceeds Cycle 24 Upper Limit



Highest >30 MeV Intensities seen in Solar Cycle 24



(GCR background has been subtracted.)

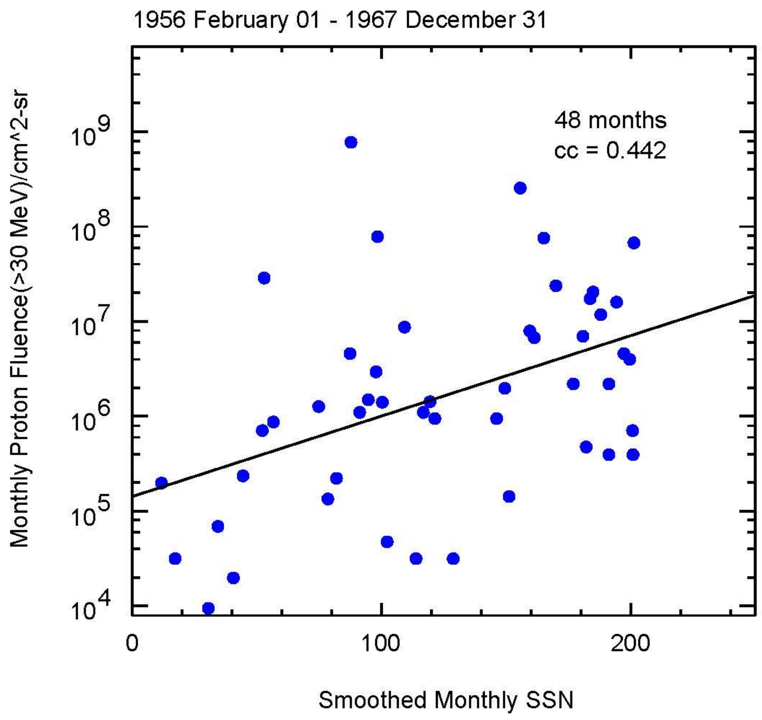
Could this be instrumental saturation? ***Very Unlikely:***

