

Major Solar Energetic Particle Events of Solar Cycles 22 and 23: Intensities above the Streaming Limit

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Space Environment
Radiation produced by
Solar Energetic Particles (SEPs)

- How intense a SEP event can be?
- Can we predict these intensities?
- What are the preventive measures to take once a SEP event is in progress?



PERGAMON

Radiation Measurements 30 (1999) 297–308

Radiation Measurements

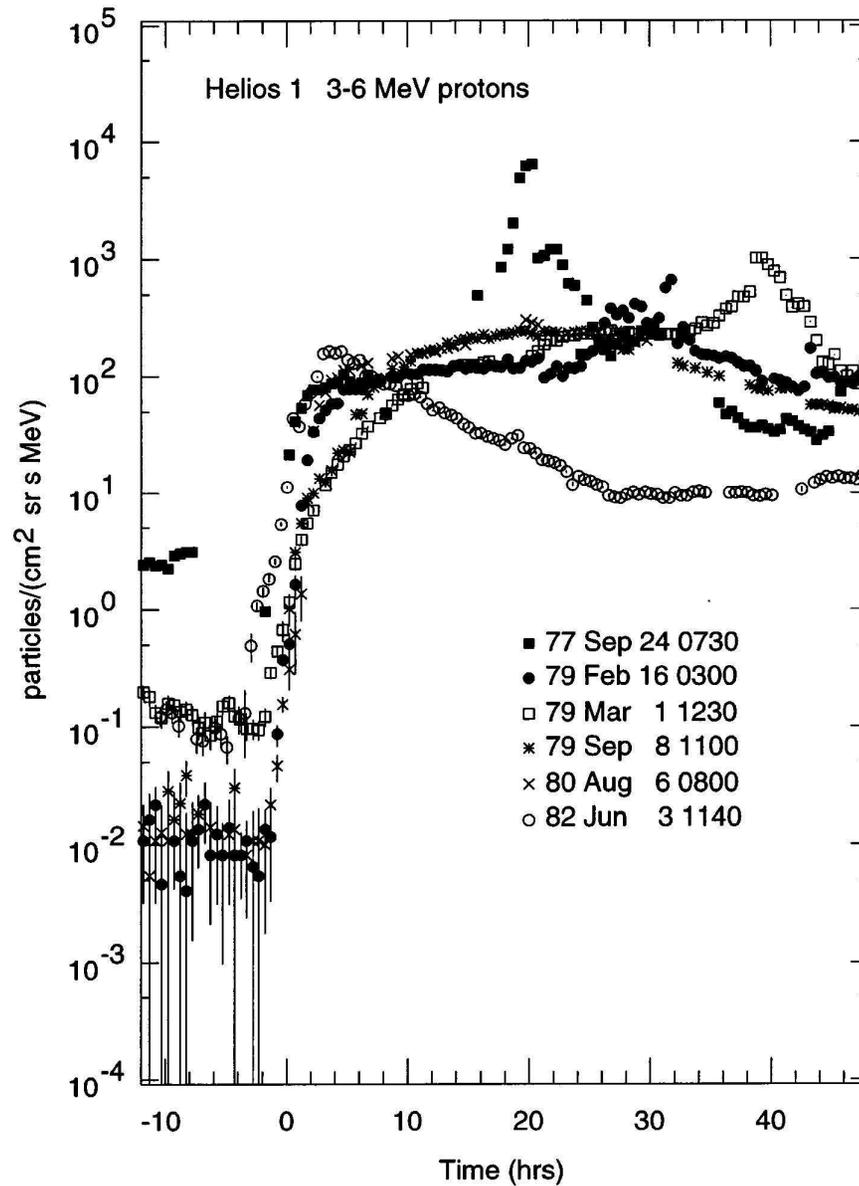
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Solar energetic particles: Is there time to hide?

Don Reames

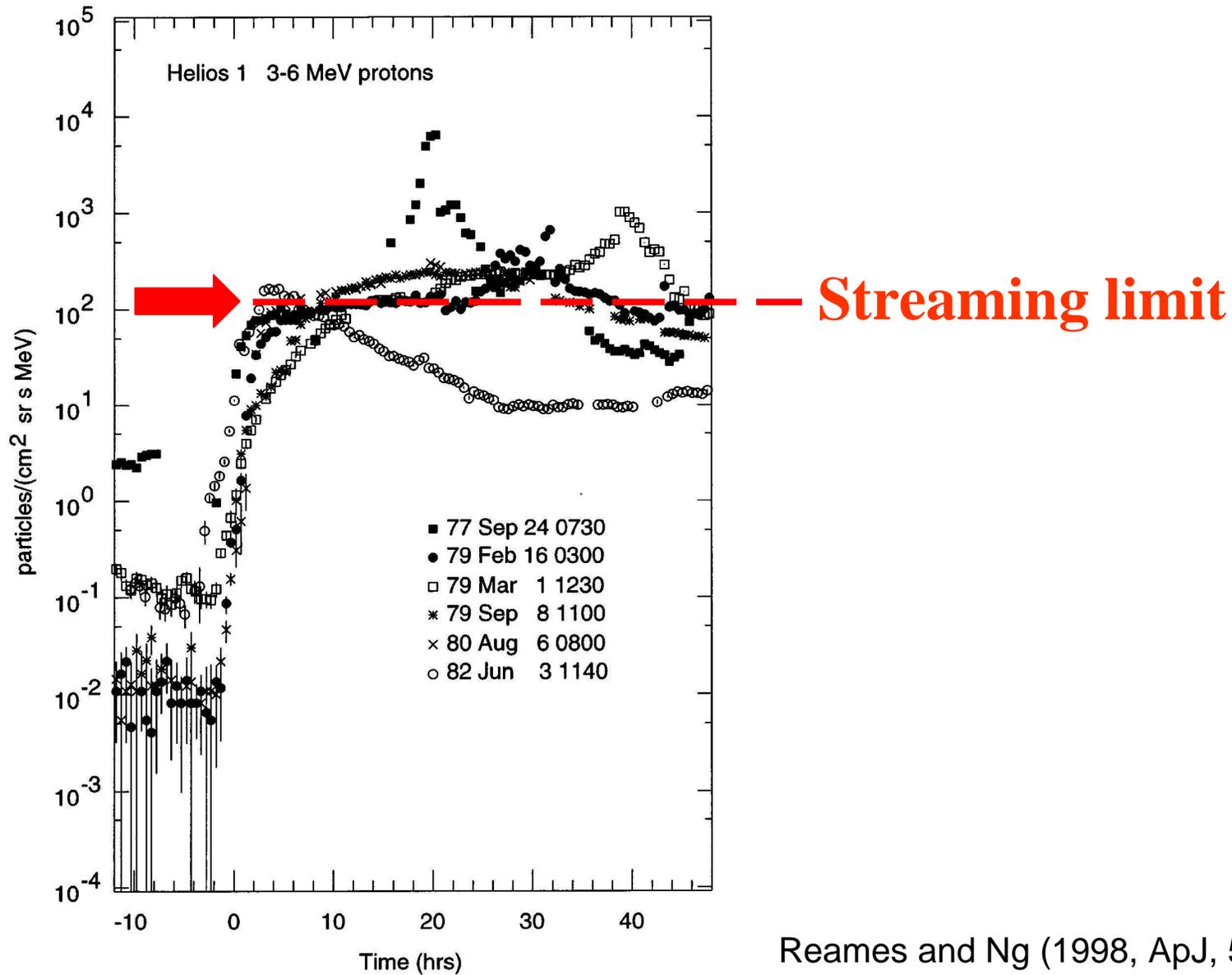
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Reames and Ng (1998, ApJ, 504, 1002)

FIG. 1.—Superposed intensity-time profiles of 3–6 MeV protons observed by *Helios 1* are shown for six large events. Streaming-limited flat profiles are seen early in the events. Shock peaks are seen to arrive later in several of the events with intensities increasing by factors up to ~ 100 near the shock (Reames 1990).



Reames and Ng (1998, ApJ, 504, 1002)

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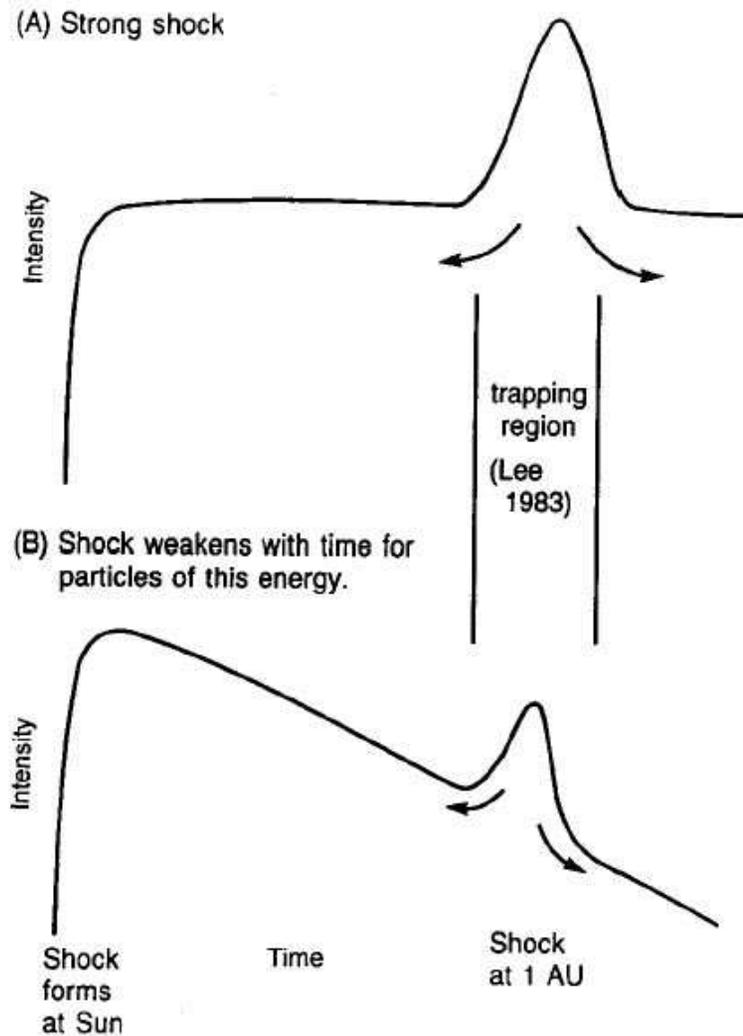


Fig. 1. Profiles of particle intensity vs time are shown when (a) strong shock acceleration continues out to the observer and (b) acceleration diminishes with time. All particles are accelerated by the shock in either case. If acceleration diminished sufficiently, the shock spike or "ESP event" may not be present.

Reames (1999, Radiation Measurements 30, 297)

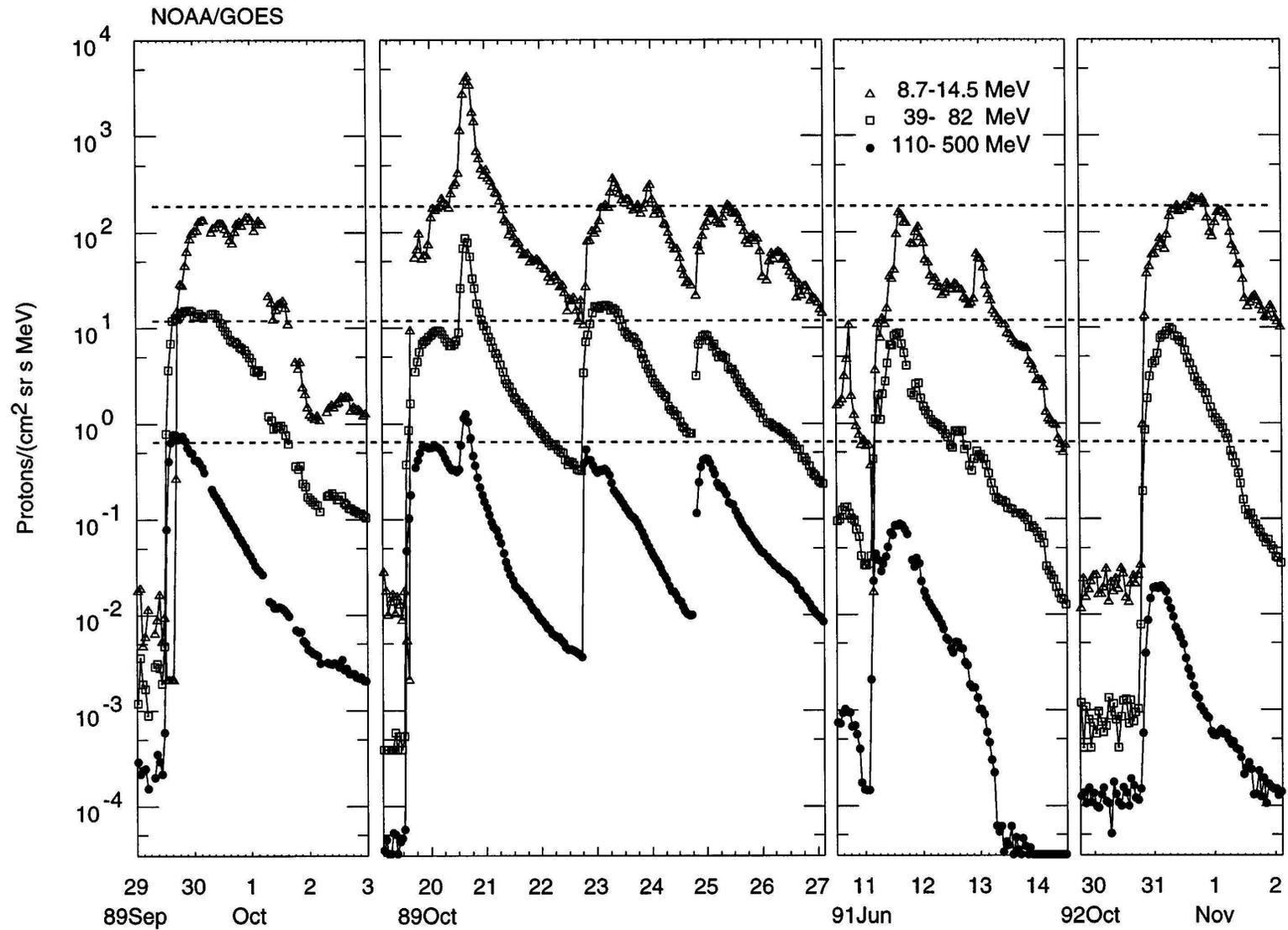
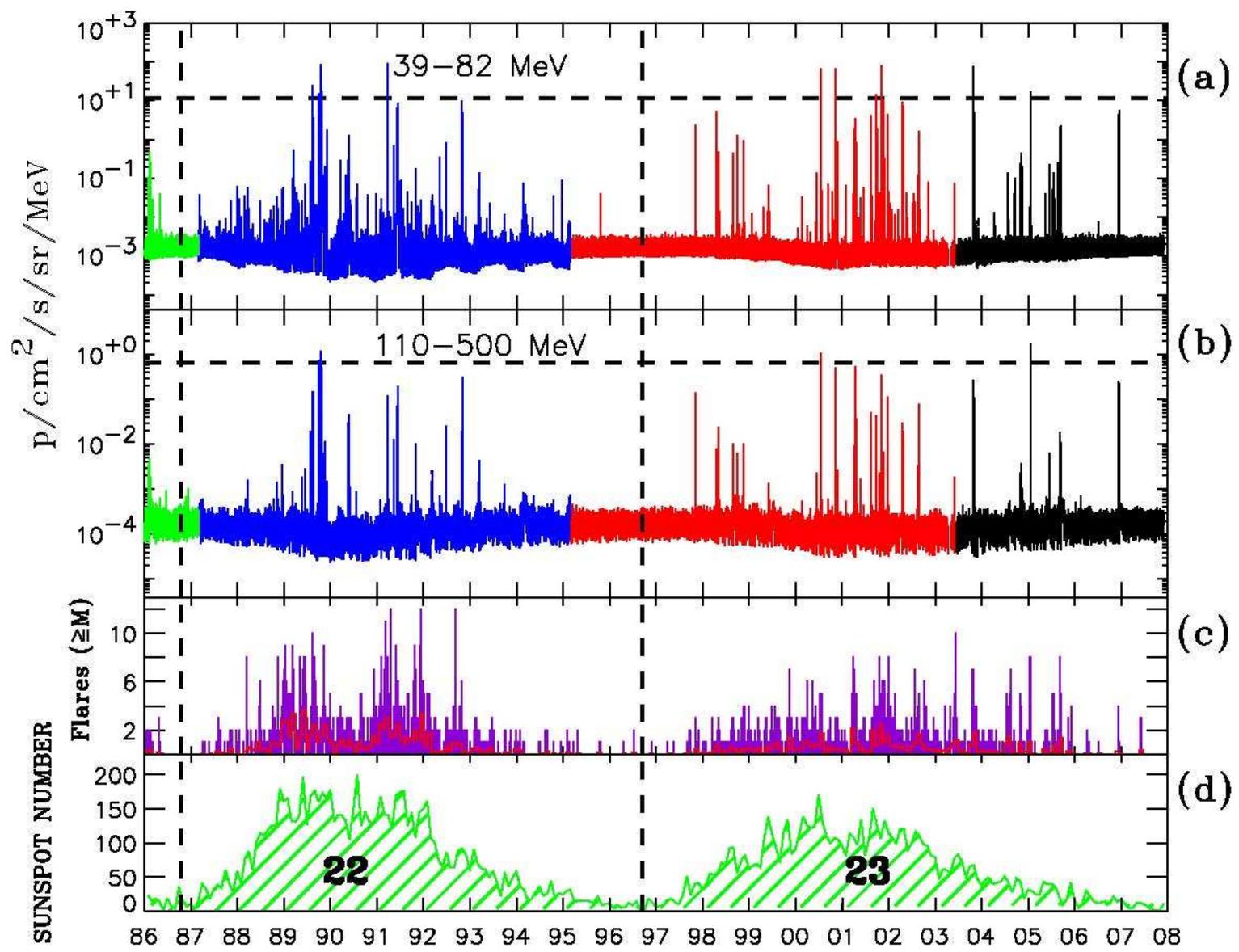
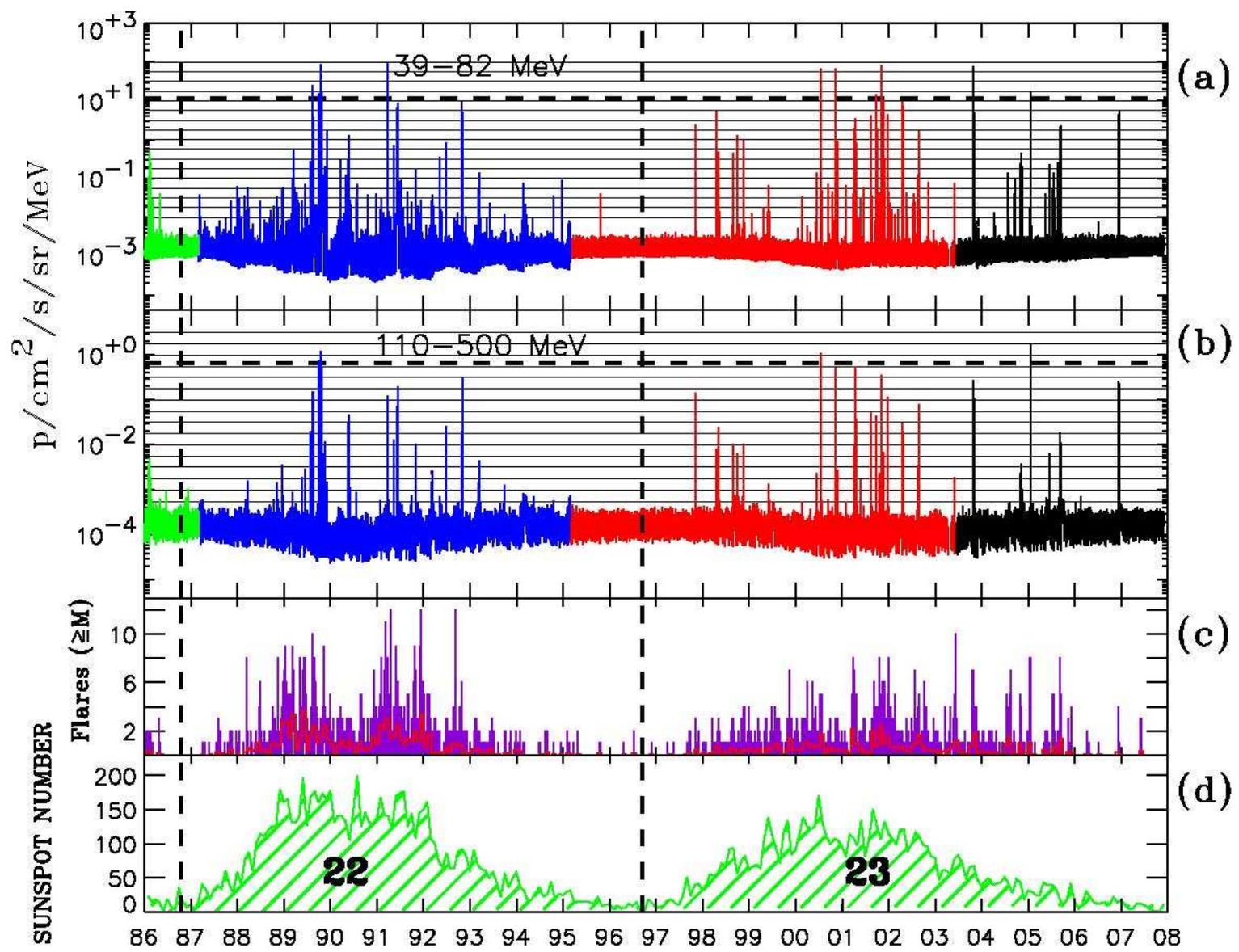


