Integrity ★ Service ★ Excellence

A Super Storm: Current Limits of Extreme Space Weather

E.W. Cliver
Space Vehicles Directorate

22-24 Oct 2012

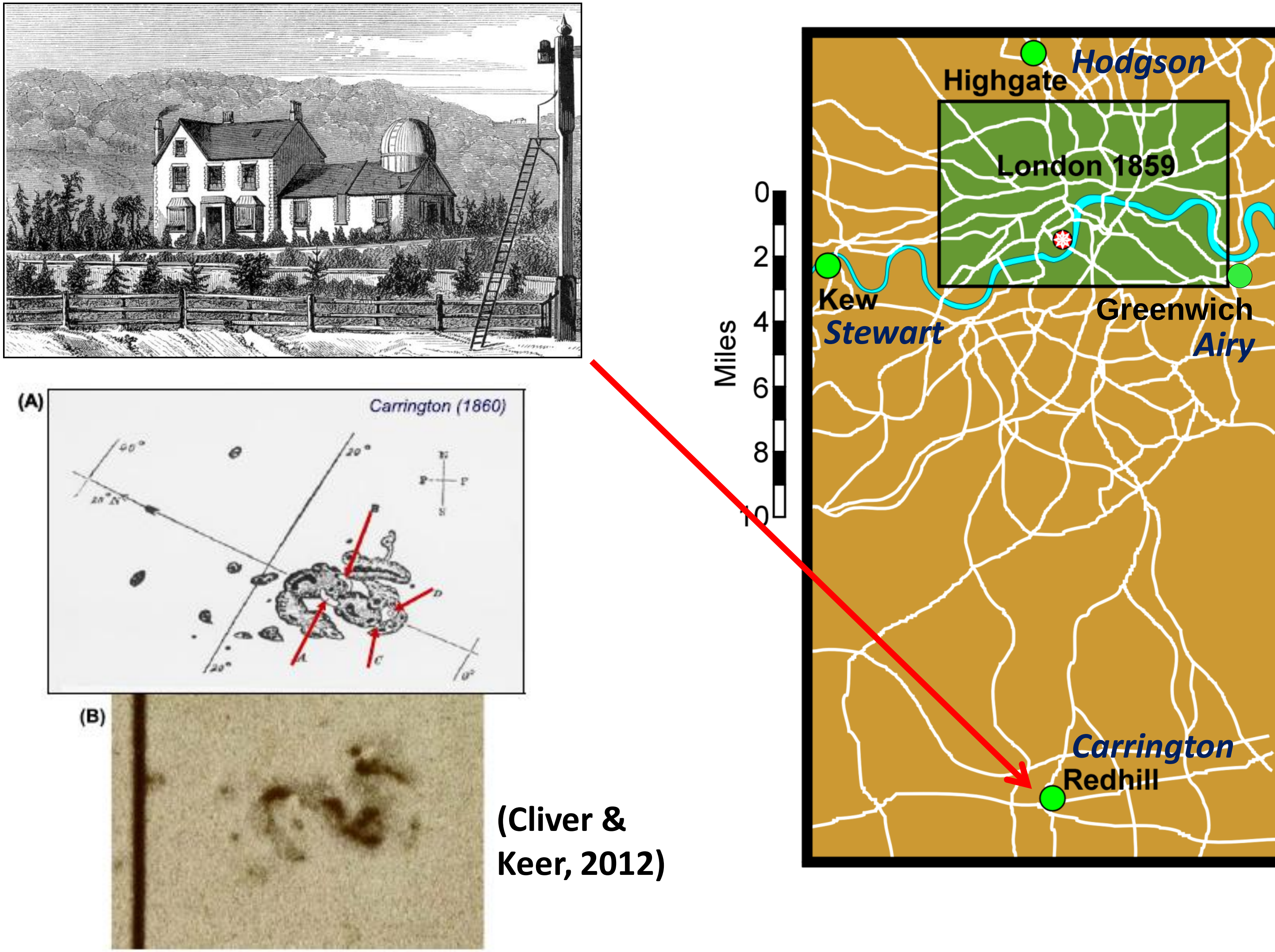
1 September 1859