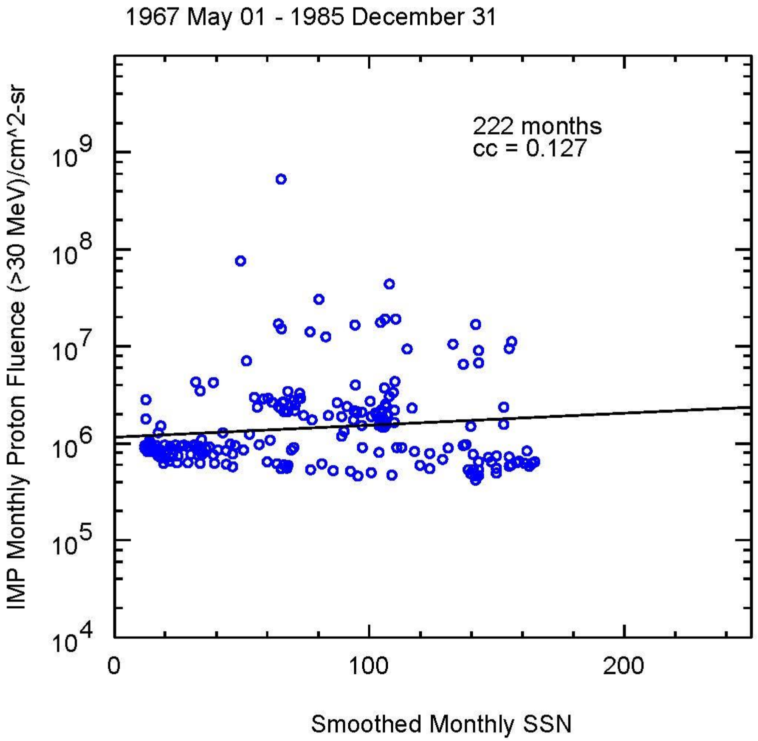
ACE/SIS intensities agree to within 30%

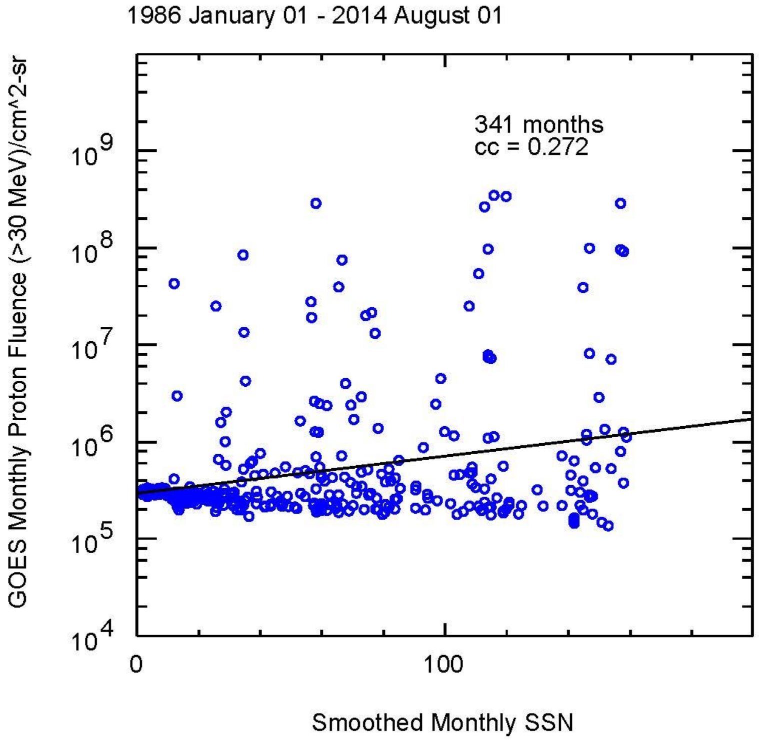
GOES design has demonstrated the ability to handle rates that are higher by at least a factor of 30.

ACE/GOES discrepancy to be investigated.