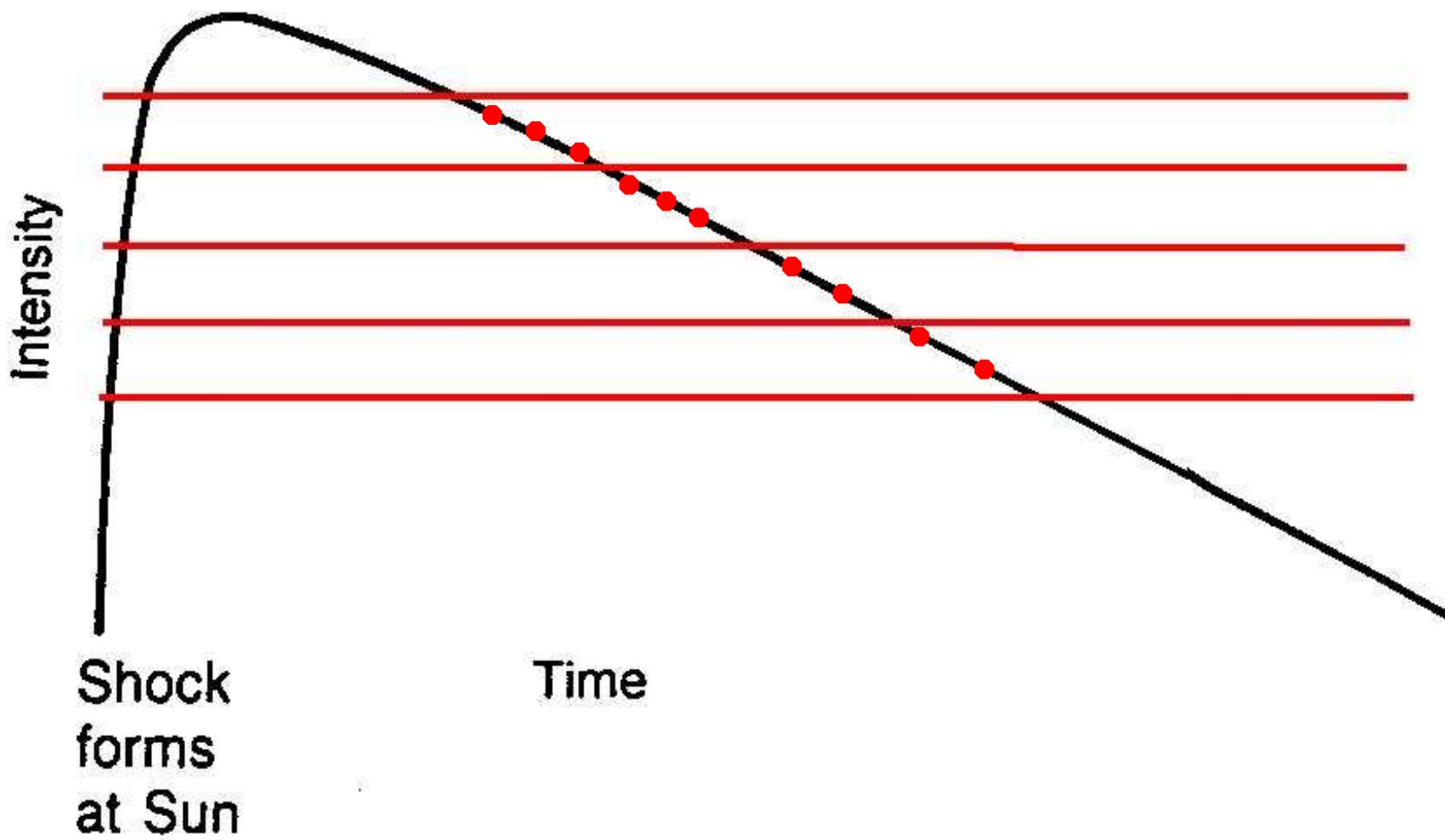
FIG. 4.—Intensity-time profiles of protons in three energy channels are shown for six large SEP events during the last solar cycle as measured on the *GOES* spacecraft. Streaming-limited intensity values for each energy channel are shown as dashed lines. Note the similarity of the high-energy profiles in the 1989 October event with the low-energy profiles in Fig. 1.

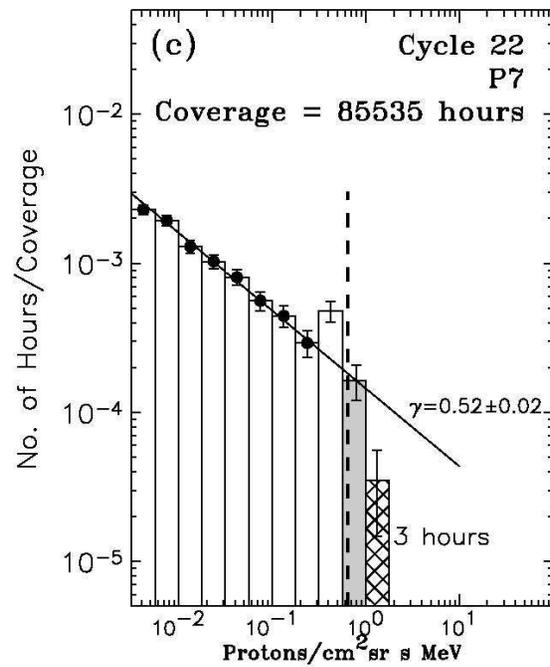
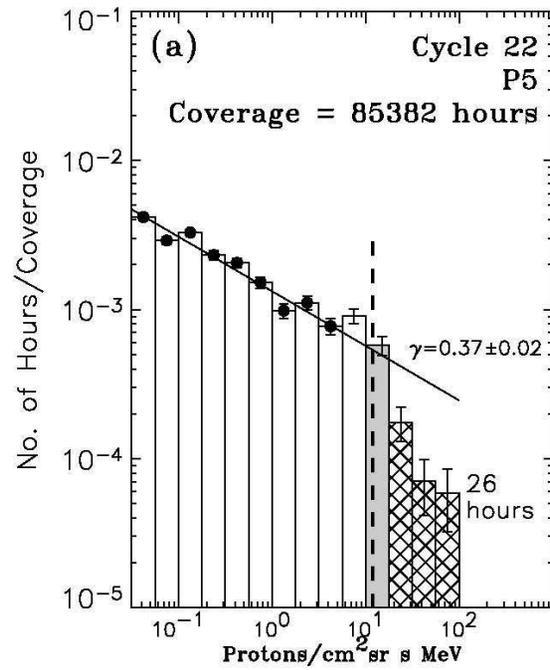
Reames' scenario on streaming limit

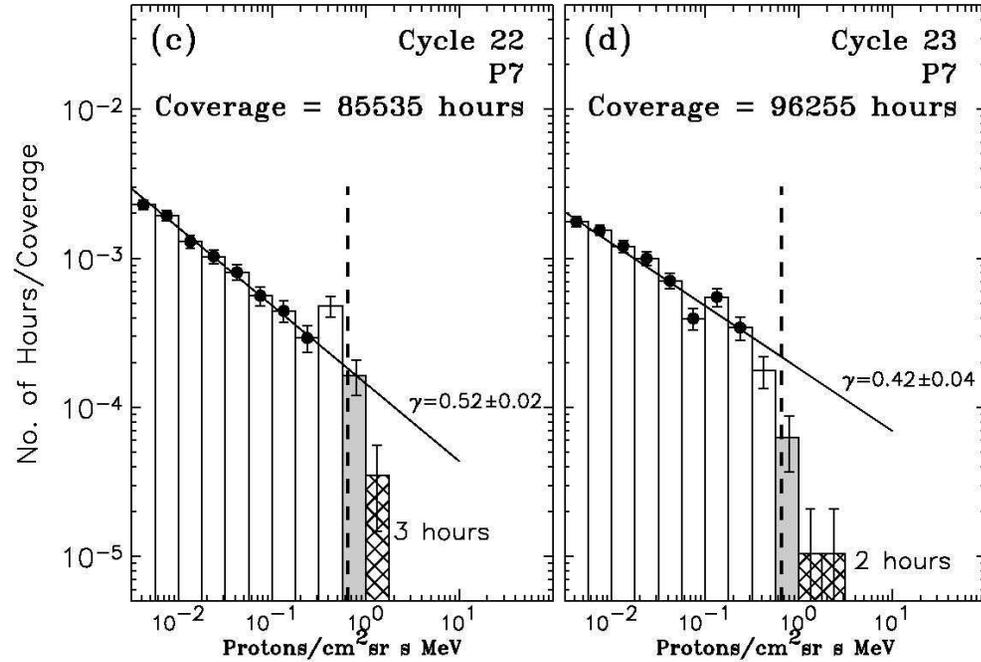
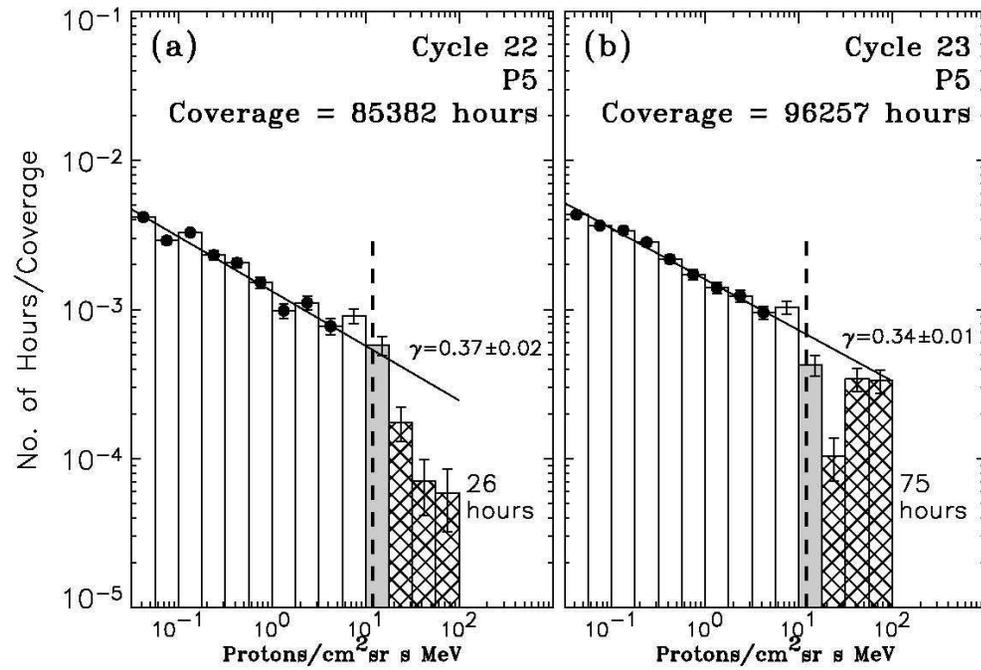
- Energetic particles streaming outward from an intense source near the Sun reach a maximum-intensity plateau when scattering by self-excited waves restricts the streaming.
- Particle intensities measured early in a large SEP event are bounded by a certain upper limit.
- This limit intensity can only be exceeded when the source of particles (i.e. the CME-driven shock) reaches the spacecraft.
- The highest proton intensities reached in a solar cycle can only be observed in association with the passage of CME-driven shocks.

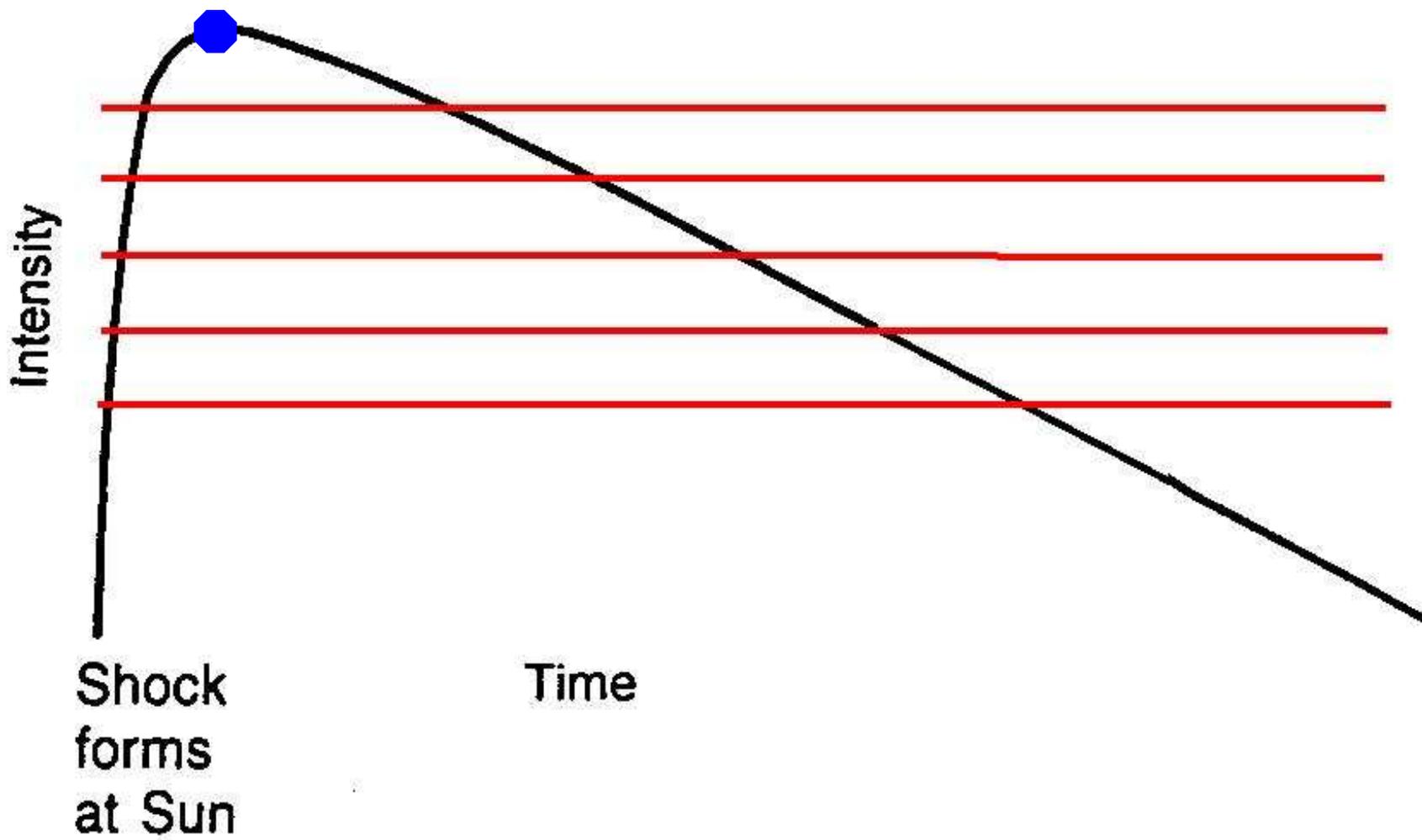


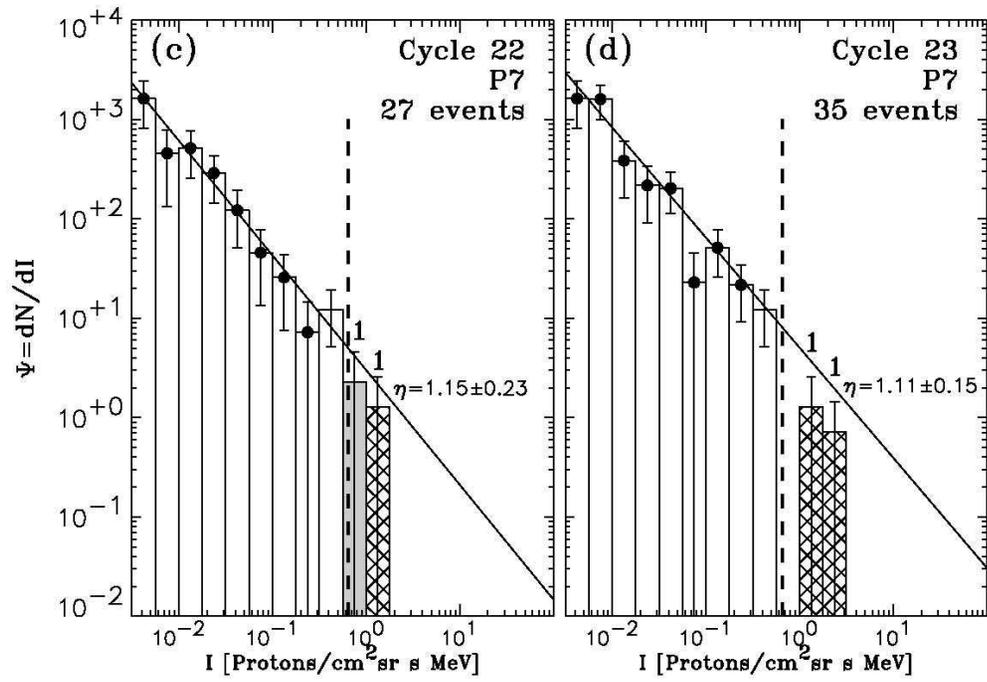
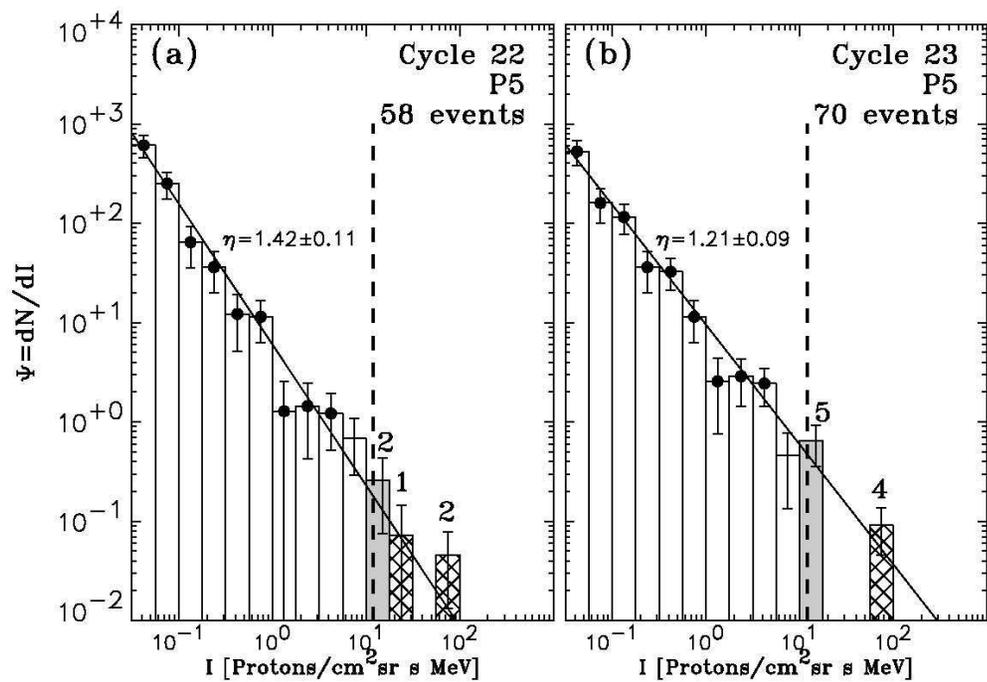