In a remarkable quirk of history,

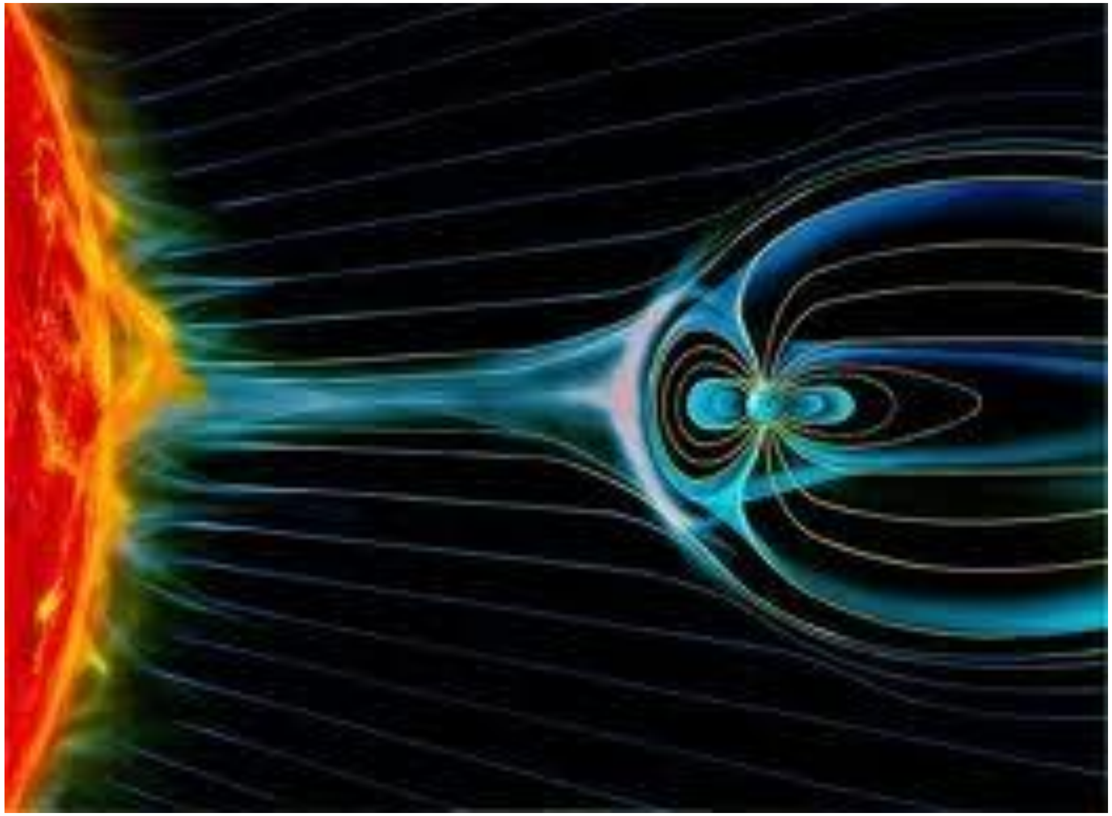
the first solar flare ever observed

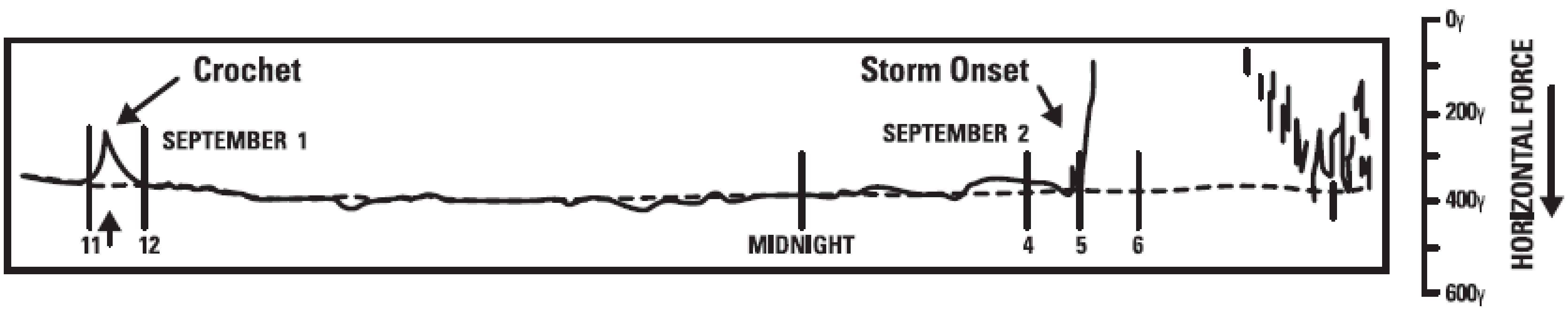
was associated with the largest

solar-terrestrial event yet recorded.



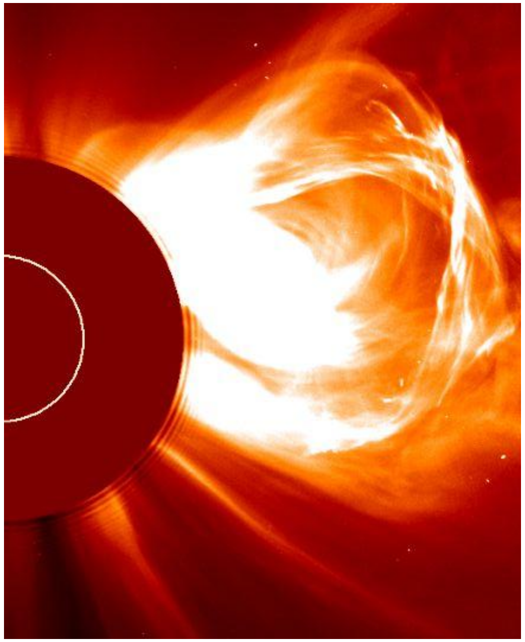
1 September 1859: The first observation of a solar flare (Carrington & Hodgson) and the first link to geomagnetic activity (Stewart)