Monthly >30 MeV Proton Fluence vs. Smoothed Sunspot Number





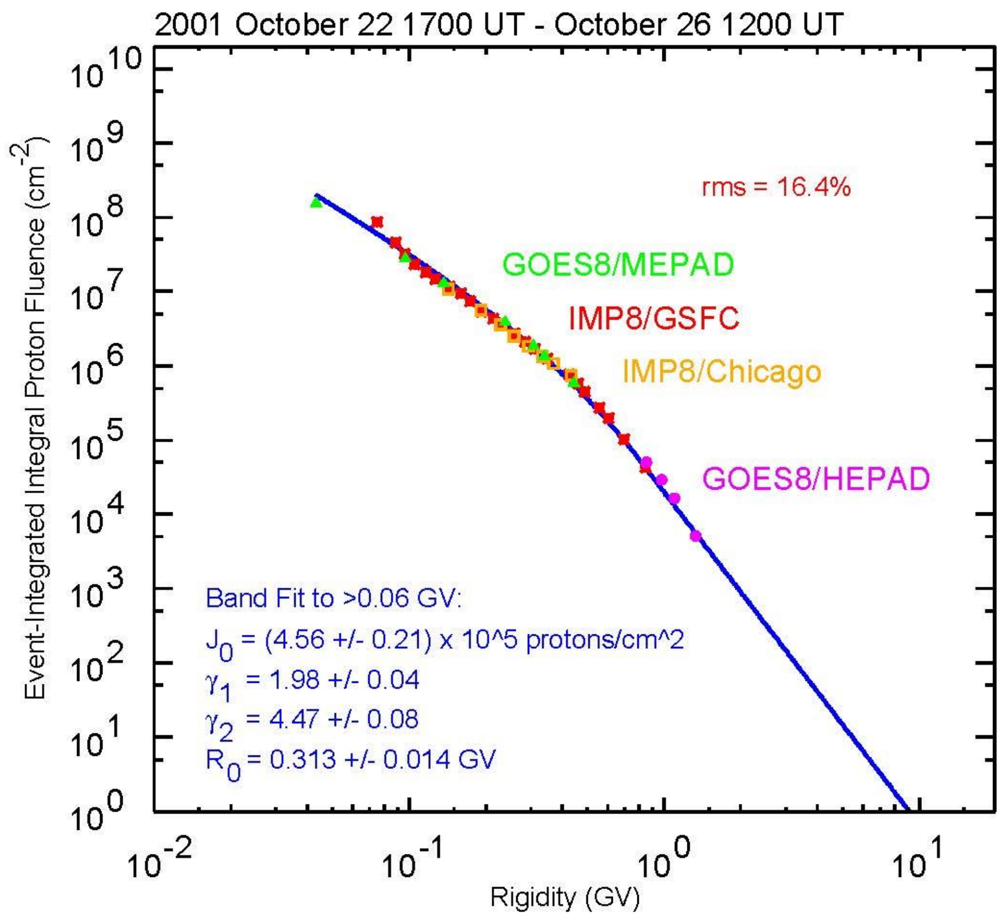


Numbers of SEP Events* in Solar Cycles 21 - 24

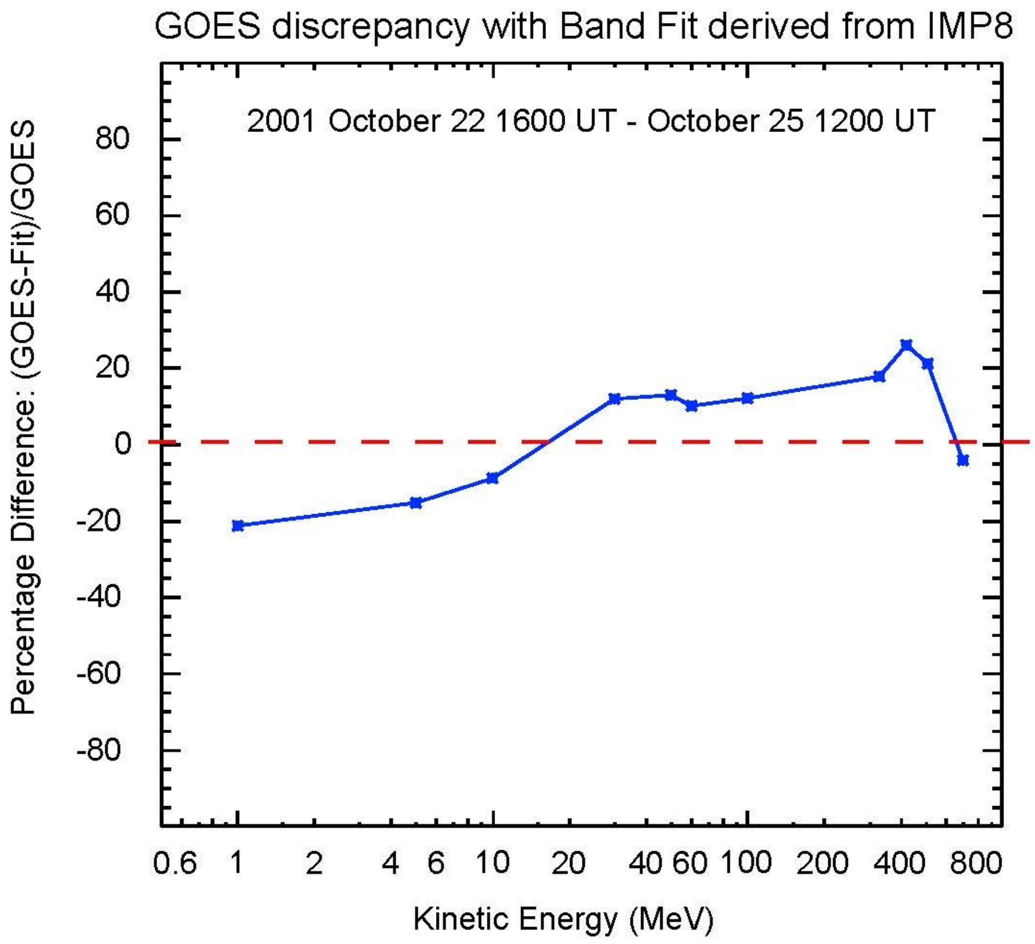
	Cycle 21		Cycle 22		Cycle 23		Cycle 24	
	Dates	# Events	Dates	# Events	Dates	# Events	Dates	# Events
Year 1	May 76-Apr 78	5	Mar 86-Feb 87	2	May 96-Apr 97	0	Jan 08-Dec 08	0
Year 2	May 77-Apr 78	5	Mar 87-Feb 88	2	May 97-Apr 98	3	Jan 09-Dec 09	0
Year 3	May 78-Apr 79	8	Mar 88-Feb 89	9	May 98-Apr 99	9	Jan 10-Dec 10	1
Year 4	May 79-Apr 80	6	Mar 89-Feb 90	22	May 99-Apr 00	5	Jan 11-Dec 11	7
Year 5	May 80-Apr 81	4	Mar 90-Feb 91	14	May 00-Apr 01	18	Jan 12-Dec 12	13
Year 6	May 81-Apr 82	8	Mar 91-Feb 92	16	May 01-Apr 02	24	Jan 13-Dec 13	7
Year 7	May 82-Apr 83	12	Mar 92-Feb 93	5	May 02-Apr 03	10	Jan 14-Dec 15	6
Sum		48		70		69		34
Year 8	May 83-Apr 84	6	Mar 93-Feb 94	3	May 03-Apr 04	10	Jan 15- Mar 15	0
Year 9	May 84-Apr 85	4	Mar 94-Feb 95	1	May 04-Apr 05	6		
Year 10	May 85-Feb 86	3	Mar 95-Feb 96	1	May 05-Apr 06	6		
Year 11	n/a	-	Mar 96-Apr 96	0	May 06-Apr 07	2		
Year 12	n/a		n/a		May 07-Dec 07	0		
Total		61		75		92		?