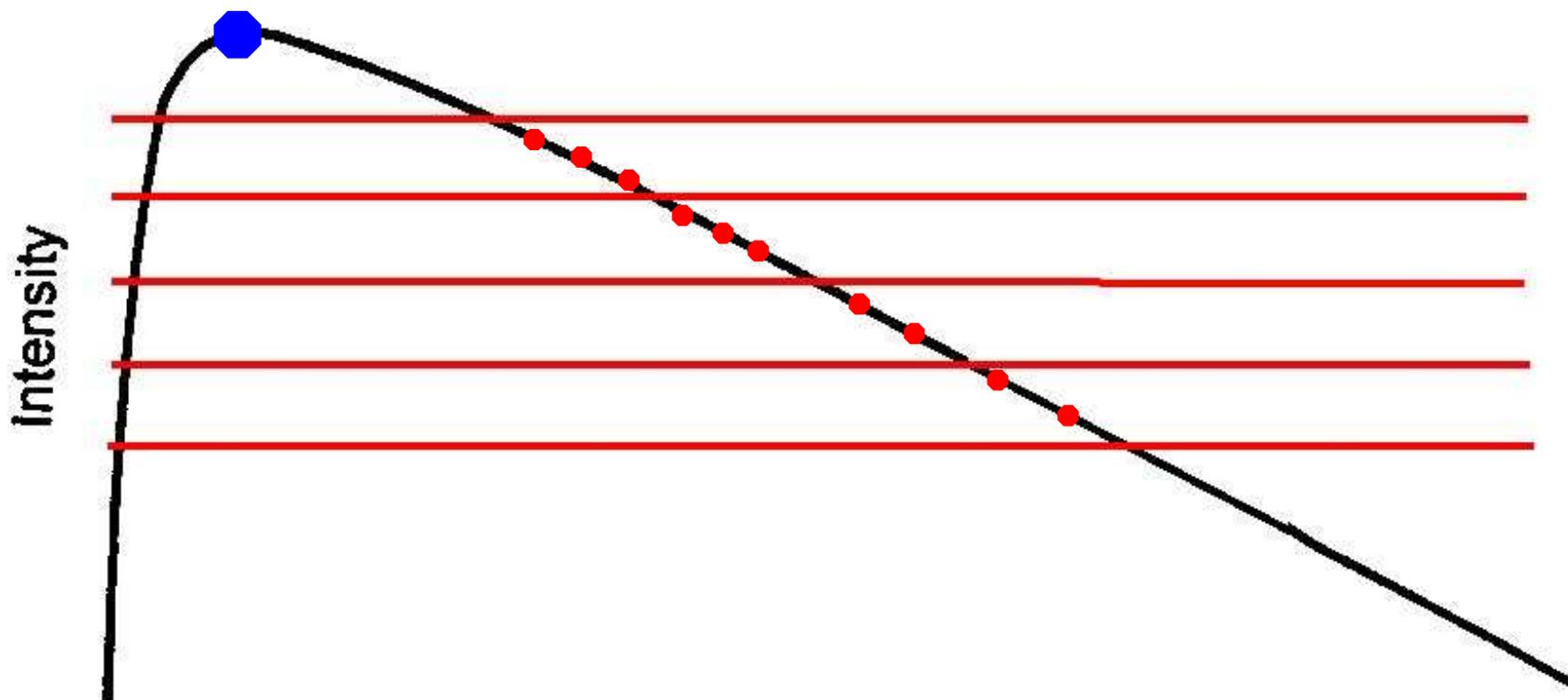








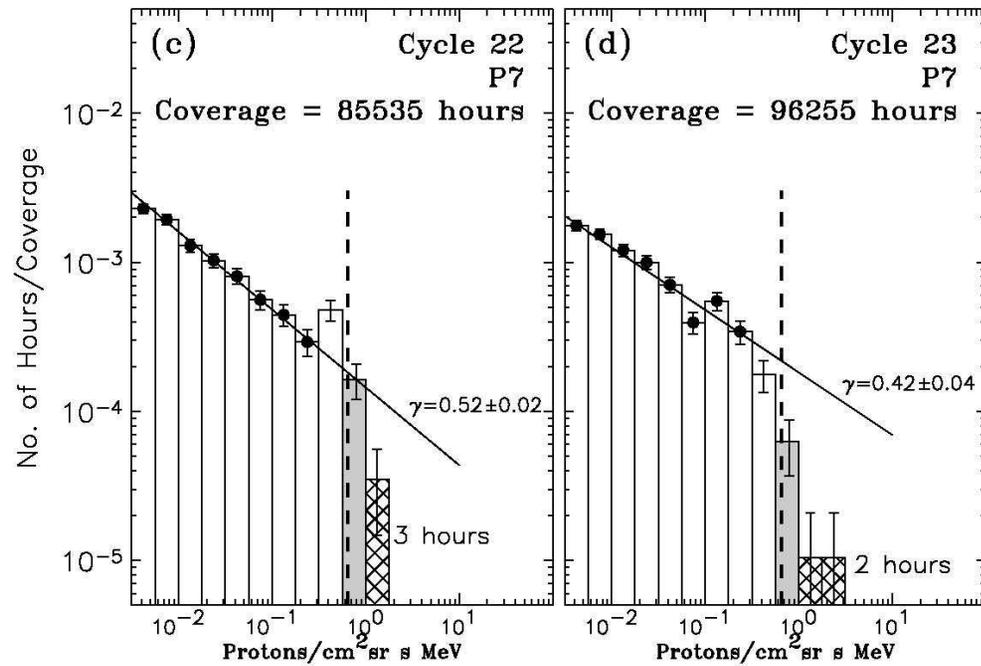
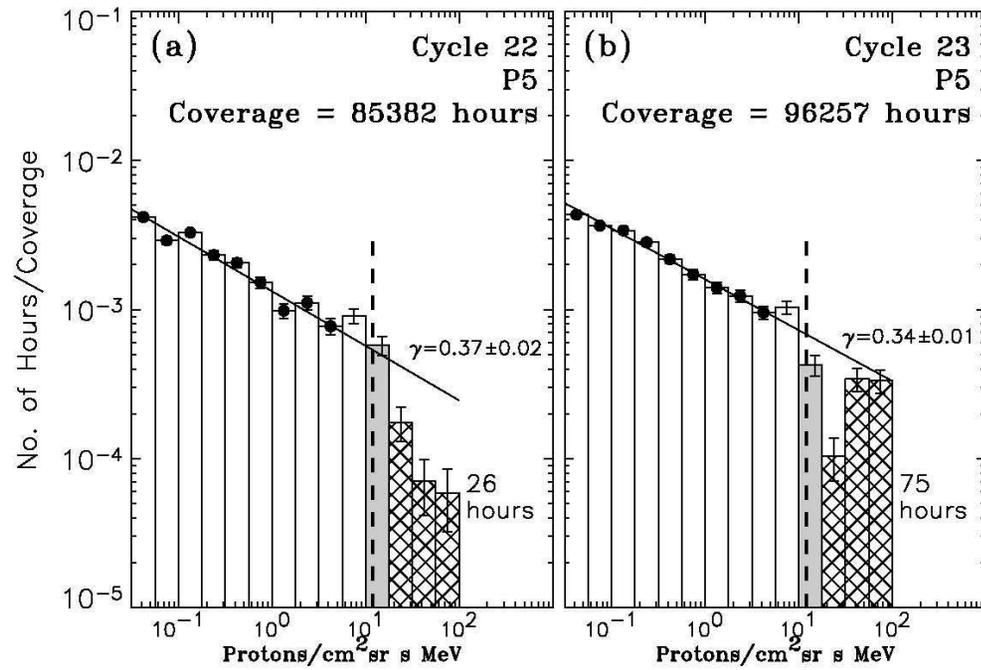


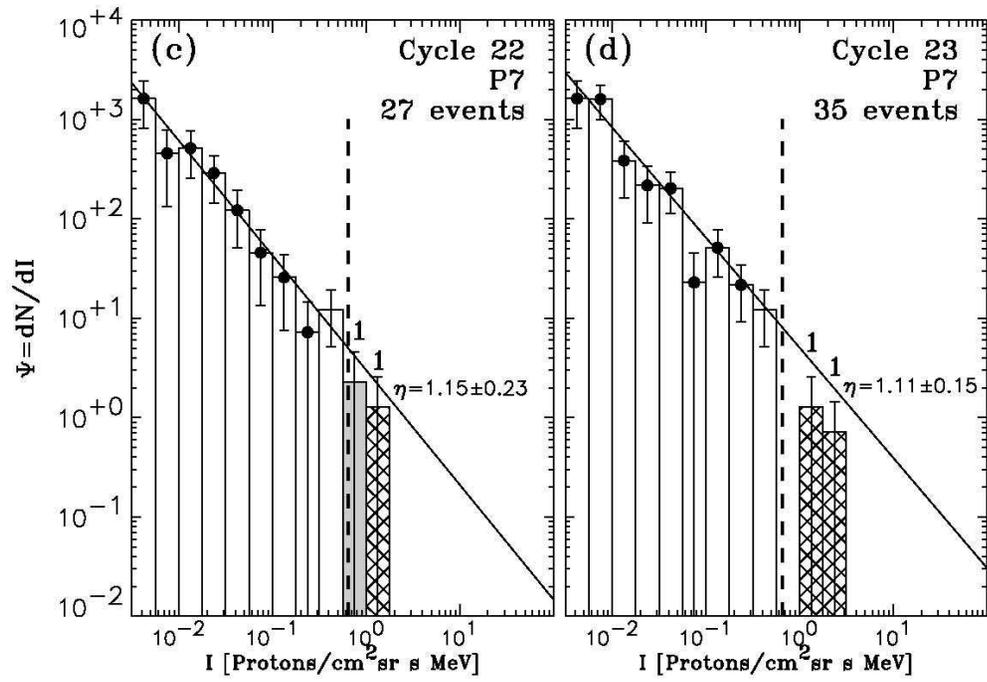
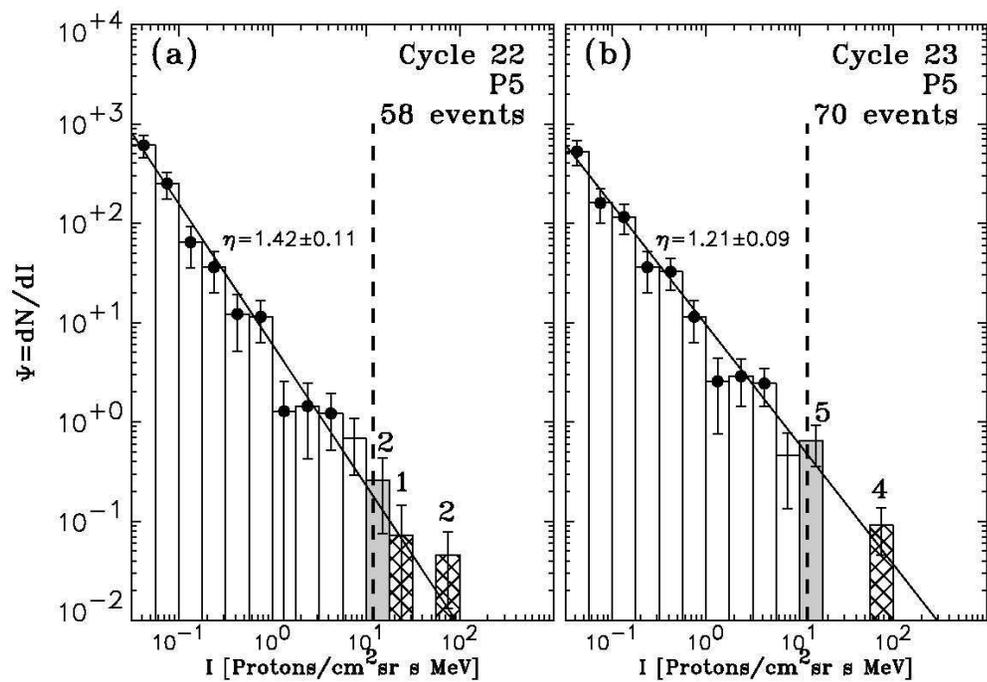