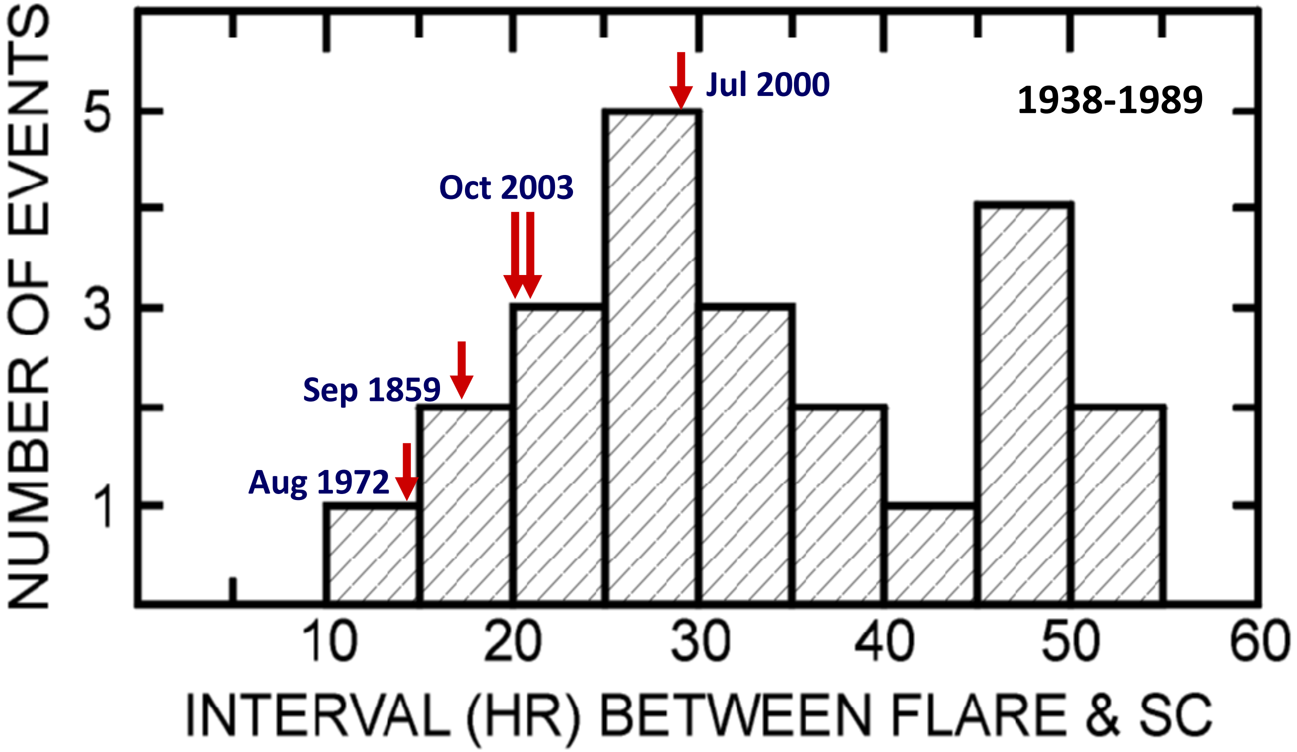




Kew record of the 1859 storm: Separation between the flare and storm onset (SC) is a measure of flare energy

Transit Times of Major Solar-Terrestrial Events



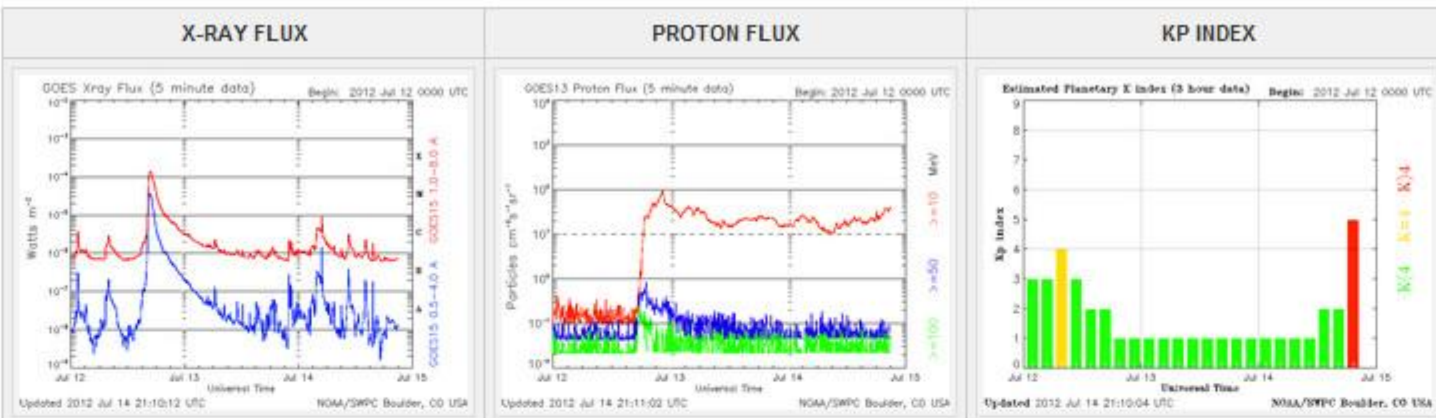


Cliver et al. (1990)

Three Types of Solar Emissions & Their Impacts

	Current	Past 24h
Geomagnetic storm	G1	G1
Solar radiation storm	S1	S1
Radio blackout	none	R1
VHF Aurora	Mid Lat AURORA!!	