*An event starts with three consecutive 5-minute intervals with flux of $\geq$10 MeV protons exceeding 10 p/cm^2-sr-s and ends when with this flux is $\leq$ 10 p/cm^2-sr-s. Some GOES "events" therefore comprise multiple events.

The SEP event of 2001 October 22 was the last for which we have spectral measurements from both IMP8 and GOES. We derived the Band-function spectrum using ***only*** IMP8 data. We then compared that Band-fit to the GOES measurements.



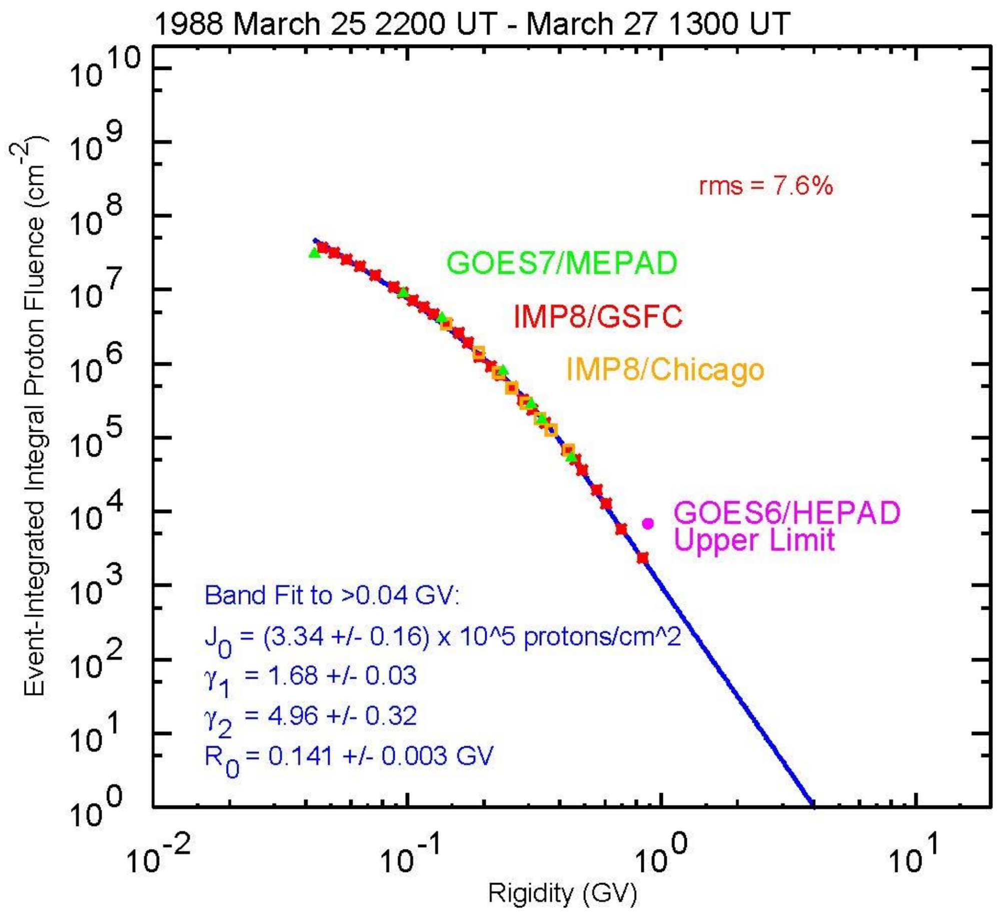
Note: GOES data points NOT used in making the Band fit.