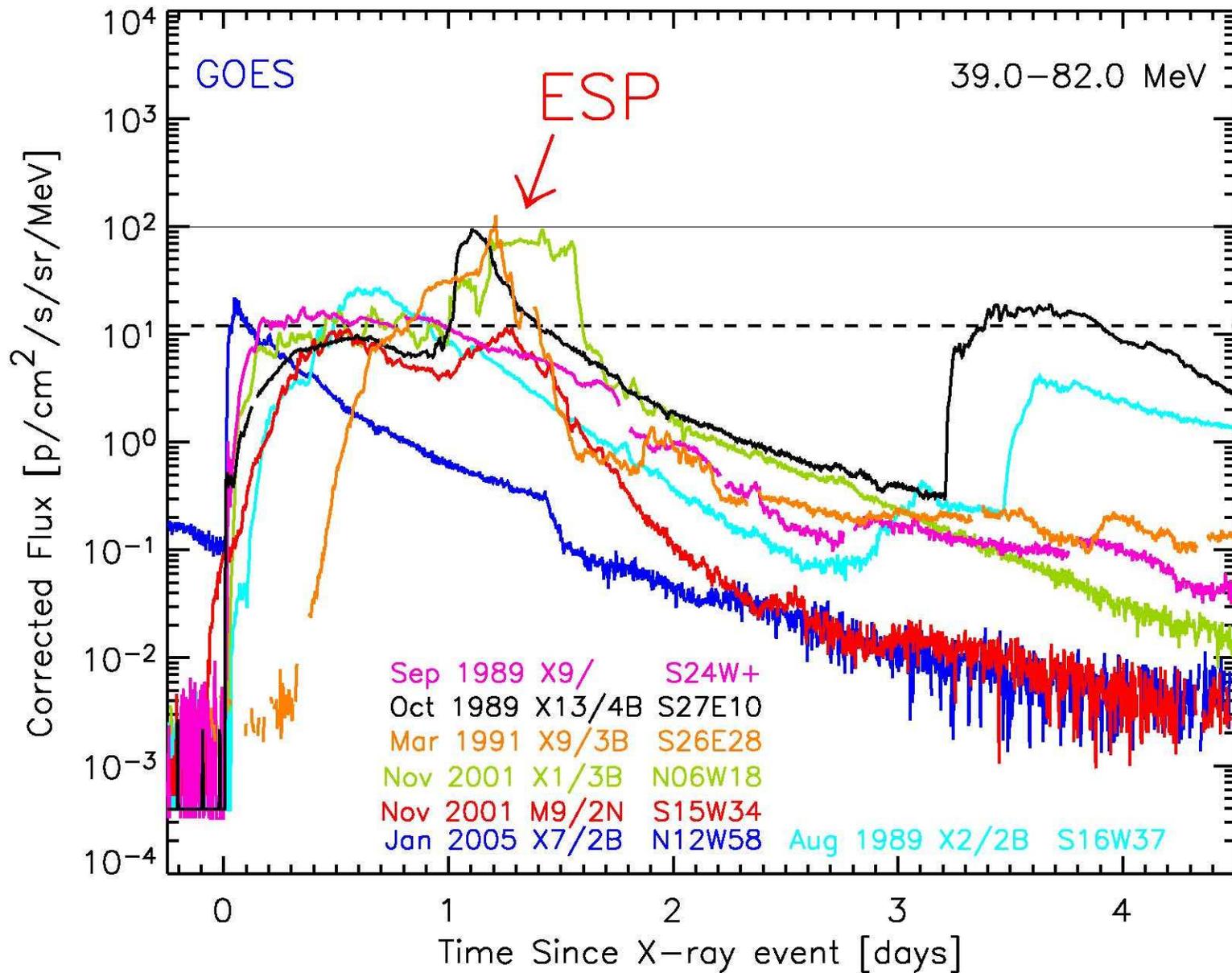
Shock
forms
at Sun

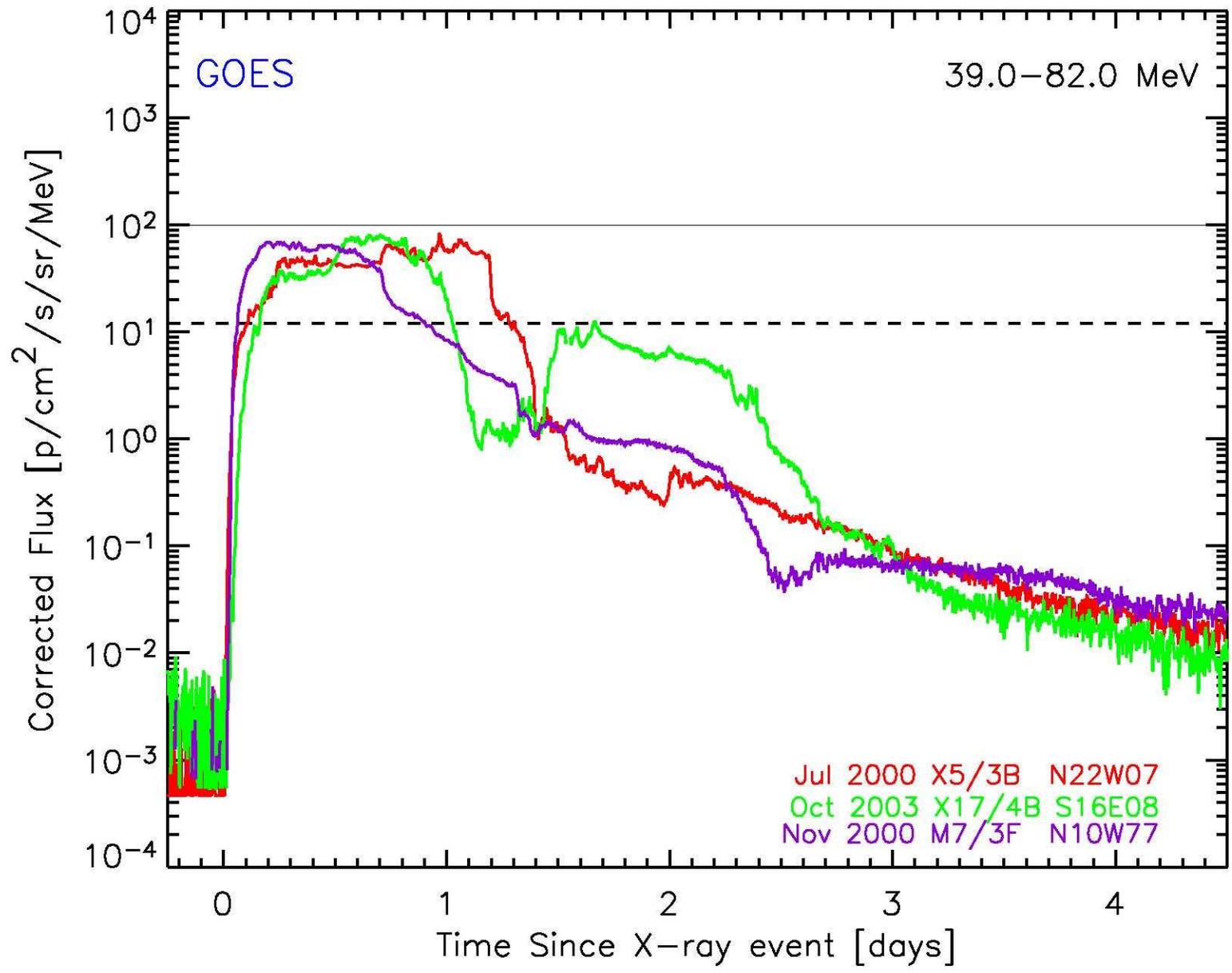
Time

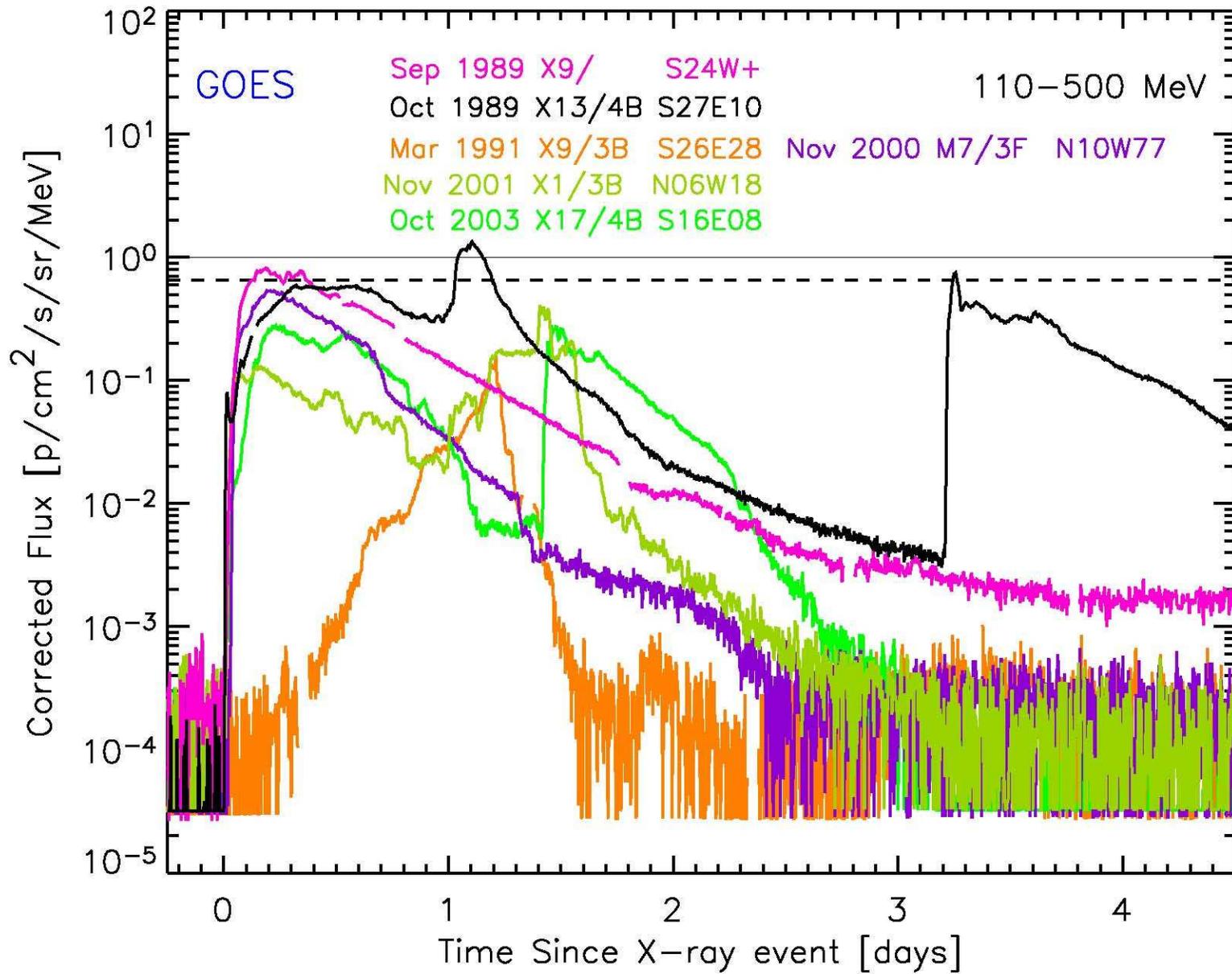
$$\gamma = \eta - 1$$

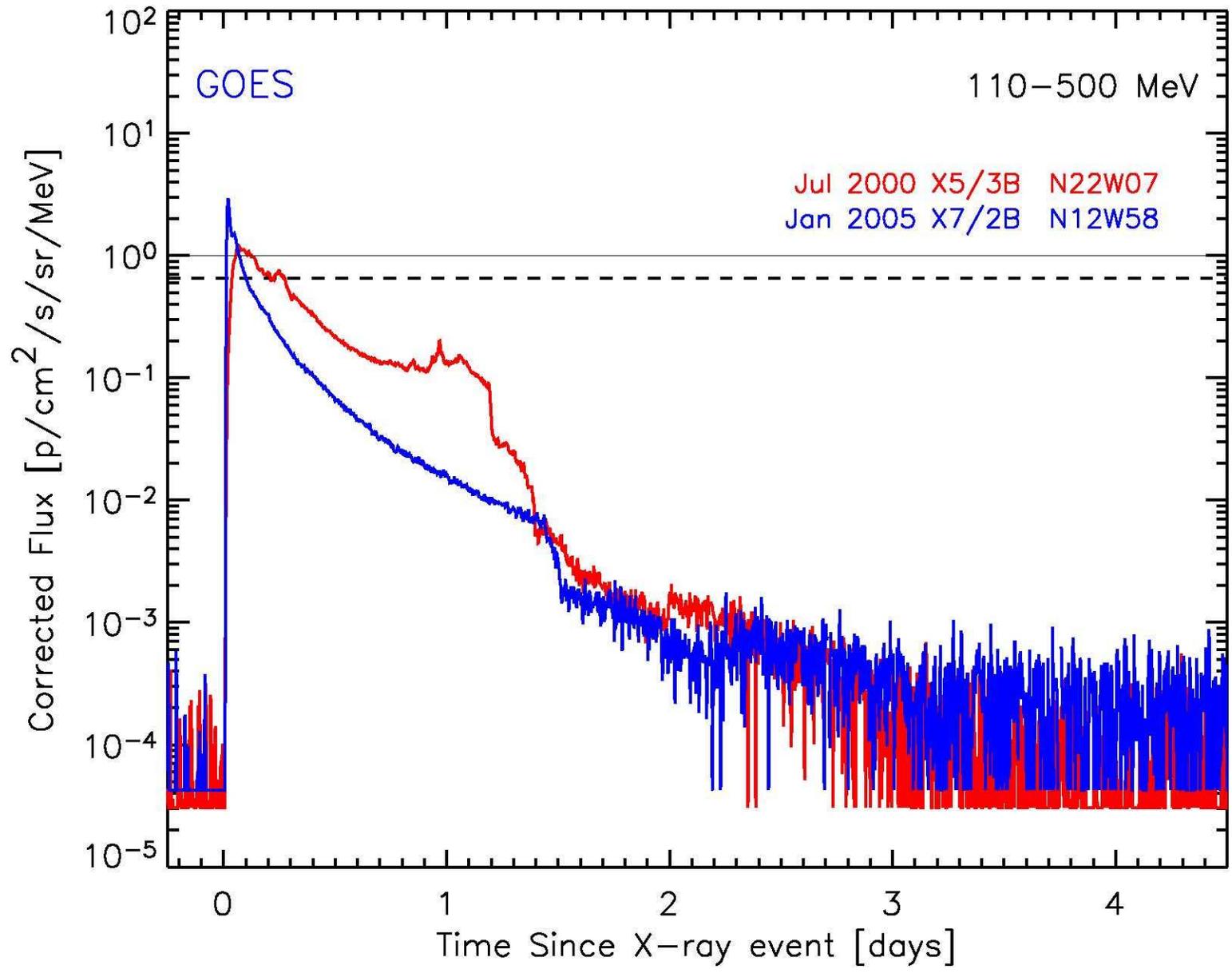


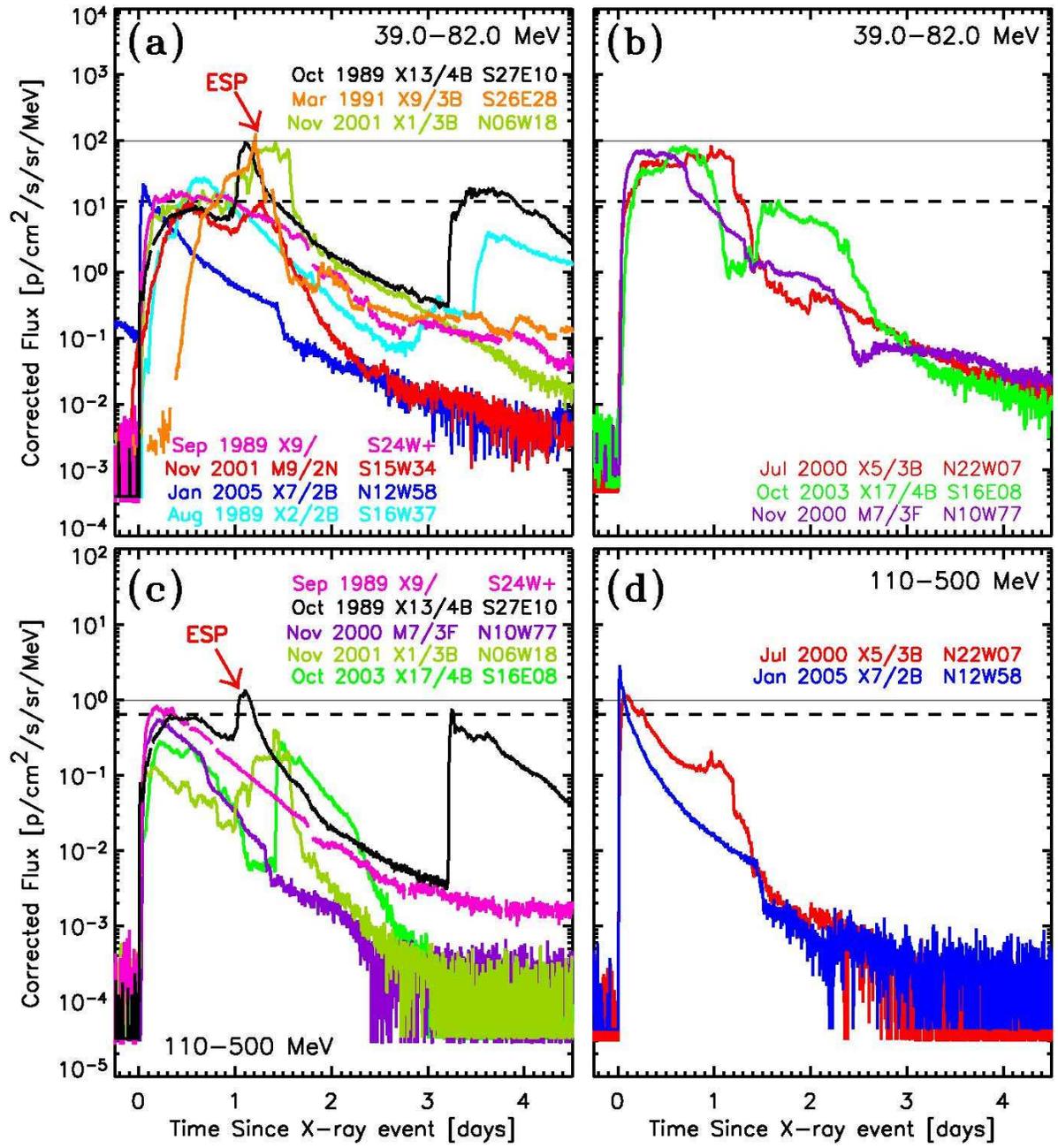












SEP events with peak intensity exceeding by a factor of 4 or more the previous determined streaming limit

Solar Cycle	Energy [MeV]	Event	Solar Flare	Reference
22	39-82	Oct 20, 1989 (ESP component)	X13/4B S27E10	<i>Lario and Decker</i> [2002]
	39-82	Mar 23, 1991 (ESP component)	X9/3B S26E28	<i>Shea and Smart</i> [1993]
	110-500	Oct 20, 1989 (ESP component)	X13/4B S27E10	<i>Lario and Decker</i> [2002]
23	39-82	Jul 14, 2000 (prompt component)	X5/3B N22W07	<i>Reames et al.</i> [2001]
	39-82	Nov 8, 2000 (prompt component)	M7/3F N10W77	<i>Lario et al.</i> [2001]
	39-82	Nov 6, 2001 (ESP component)	X1/3B N06W18	<i>Shen et al.</i> [2008]
	39-82	Oct 28, 2003 (prompt component)	X17/4B S16E08	<i>Lario et al.</i> [2005]
	110-500	Jul 14, 2000 (prompt component)	X5/3B N22W07	<i>Reames et al.</i> [2001]
	110-500	Jan 20, 2005 (prompt component)	X7/2B N12W58	<i>Bieber et al.</i> [2005b]

Forecasting Dose for Large Solar Energetic Particle Events: Is There Time to Predict?

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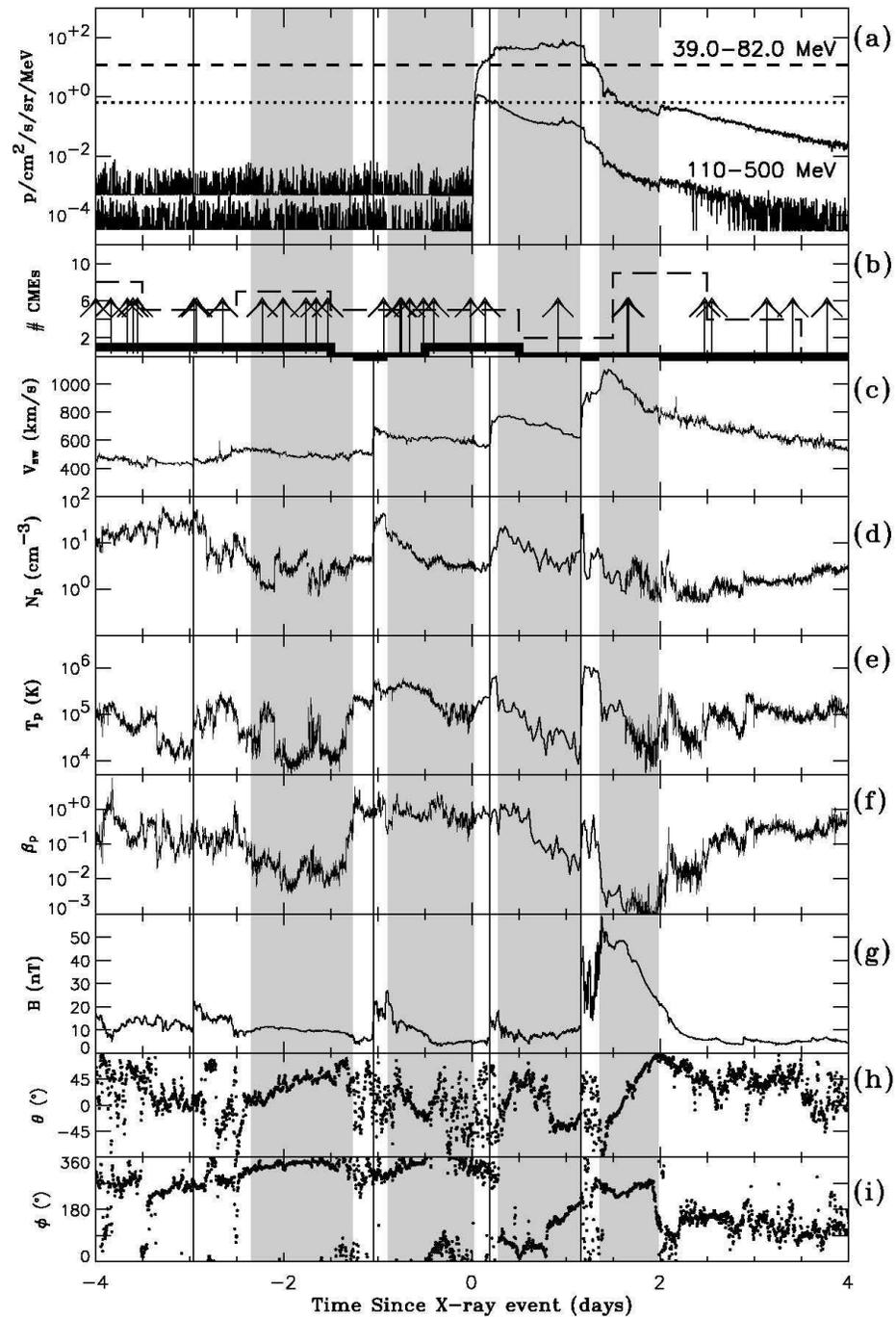
Solar energetic particles: Is there time to hide?

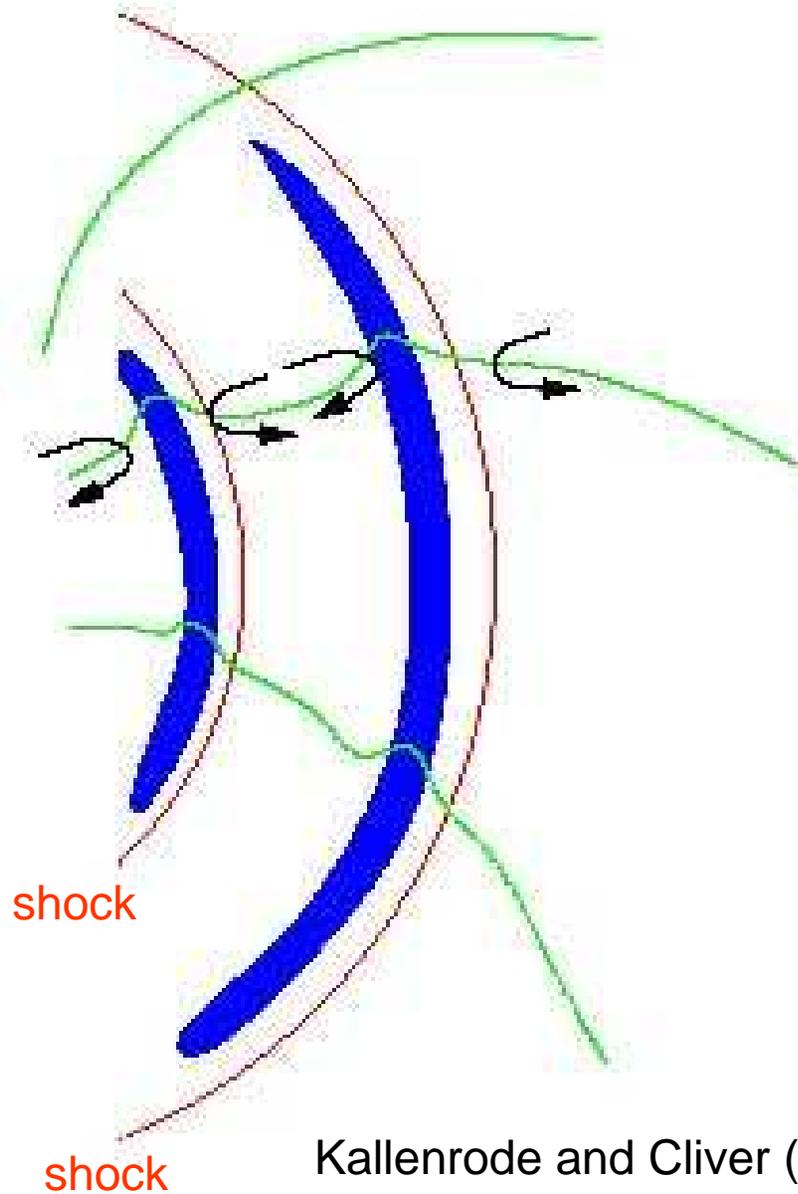
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Received 13 March 1998; received in revised form 3 December 1998

Bastille Day 2000 SEP event





Kallenrode and Cliver (2001): *"...pairs of converging shocks are believed to play an important role in the formation of large events such as the August 1972 SPE or the Bastille Day 2000 event"*.

Kallenrode and Cliver (2001, ICRC, pp. 3318-3321)

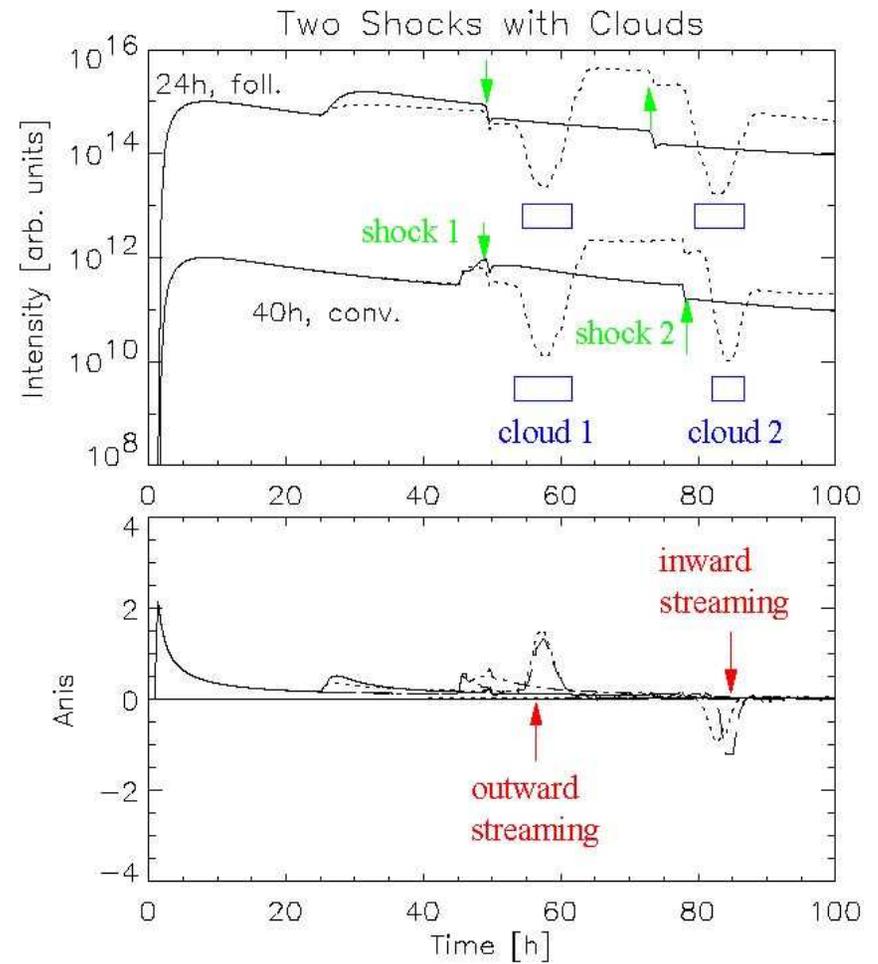
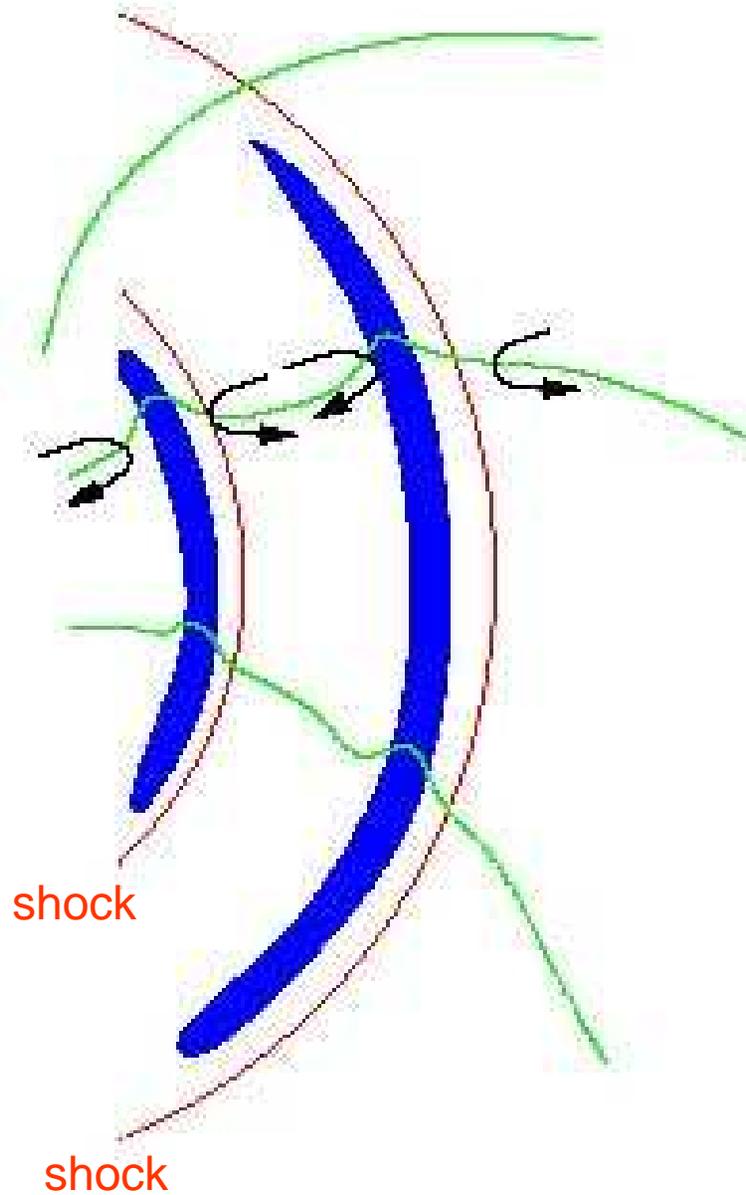
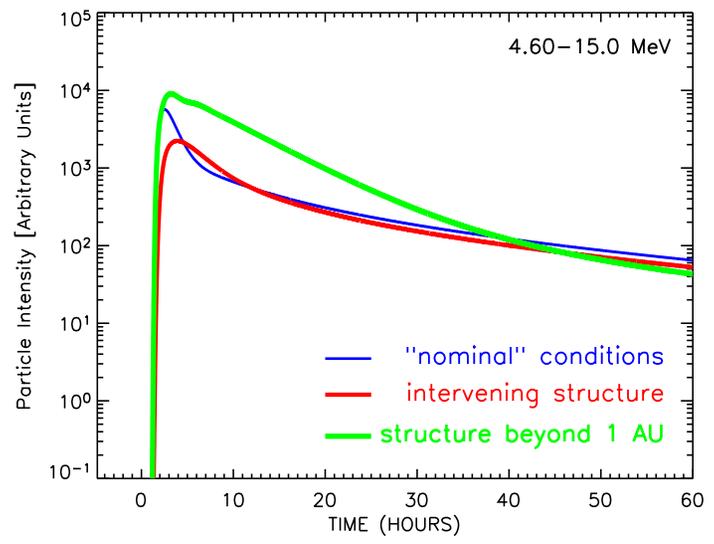
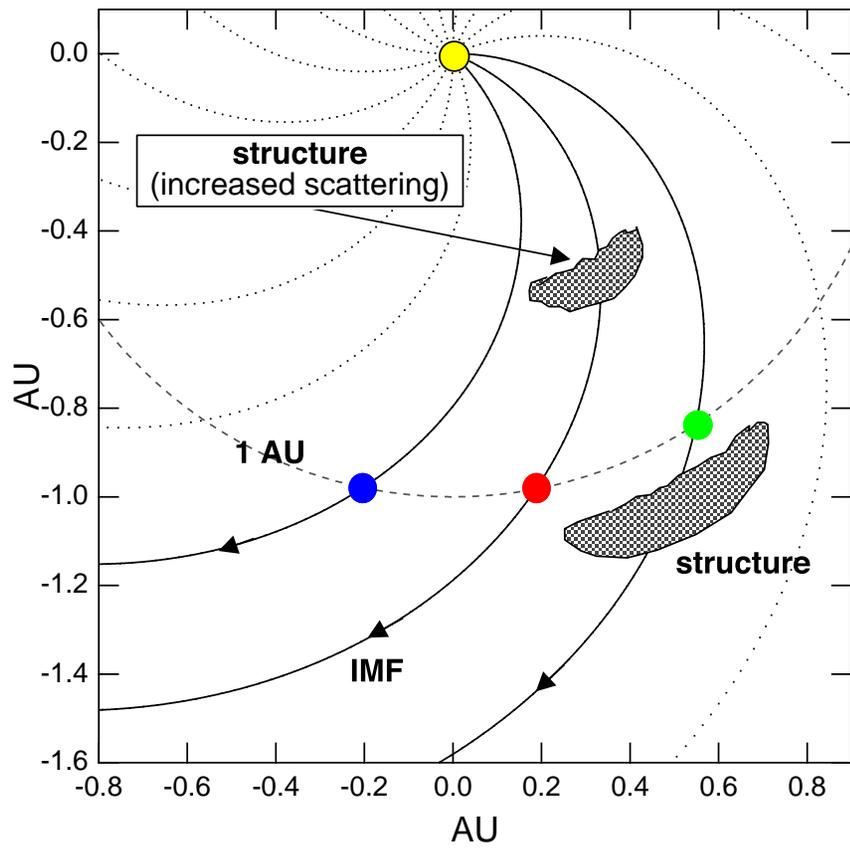
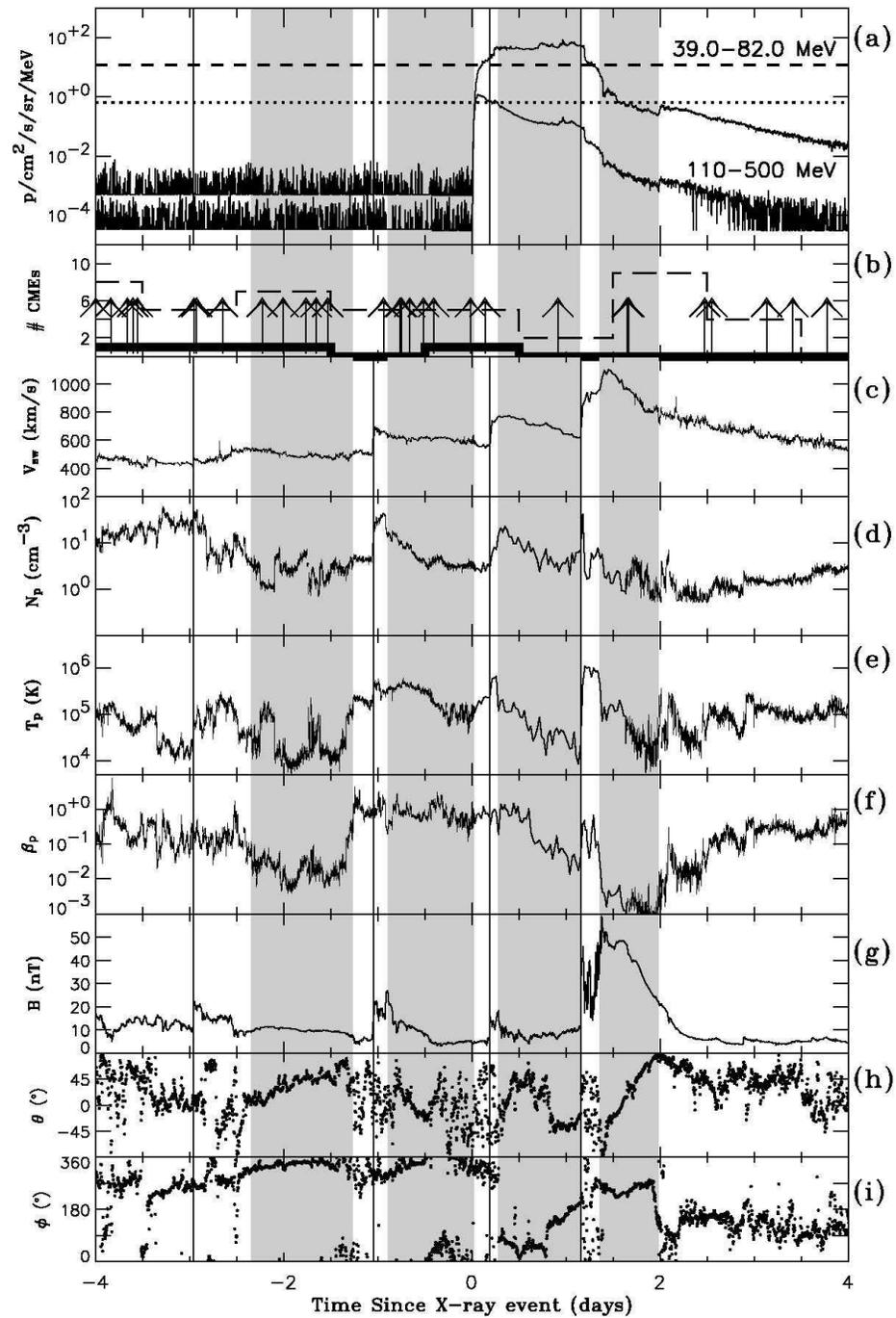