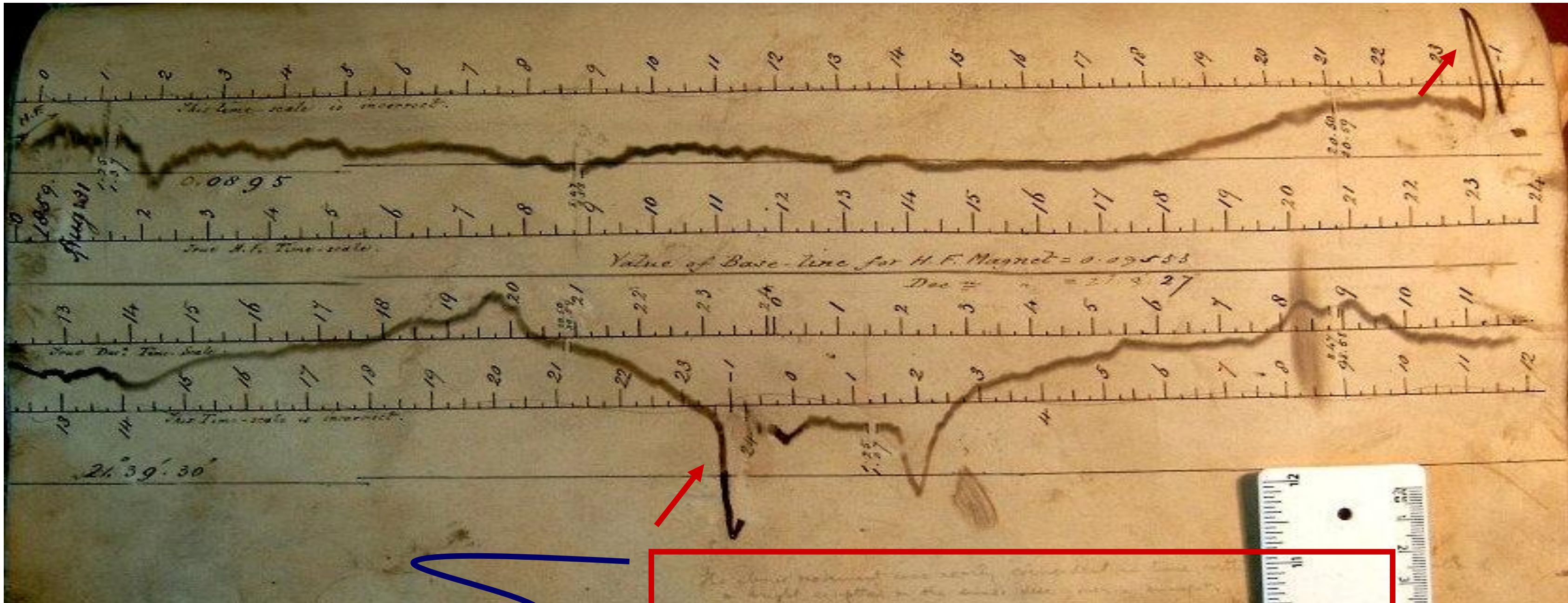
Quick overview



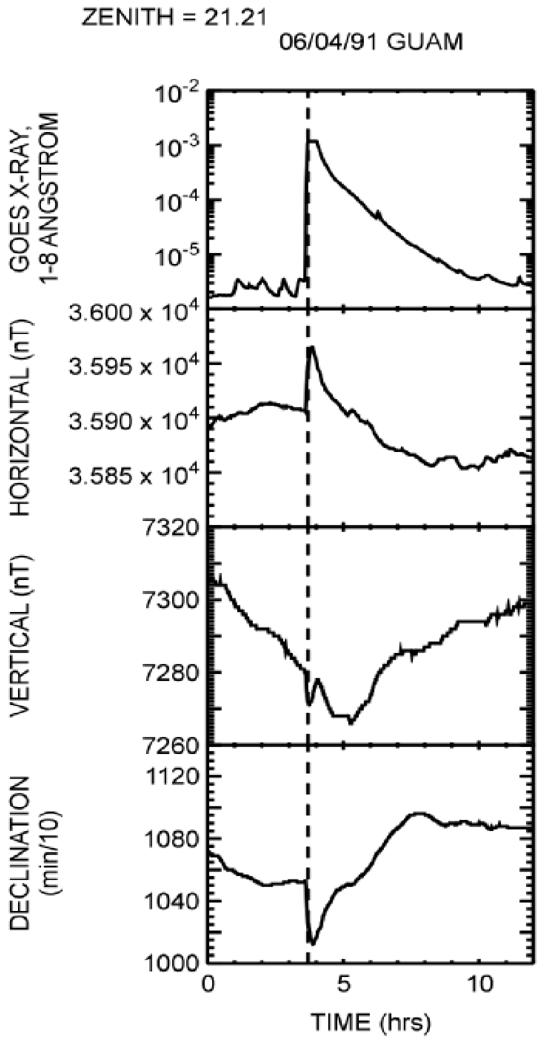
Flare Electromagnetic Emission	Solar Energetic Protons (SEPs)	Coronal Mass Ejections (CMEs)
Short-wave Fades	Radiation Damage To Satellites	Power Grid