The distribution of deviations of IMP8 datapoints from the fit has rms of 16.4%.

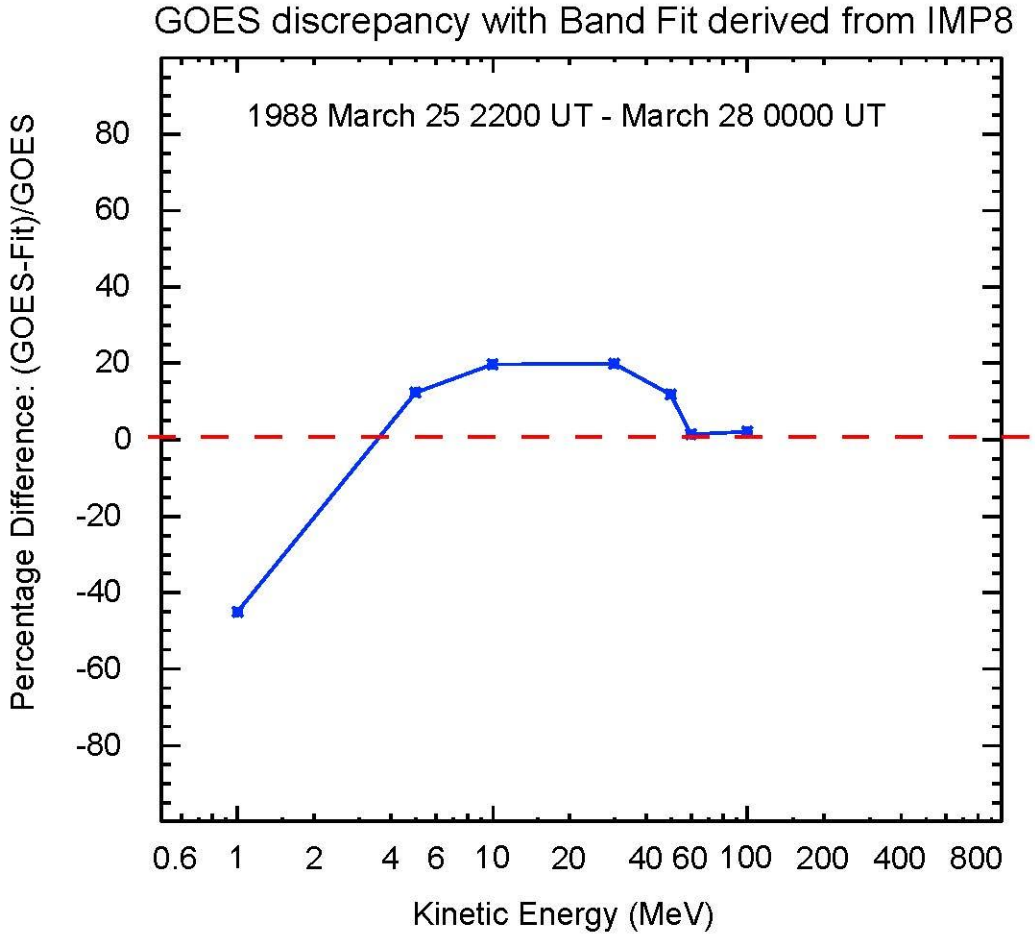
Nearly all of the GOES datapoints agree with the IMP8 Band fit to within ± 20%.

Another example, this time from near the start of GOES observations. This event is one of the earliest events of the GOES era in which IMP8 also had good data recovery. The event was too small, however, to be detected by HEPAD.



Note: GOES data points NOT used in making the Band fit.

The distribution of deviations of IMP8 datapoints from the fit has rms of 7.6%.



Except for the >1 MeV datapoint (unimportant for radiation effects), the GOES agrees with the IMP8 Band fit to within ± 20%.