Fig. 3. Storage region between two consecutive same-speed shocks (upper set of curves) and two converging shocks (lower set). Solid lines are without consideration of the magnetic clouds, dashed ones include the magnetic clouds.

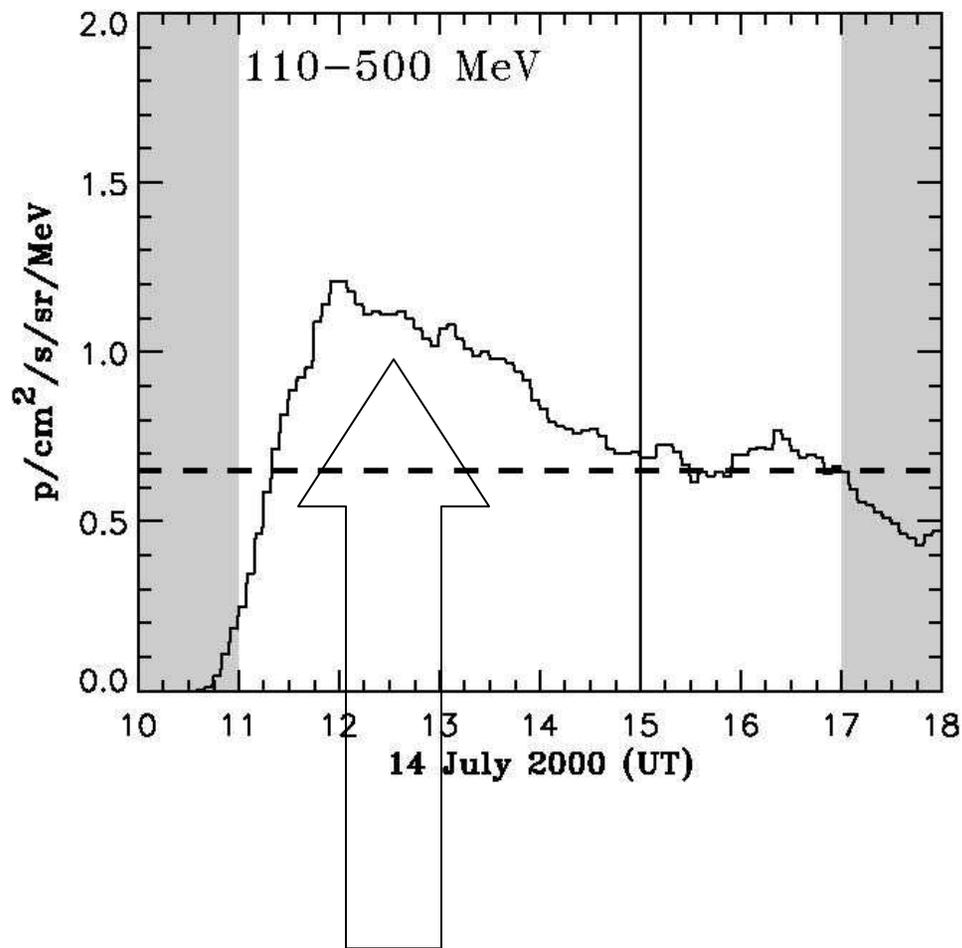
Kallenrode and Cliver (2001, ICRC, pp. 3318-3321)



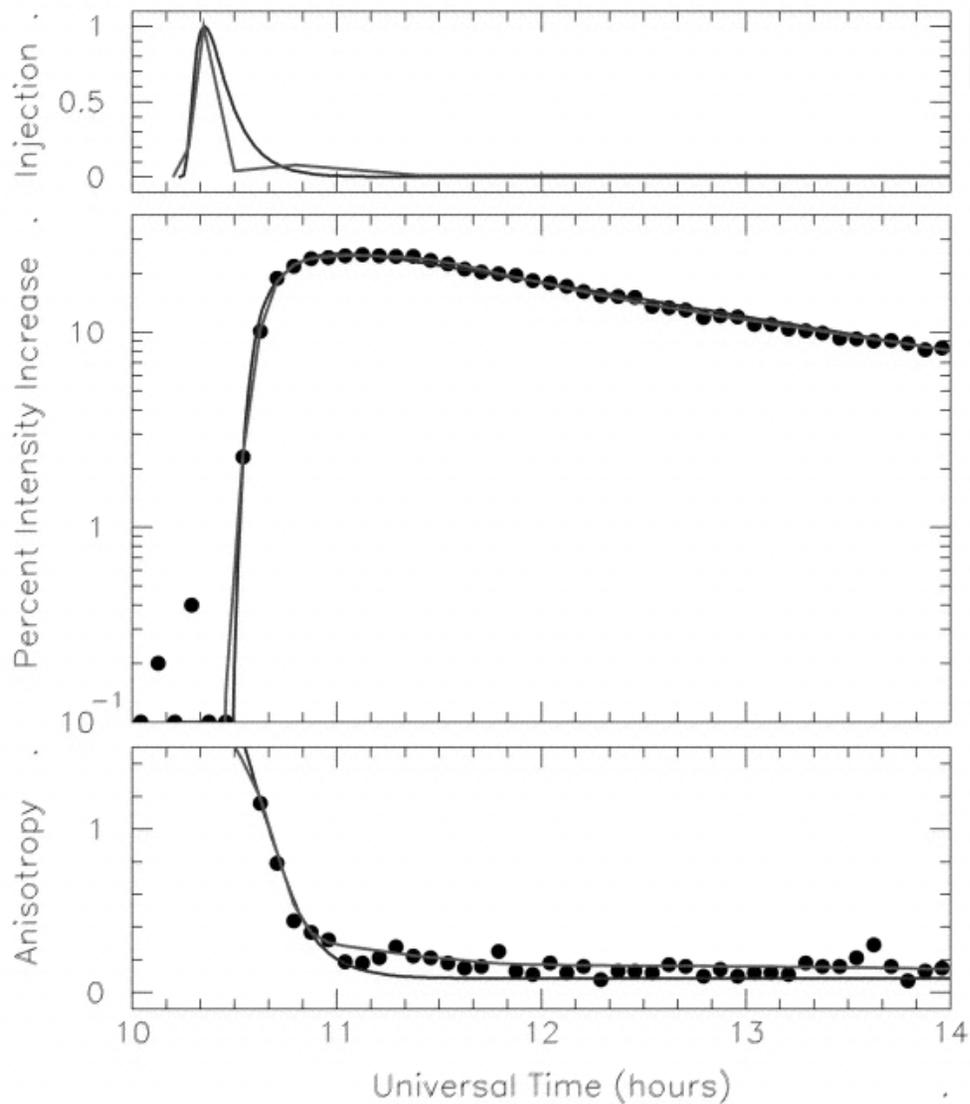
Bastille Day 2000 SEP event



**Bastille
Day 2000
SEP event**



Streaming limit exceeded during the prompt component of the SEP event



GLE

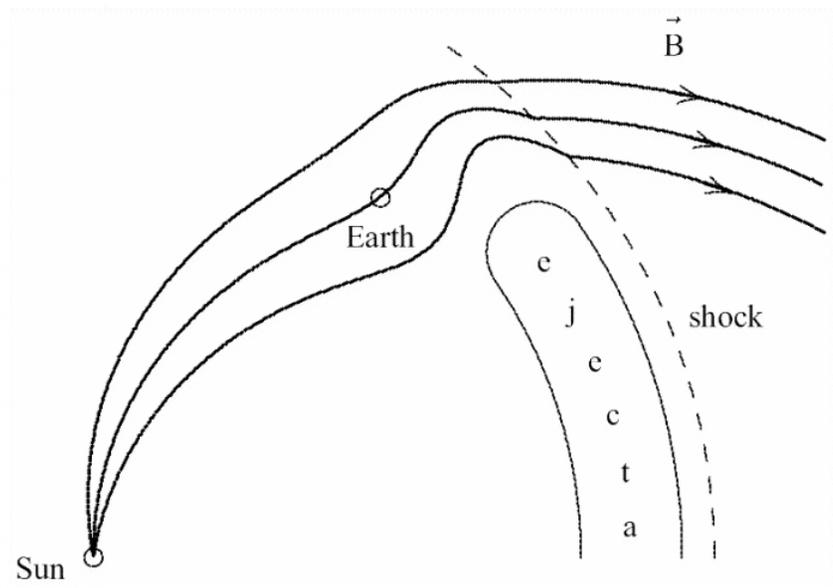
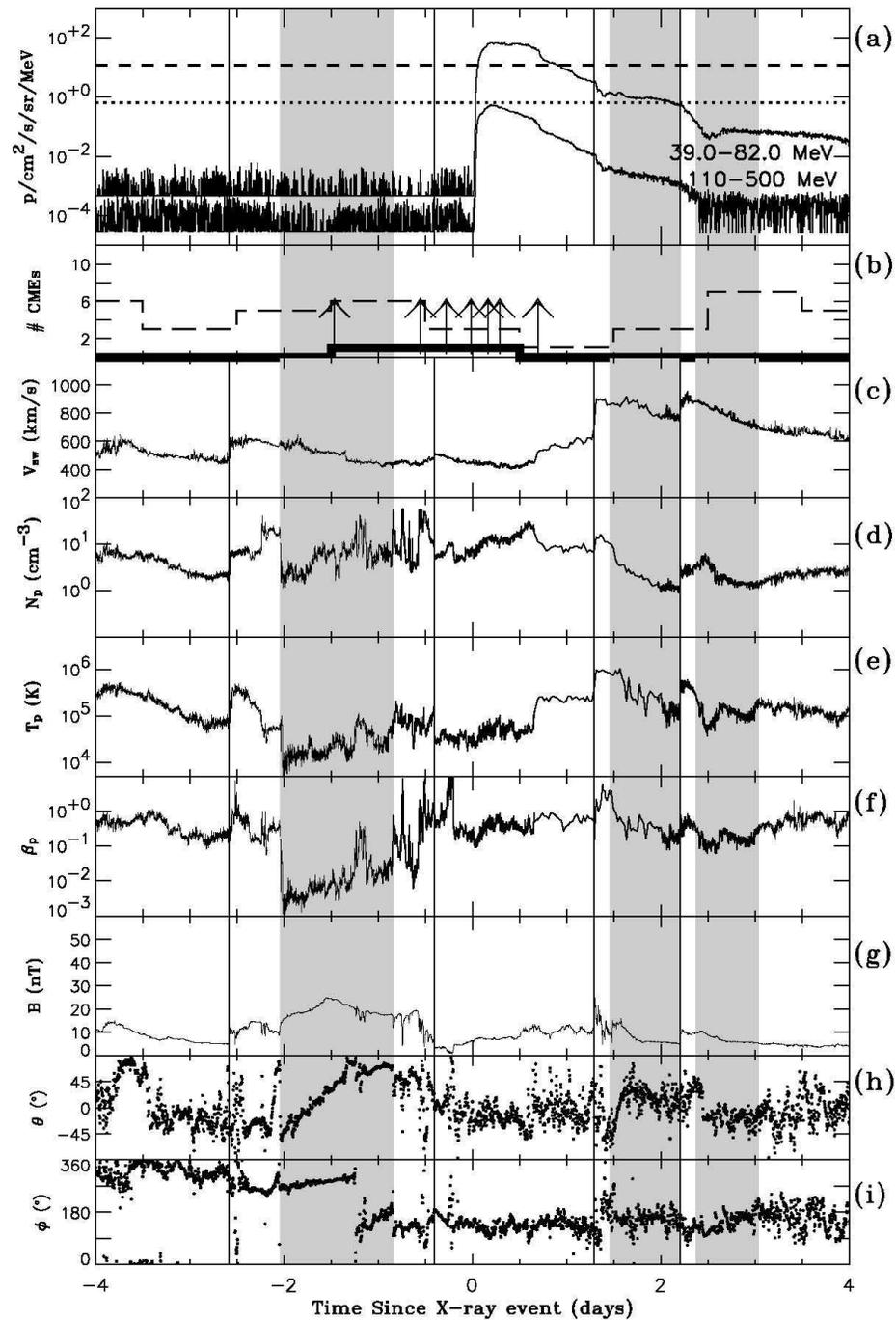
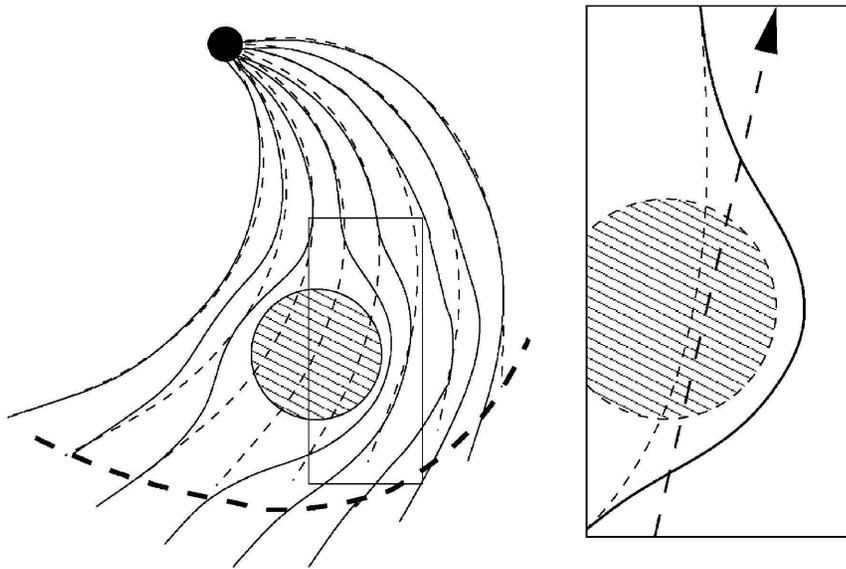


Fig. 11.— Modeling results with a magnetic barrier located beyond Earth. Both model 1 (blue) and 2 (red) use a radial mean free path $\lambda_{\{r\}}=0.18$ AU. The magnetic bottleneck has 85% reflectivity and is located at a heliocentric distance of 1.27 AU.

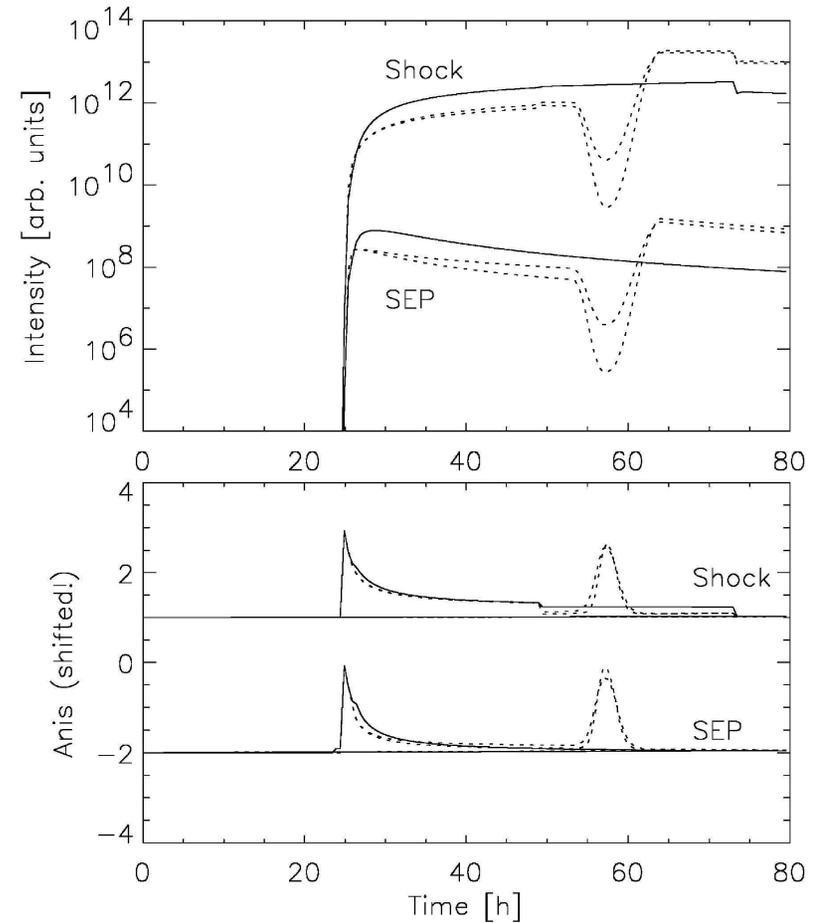
Bieber et al. (2002, ApJ)

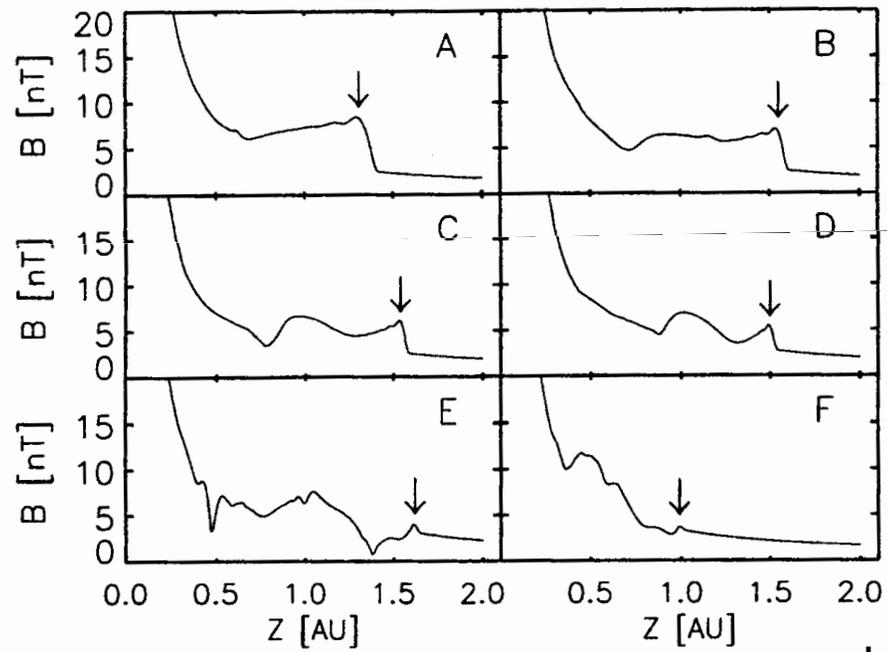
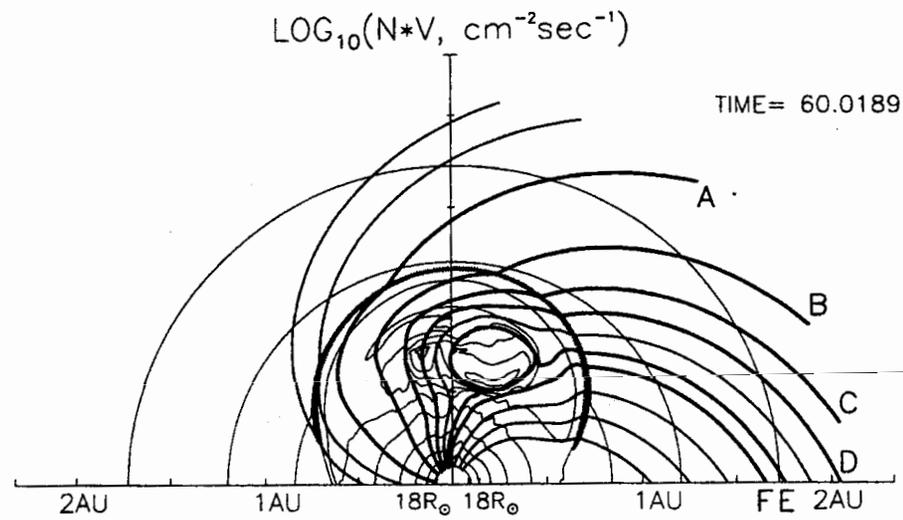
**November
8, 2000
SEP event**