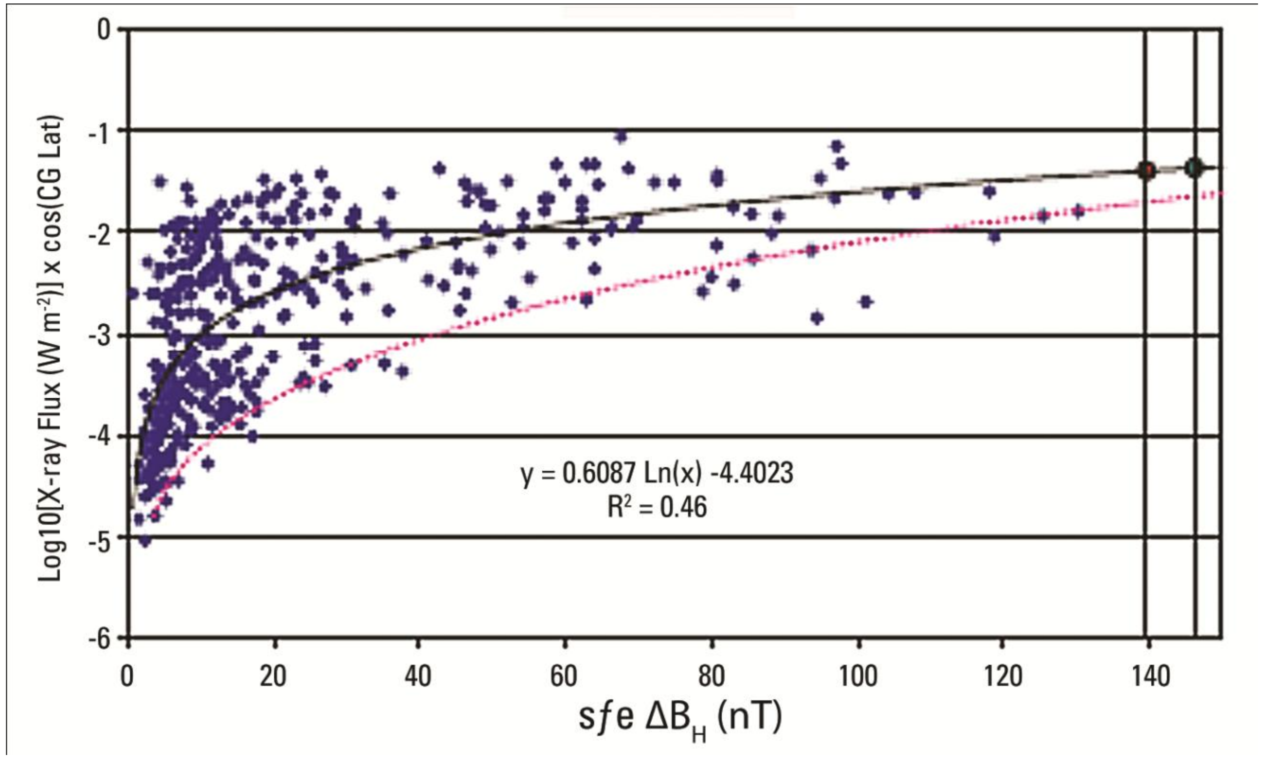
Biggest Flare Ever Recorded

Greenwich Magnetogram Showing the Solar Flare Effect (SFE) for Carrington’s Event



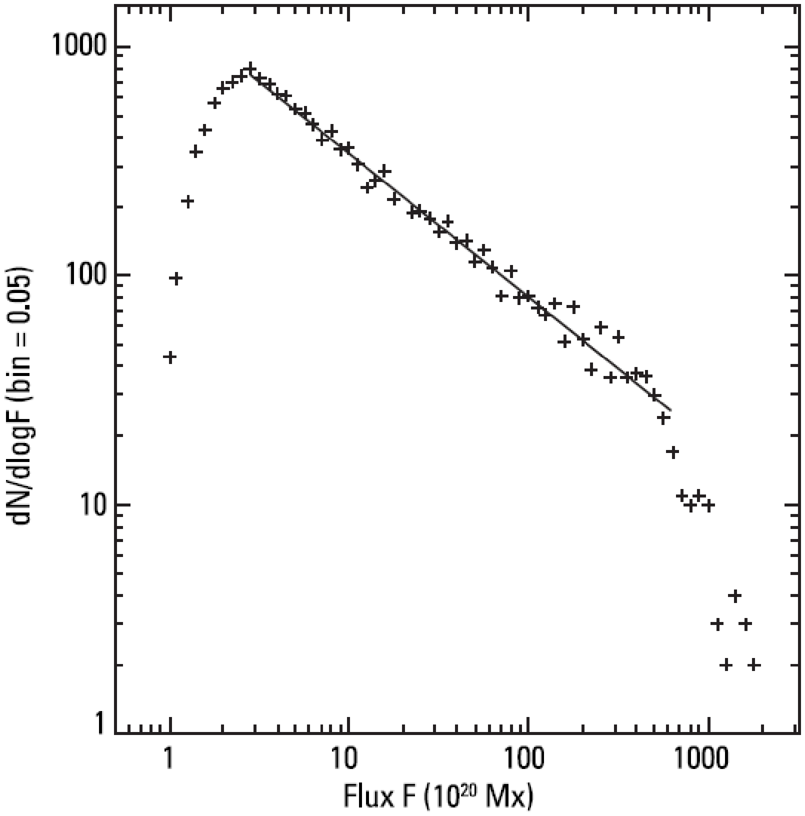
“The above movement was nearly coincidental in time with Carrington's observation of a bright eruption on the sun. Disc over a sunspot.” **(H.W.N., 2 Dec 1938)**





Clarke et al. (2010) determined that the 1859 flare had a soft X-ray (SXR) classification of ~X40 vs. ~X30 for the largest flare recorded during the space age (on 4 November 2003)

From a SOHO/MDI based study of active regions from 1998-2008, Zhang et al. (2010) found a power law distribution of active region magnetic fluxes with no value > 2 x 10^{23} Mx.