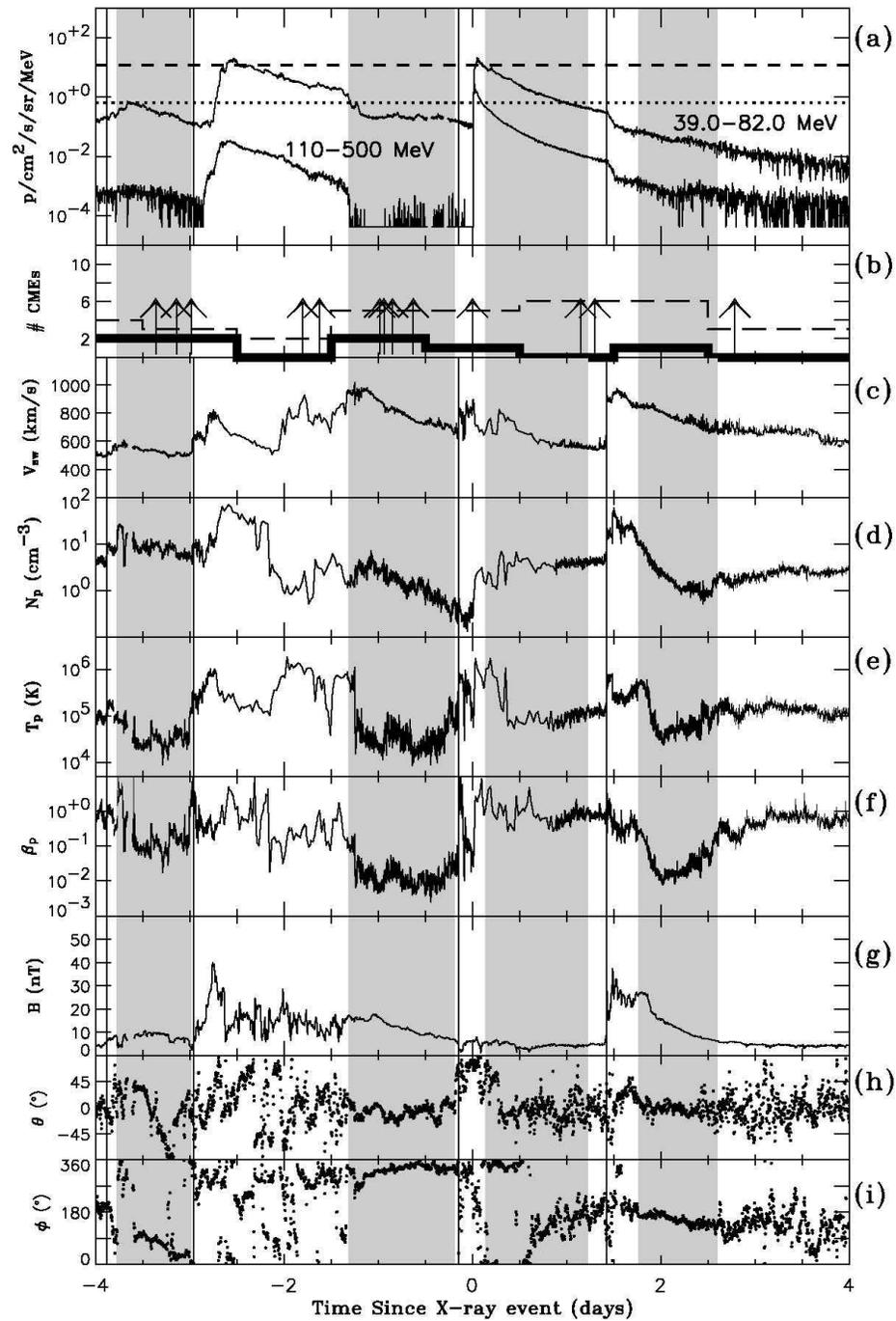
Kallenrode (2002, JASTP 64, 1973-1978): “when a magnetic cloud is already present in interplanetary space at the time of a SEP event it acts as a barrier, storing the bulk of particles in its downstream medium”.

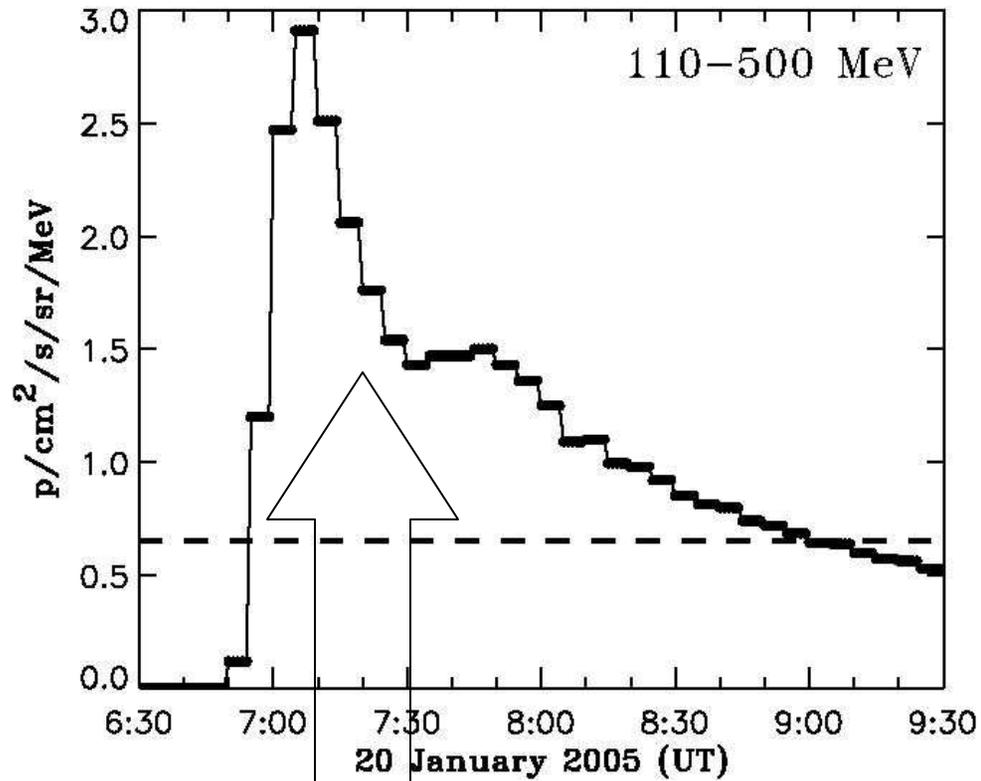




Lario et al. (1999, SW9, pp. 741-744)

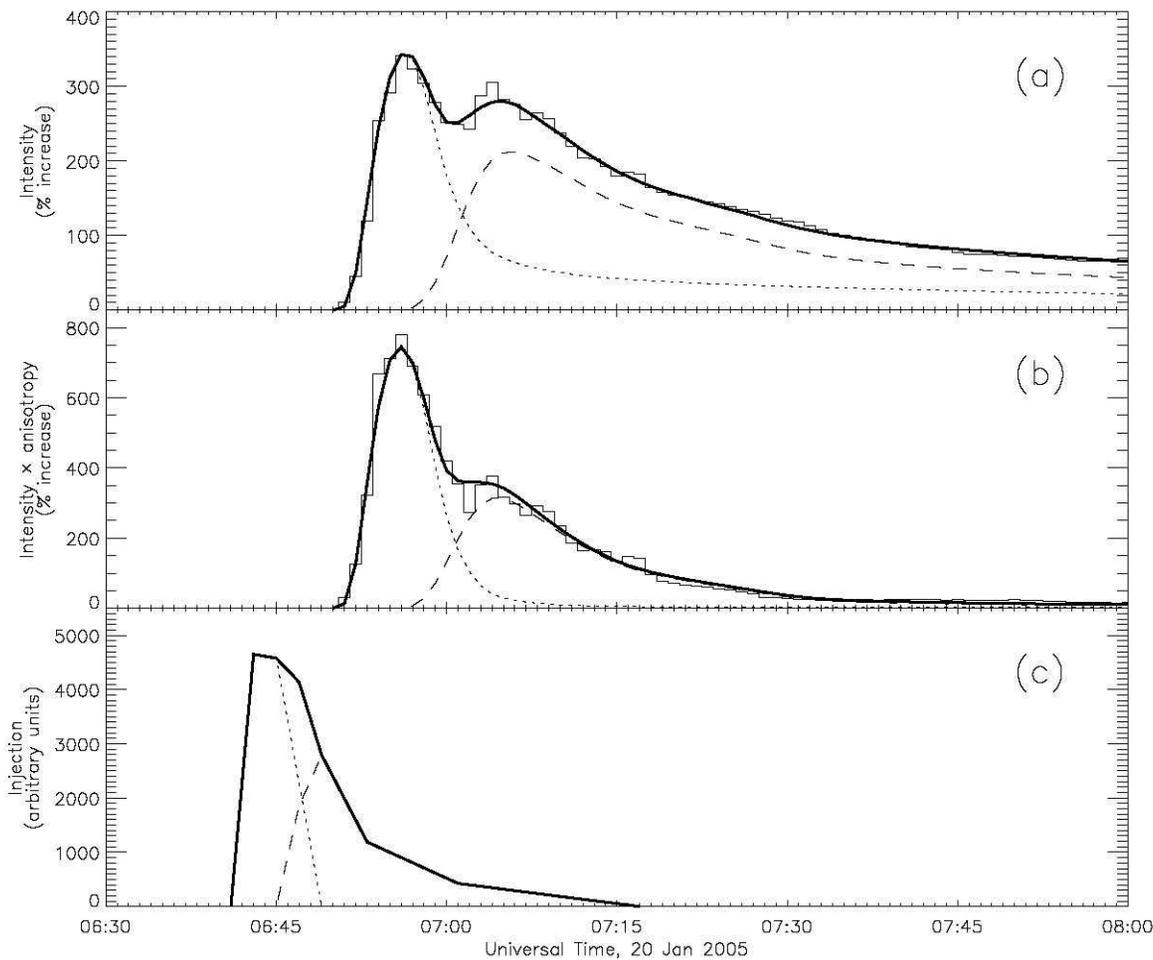
January 20, 2005 SEP event





**January 20,
2005 SEP
event**

**Streaming limit exceeded during the
prompt component of the SEP event**



GLE

Saiz et al. (2005):
“The transport conditions changed rapidly during the event (from low to high scattering conditions) due to high density of SEPs, which generated waves that resonantly scattered the particles injected later in the event.”

Saiz et al. (2005, ICRC, pp. 229-232)

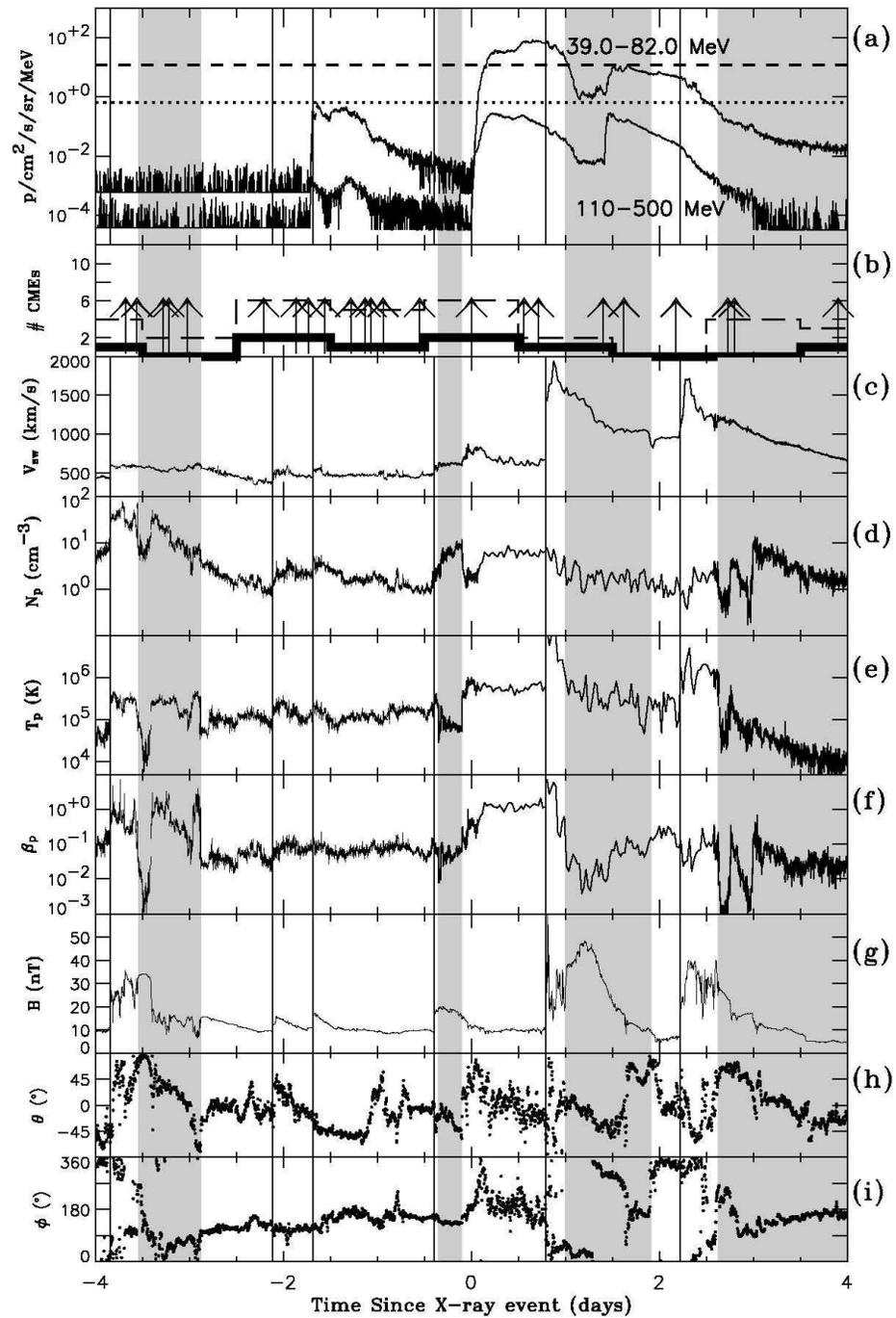
SUMMARY

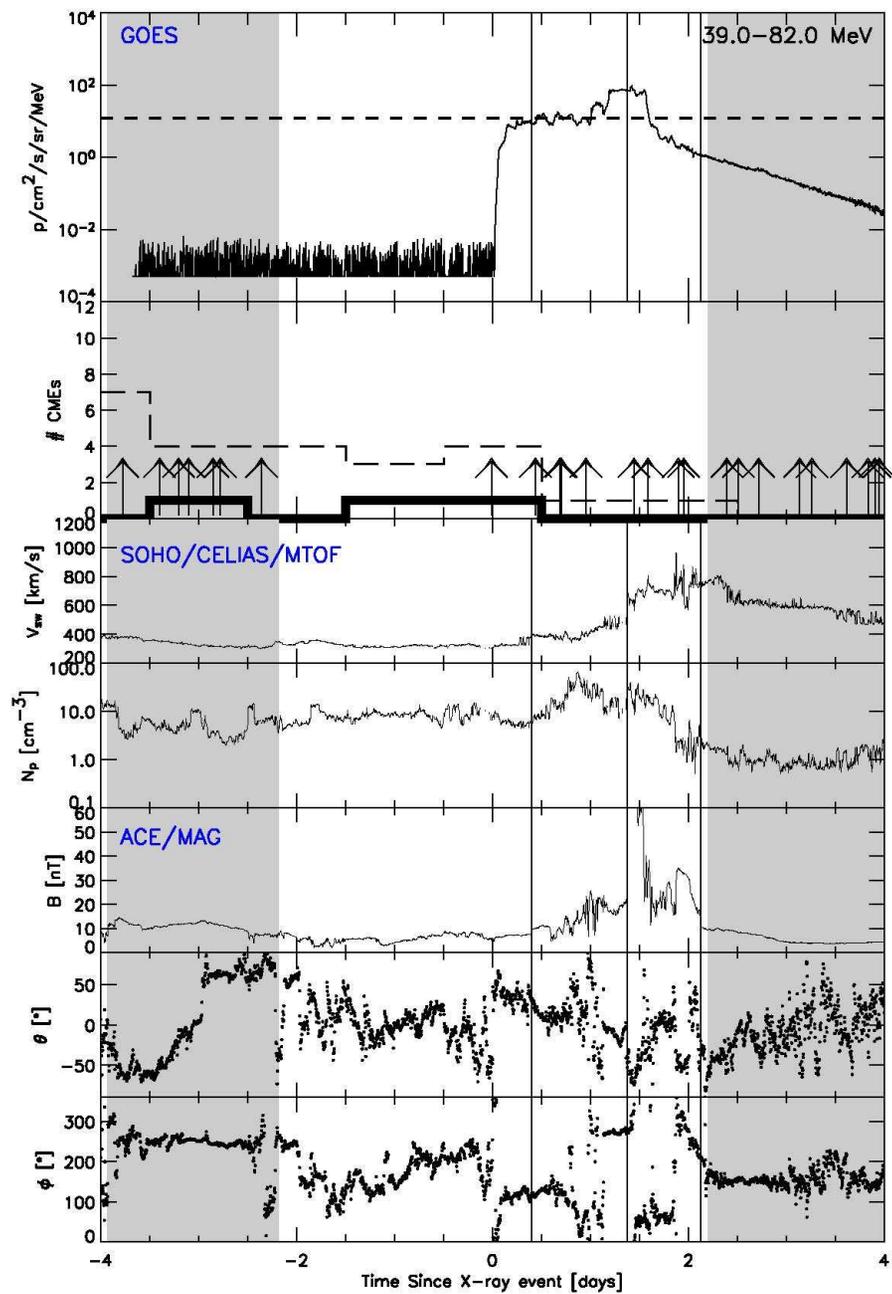
The hazardous intensities not only occur when the CME-driven shock arrives at the spacecraft, but they can also be observed at the prompt component of the SEP events.

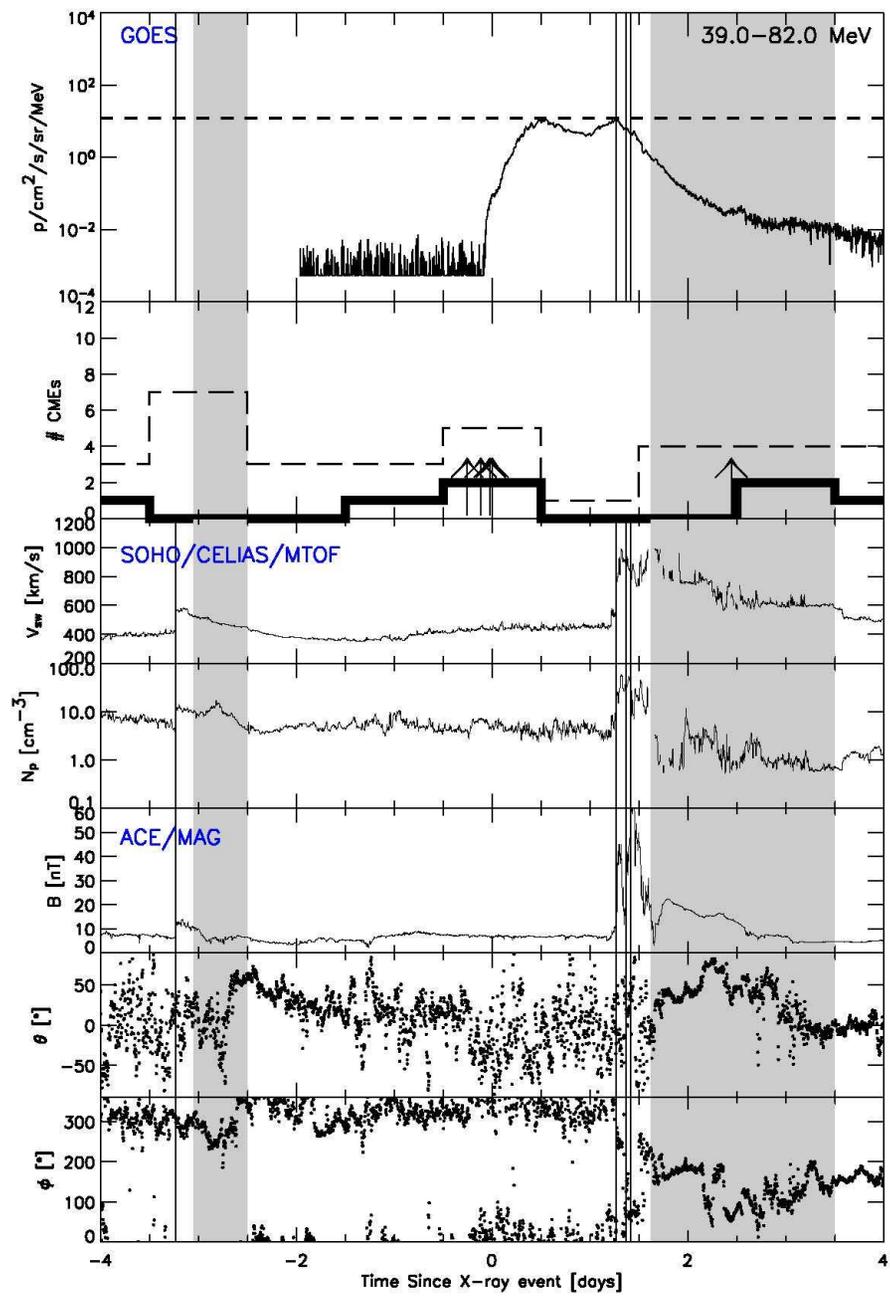
Either:

- Interplanetary structures modify the nominal SEP transport conditions by confining energetic particles in regions of the heliosphere (Bastille Day 2000, 8 Nov 2000, 28 Oct 2003), or
- Interplanetary conditions are such that inhibit the generation of waves by streaming energetic particles (20 Jan 2005).

October 28, 2003 SEP event







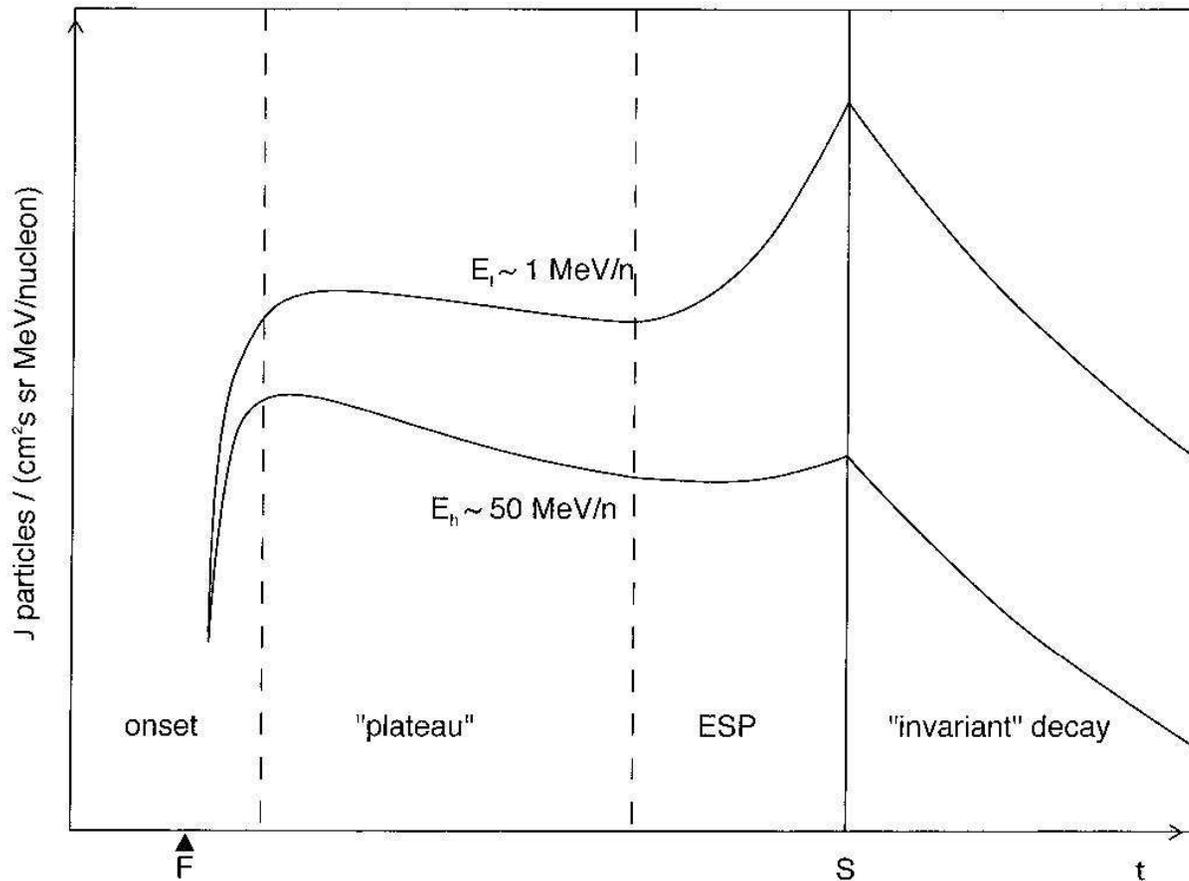


FIG. 1.—Schematic diagram of the time variation of the differential intensity at Earth orbit for $E_l \sim 1$ MeV nucleon⁻¹ and $E_h \sim 50$ MeV nucleon⁻¹ ions during a gradual event. The flare (CME liftoff) is denoted by “F” and a solid triangle, and shock passage is denoted by “S”. The four phases of a typical event are shown separated by vertical lines.

At large distances from the shock $f_{0i}(v > \bar{v}_i, z \rightarrow \infty) = (r_s/r)^2 H_i(v) G_i(v) \Lambda_i(v)$. For protons a particularly simple expression obtains. As long as $G_p(v)$ is not too small (i.e., when the adiabatic approximation is valid), it dominates the other terms in the denominator of equation (74). Then the proton differential intensity is given by

$$J_p = (8\pi^2)^{-1} V \alpha n_p(r) (\beta - 4)(\beta - 2) V_A (|\Omega_p| r_s)^{-1} \cos \psi E^{-1} \\ \times [1 + 2\pi^2 \alpha^{-1} (r_s/\lambda_c) \varepsilon \cos^{-2} \psi (\delta - 1) \delta^{-1} \\ \times (2V k_c / |\Omega_p|)^{\delta-2} (E/E_{0p})^{(\delta-2)/2}], \quad (75)$$

which is in fact independent of $v_{0p} (= 2V)$. We note that factors $G_p(v)$ and ξ_p cancel in expression (75), and $n_p(r_s)(r_s/r)^2 = n_p(r)$, thus yielding a robust expression independent of the injection fraction ξ_p , which is probably variable and not well known. Indeed, if the second term in square brackets dominates, then the expression is independent of α , which is also not well known. Although similar expressions exist for the other ion species, the protons are special because they dominate wave excitation. Two factors in expression (75) are approximately independent of r_s : $V_A (|\Omega_p| r_s)^{-1}$ and (r_s/λ_c) (if $\lambda_c \propto r_s$). If the remaining factors ($\beta, V, \psi, \varepsilon, \delta, V_A^{2-\delta}$) depend weakly on r_s , then $J_p(E, r)$ will exhibit a “plateau” as a function of time at position r until $g_p(v, z)$ deviates substantially from $g_p(v, z \rightarrow \infty)$, signaling the start of the shock-associated enhancement, or ESP event.

$$\beta = 3V/(V - V_d)$$

V = plasma flow velocity along the normal to the shock

V_d = normal component of the downstream flow relative to the shock

$n_p(r)$ = plasma density

r_s = spatial scale length of the shock surface

$\cos(\psi) = \cos(\theta_{Bn})$

E_{0p} = proton injection energy

δ = power spectrum of field fluctuations

ε related to the level of turbulence

K_c = correlation wave number

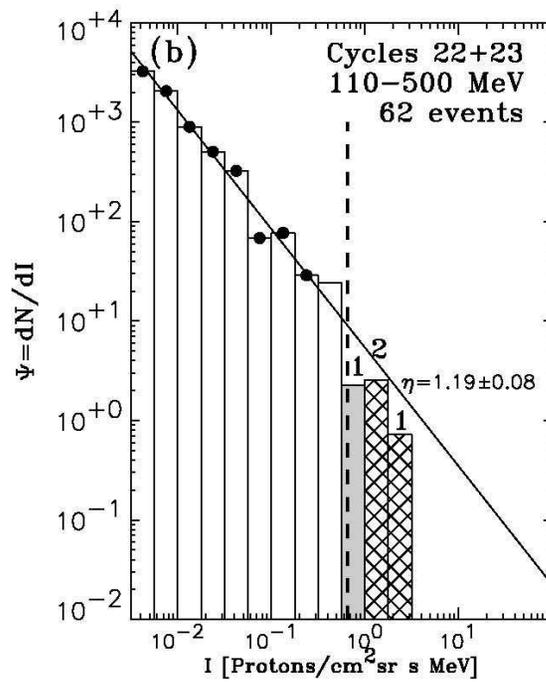
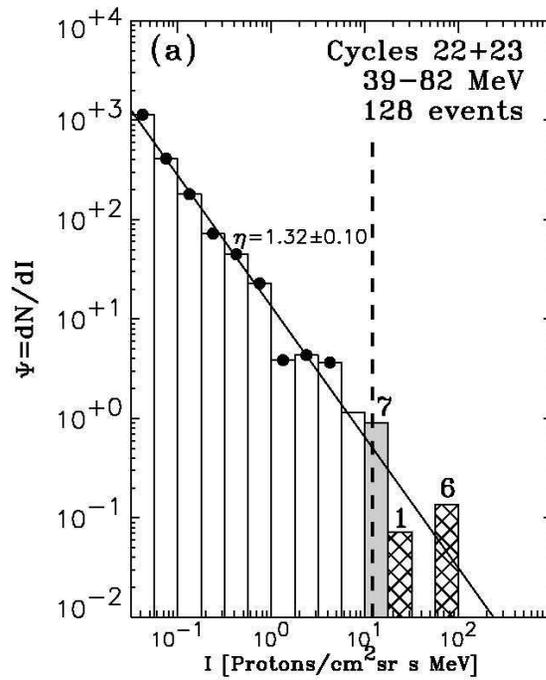
α related to the acceleration time at the shock

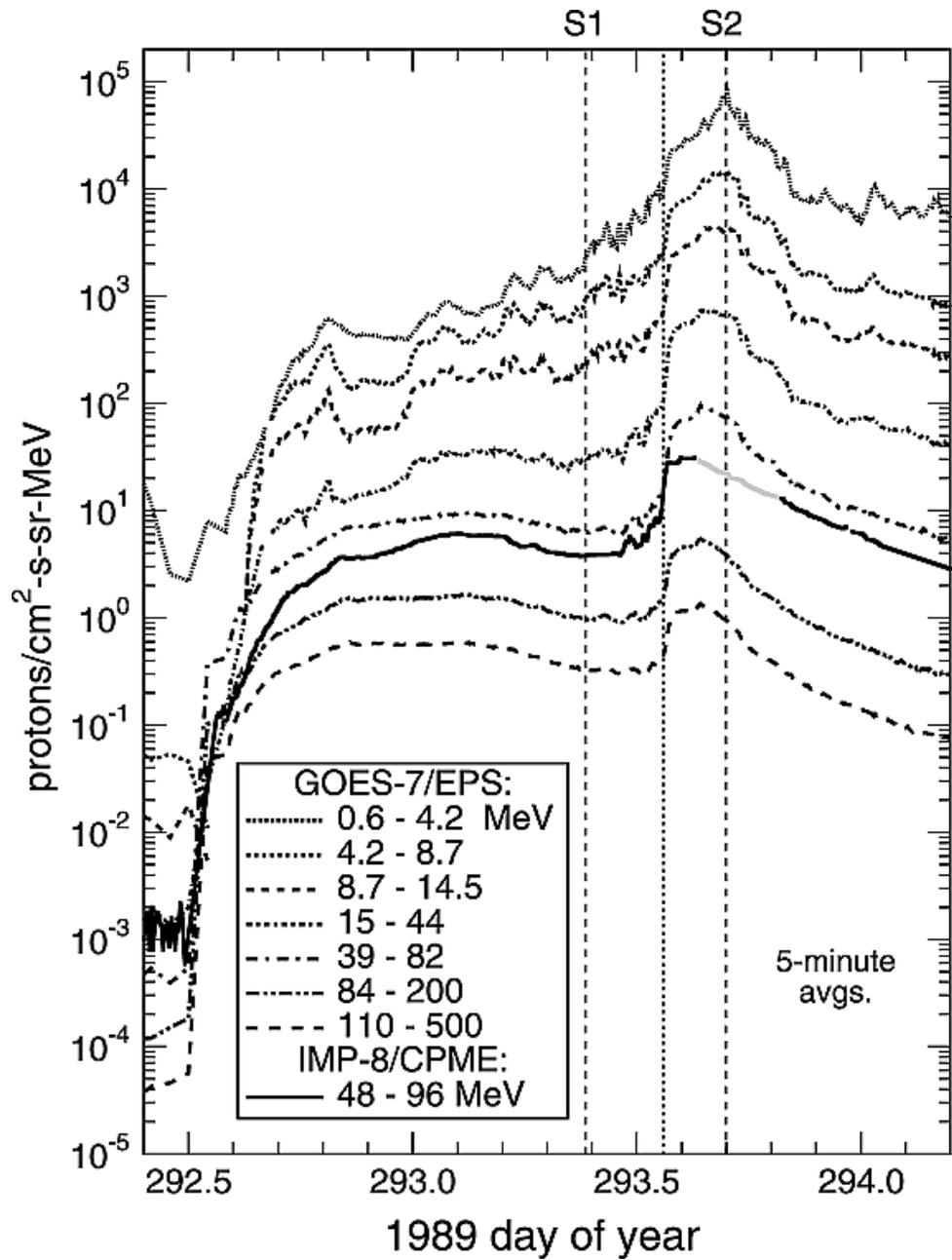
With $\alpha = 3$, $\beta = 5$, $n_p(r) = 8 \text{ cm}^{-3}$, $\psi = 0$, $r_s/\lambda_c = 10$, $\delta = 5/3$, and $|\Omega_p| = 0.5 \text{ s}^{-1}$ at 1 AU, we obtain in units of protons $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}$

$$J_p = 25(V/500 \text{ km s}^{-1})(1 \text{ MeV}/E) \times [1 + 116\varepsilon(r_s/1 \text{ AU})^{-1/3}(E/1 \text{ MeV})^{-1/6}]. \quad (76)$$

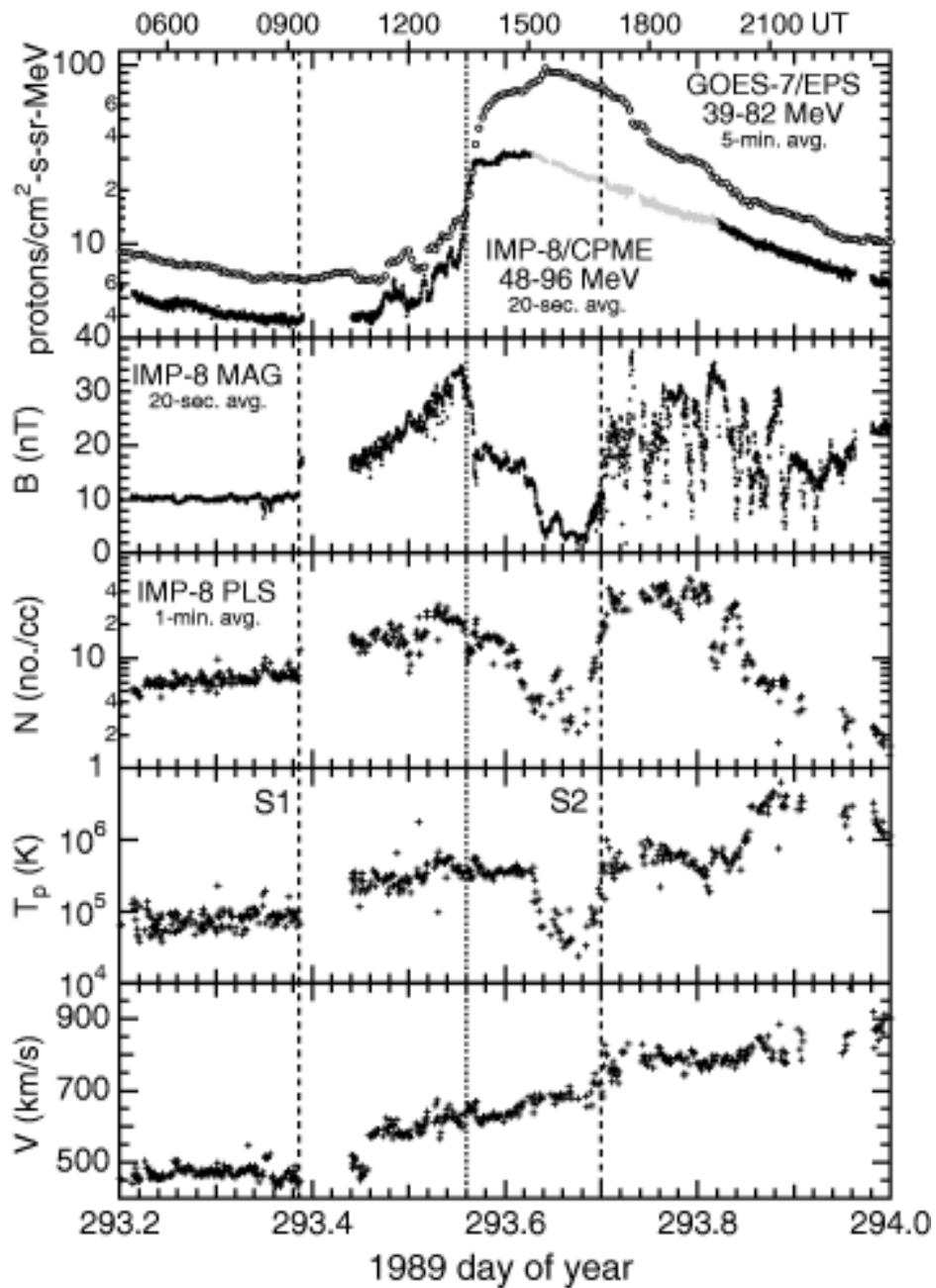
For nominal values of $V = 500 \text{ km s}^{-1}$ (during the plateau phase), $E = 1 \text{ MeV}$, $\varepsilon = 0.002$ (corresponding to $\lambda_{p\parallel}^0 \cong 1 \text{ AU}$ for 1 MeV protons at 1 AU), and $r_s = 0.2 \text{ AU}$, we obtain $J_p = 35$ protons $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}$ at 1 AU. However, if we assume more extreme but still reasonable values of $V = 1000 \text{ km s}^{-1}$, $\varepsilon = 0.01$, and $\beta = 6$, we obtain $J_p = 467$ protons $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}$. At Earth orbit this plateau provides a limit on the intensity of a proton event prior to the onset of the ESP event. At the orbit of *Helios* these values are increased.

This limit on J_p is the “streaming limit” due to proton-excited waves discovered by Reames (1990a) and established by Ng & Reames (1994). Reames (1990a) found that proton events observed by *Helios* in the energy range 3–6 MeV reached plateau intensities (excluding possible ESP events) in a fairly narrow range of $\sim 80\text{--}300$ protons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}^{-1}$. Assuming an average energy of 4 MeV, $V = 1000 \text{ km s}^{-1}$, $\beta = 5$, $n_p(\sim 0.6 \text{ AU}) = 22 \text{ cm}^{-3}$, $r_s = 0.2 \text{ AU}$, and our other parameters, the observed range implies $0.008 \lesssim \varepsilon \lesssim 0.05$, reasonably consistent with expectations. Reames & Ng (1998) examined the streaming limit at Earth orbit using *GOES* data and as a function of r using *Helios 1* and *2*, and *GOES* data (see also Tylka 2001). The *Helios* data presented seem to show limits larger than $80\text{--}300$ protons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}^{-1}$, which would require larger ε . For the *GOES* data in the energy range 8.7–14.5 MeV, they found a limit of $J_p \lesssim 200$ protons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}^{-1}$. This limit would imply, for our choice of values, $\varepsilon \sim 0.3$, which is somewhat large.

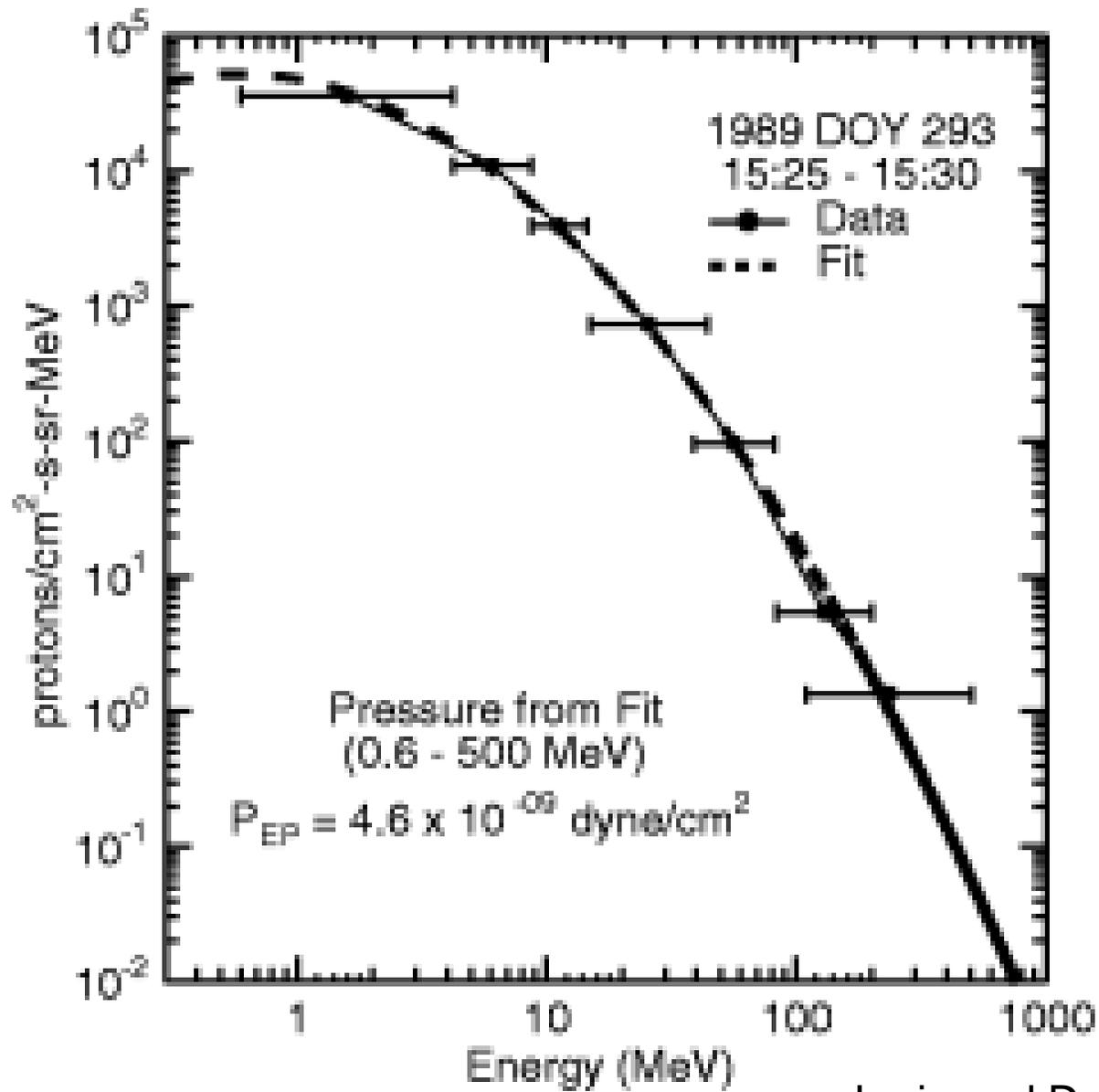




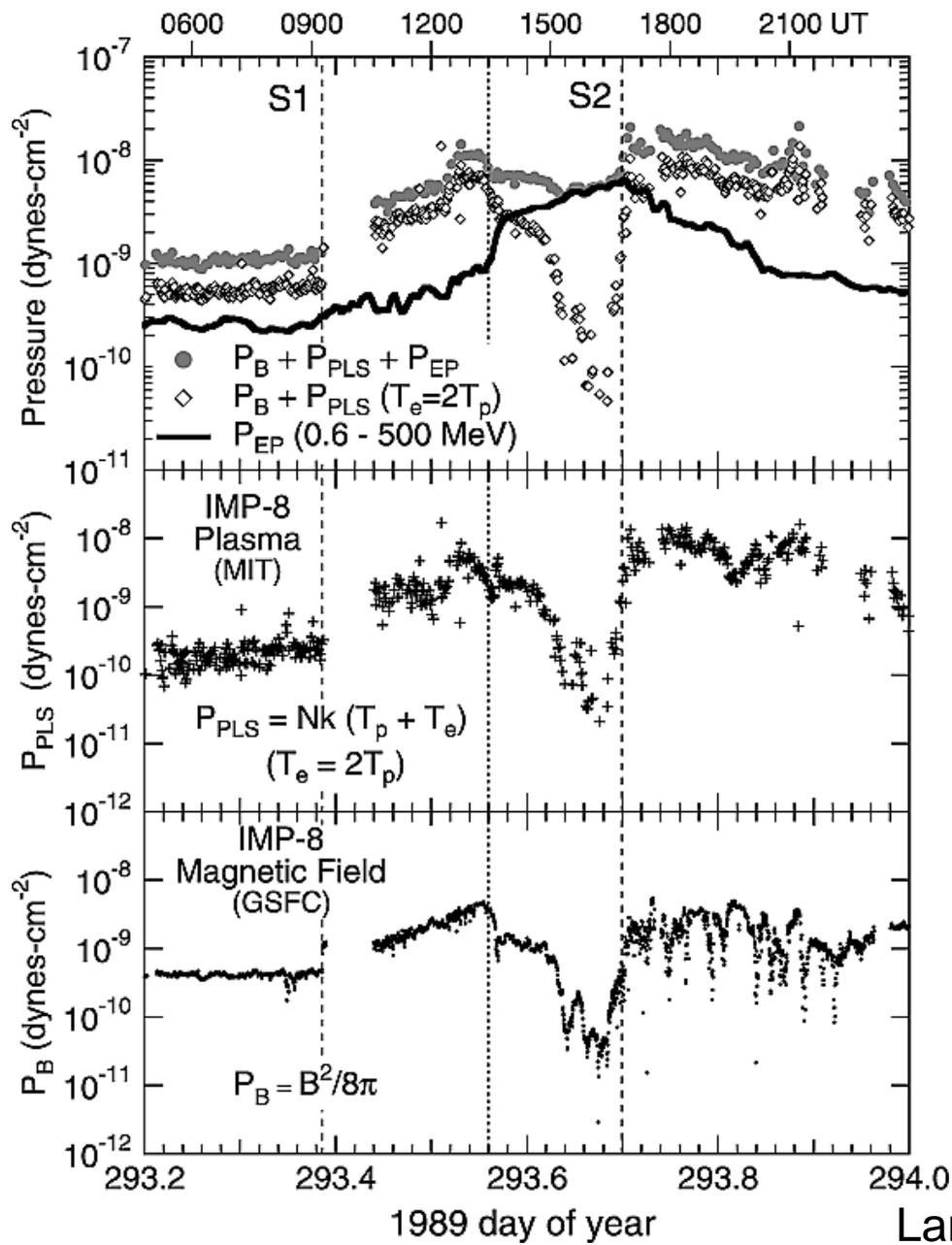
Lario and Decker (2002, GRL)



Lario and Decker (2002, GRL)



Lario and Decker (2002, GRL)



Lario and Decker (2002, GRL)

Table 1. Times of Conditions Relevant to Cycle Minimum

Sunspot Cycle Numbers	Year of Min	From Smoothed Means		From Monthly Averages		
		Minimum in Sunspot Number	Old Cycle = New Cycle Regions	Smallest Sunspot Number	Smallest Number of Regions	Largest Number Spotless Days
11–12	1878.9 ^a	1879.0	1879.2	1878.6	1879.2	1878.7
12–13	1889.6 ^b	1890.1	1889.5	1889.9	1889.9	1889.9
13–14	1901.7 ^c	1902.1	1901.8	1902.0	1901.6	1901.7
14–15	1913.6 ^d	1913.6	1913.0	1913.5	1913.5	1913.6
15–16	1923.6 ^e	1923.6	1923.6	1923.6	1924.0	1923.6
16–17	1933.8 ^f	1933.7	1933.8	1933.6	1933.9	1933.9
17–18	1944.2 ^g	1944.2	1944.2	1944.3	1944.1	1944.3
18–19	1954.3 ^h	1954.3	1954.3	1954.5	1954.5	1954.4
19–20	1964.7 ⁱ	1964.8	1964.6	1964.5	1964.7	1964.7
20–21	1976.5 ^j	1976.5	1976.5	1976.5	1976.5	1976.5
21–22	1986.8 ^k	1986.8	1986.8	1986.5	1986.7	1986.5
22–23		1996.4	1997.0	1996.8	1996.8	1996.8

^a*Wolf* [1880].^b*Wolf* [1892].^c*Wolfer* [1903b].^d*Wolfer* [1919, 1921].^e*Brunner* [1926].^f*Brunner* [1935].^g*Brunner* [1945].^h*Waldmeier* [1956].ⁱ*Waldmeier* [1966]. Note that minimum is 0.2 years earlier than given by *McKinnon* [1987].^j*Waldmeier* [1977].^kSolar Geophysical Data (vol. 520, part I, 1987).

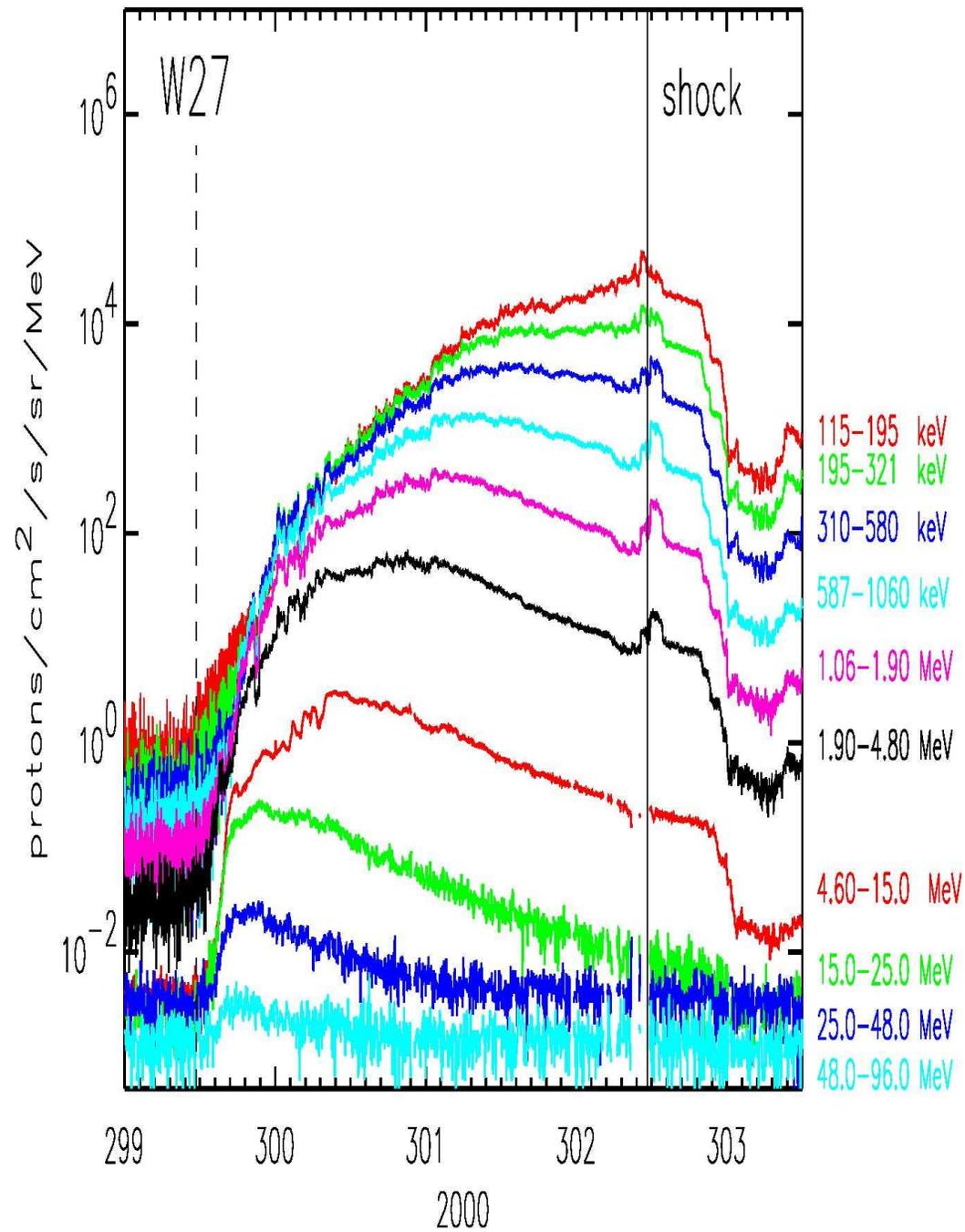
Harvey and White (1999, JGR)

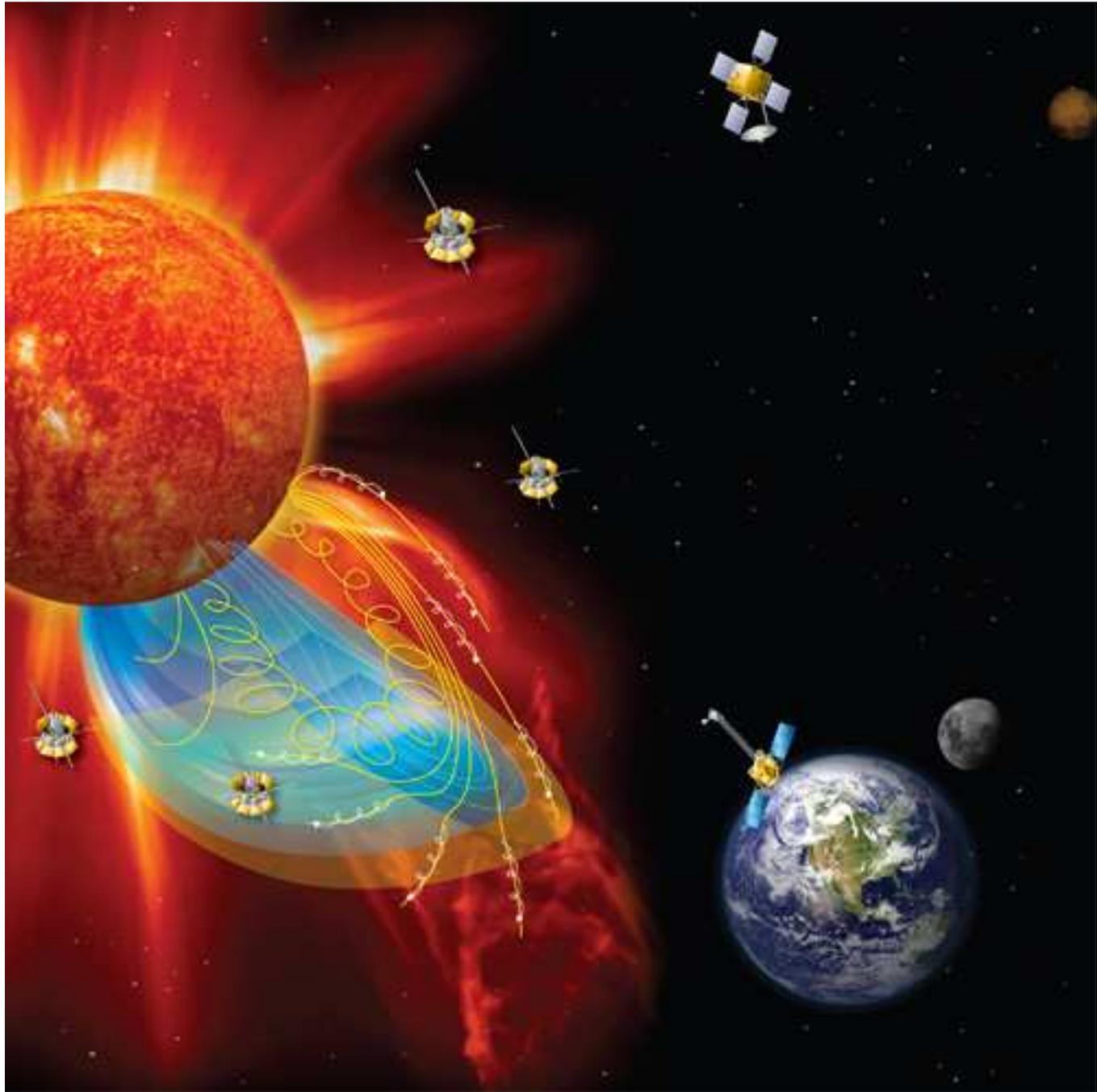
Table 2. Using the Definitions of Cycle Minimum

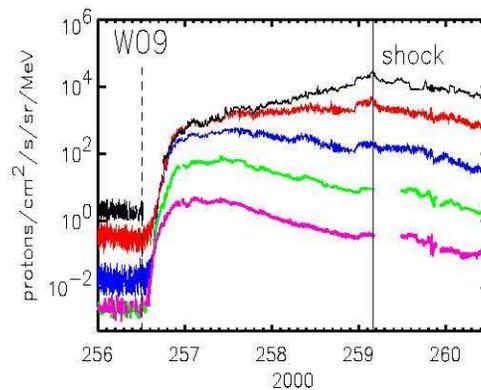
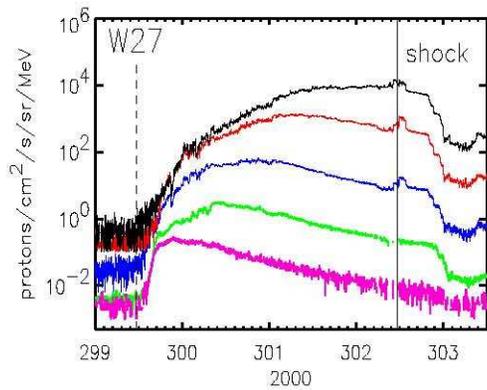
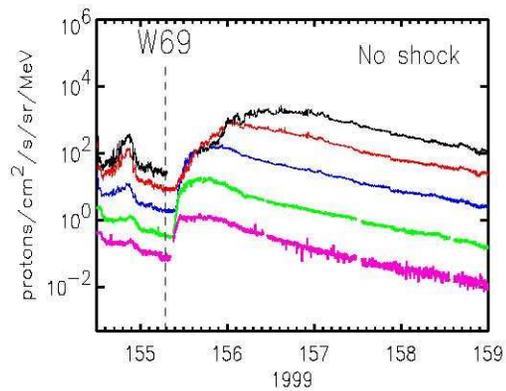
Method	Month	Time of Minimum
1. Smoothed sunspot number	May 1996	1996.4
2. Number of old-cycle = new-cycle regions	Jan. 1996	1997.1
3. Average of following parameters	Sept. 1996	1996.7
– minimum in monthly sunspot number	Oct. 1996 (1996.75)	
– minimum in smoothed sunspot number	May 1996 (1996.37)	
– minimum in monthly number of spot groups	Oct. 1996 (1996.75)	
– maximum in number of spotless days	Oct. 1996 (1996.75)	
– equal number of old-cycle and new-cycle regions	Jan. 1997 (1997.04)	

Harvey and White (1999, JGR)

Solar
Energetic
Particle (SEP)
event







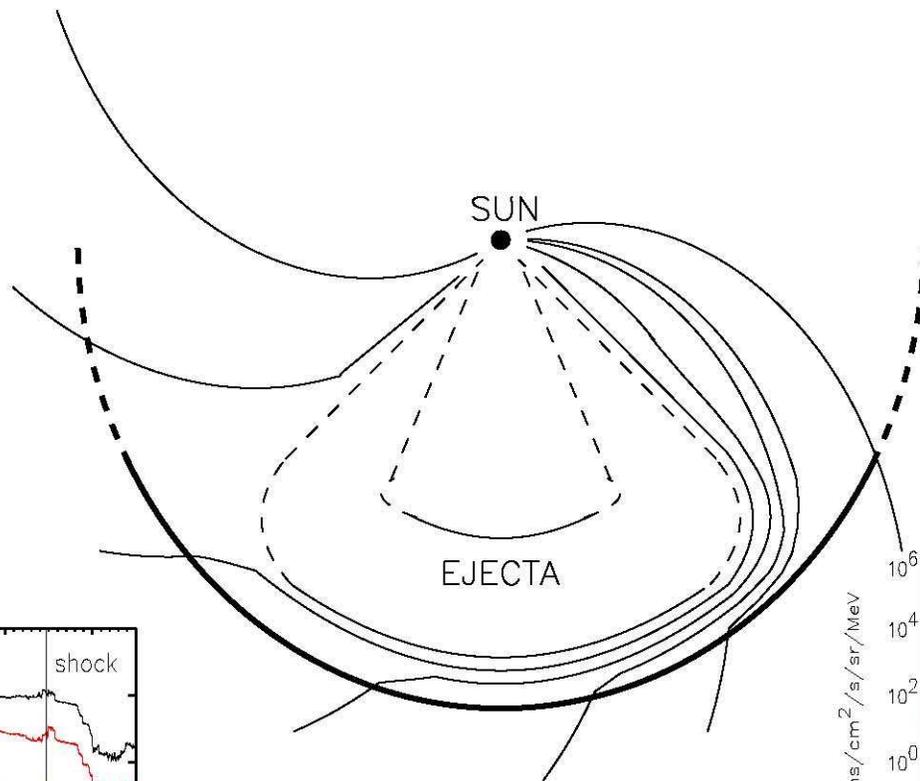
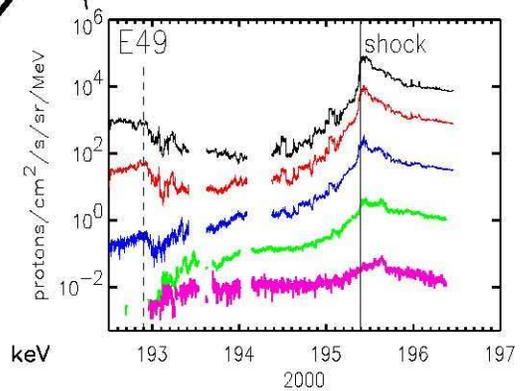
195–321 keV

587–1060 keV

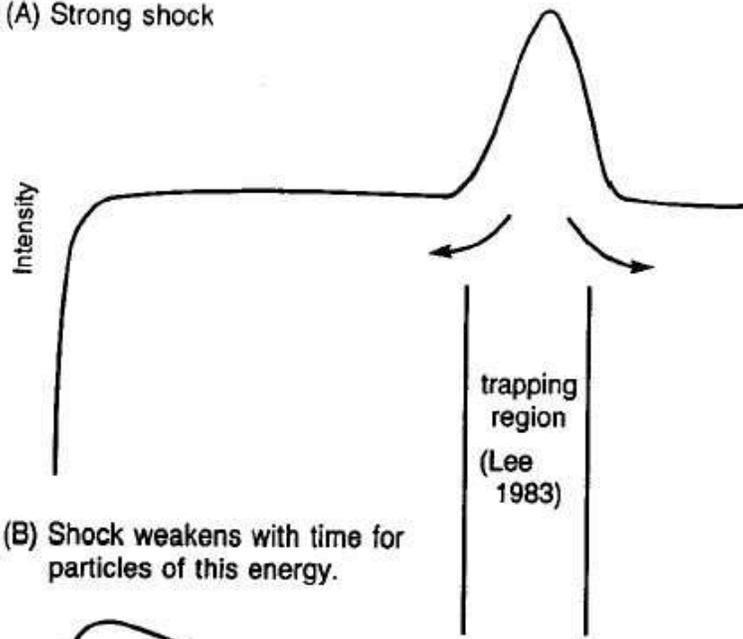
1.90–4.80 MeV

4.60–15.0 MeV

15.0–25.0 MeV



(A) Strong shock



(B) Shock weakens with time for particles of this energy.

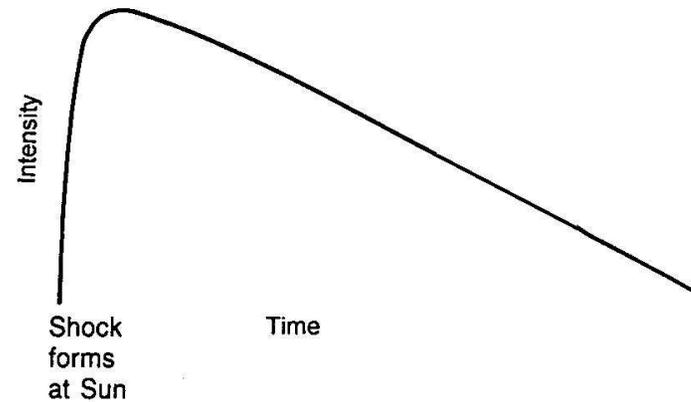
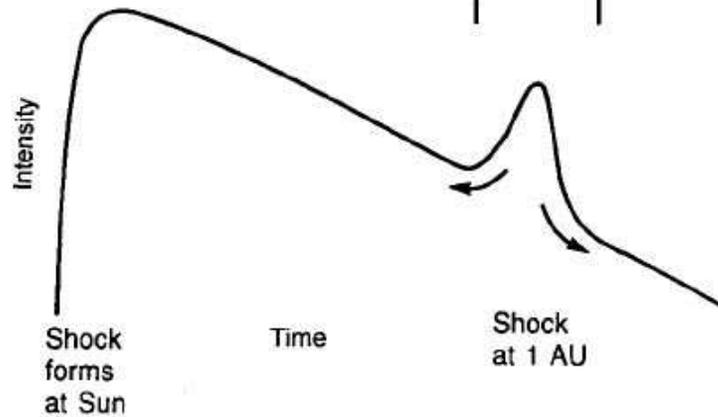


Fig. 1. Profiles of particle intensity vs time are shown when (a) strong shock acceleration continues out to the observer and (b) acceleration diminishes with time. All particles are accelerated by the shock in either case. If acceleration diminished sufficiently, the shock spike or "ESP event" may not be present.