Assume that regions with fluxes 10 X larger, i.e., ~2 x10^{24} Mx, can occur, then assuming a 50% conversion rate, the largest possible flare would have an energy of

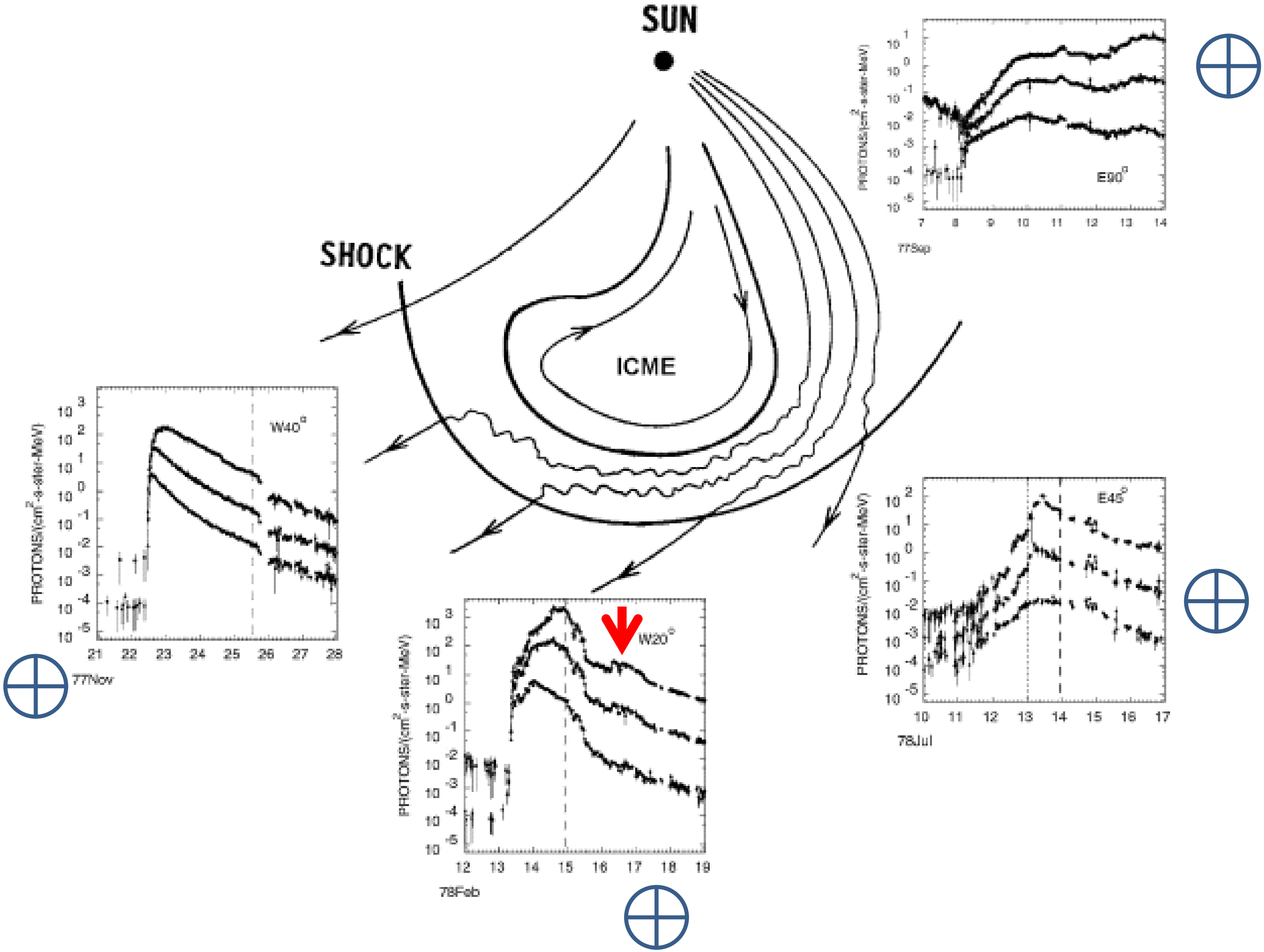
$$E = [(0.5)\ (2 \times 10^{24})^{3/2}]\ /\ (4\pi \langle B \rangle)$$

where <B> = 100 G (Schrijver & Harvey, 1994)

=> E_{MAX} ~10^{33} ergs [SXR: X40]

Schrijver et al. (2012)
Woods et al. (2006)

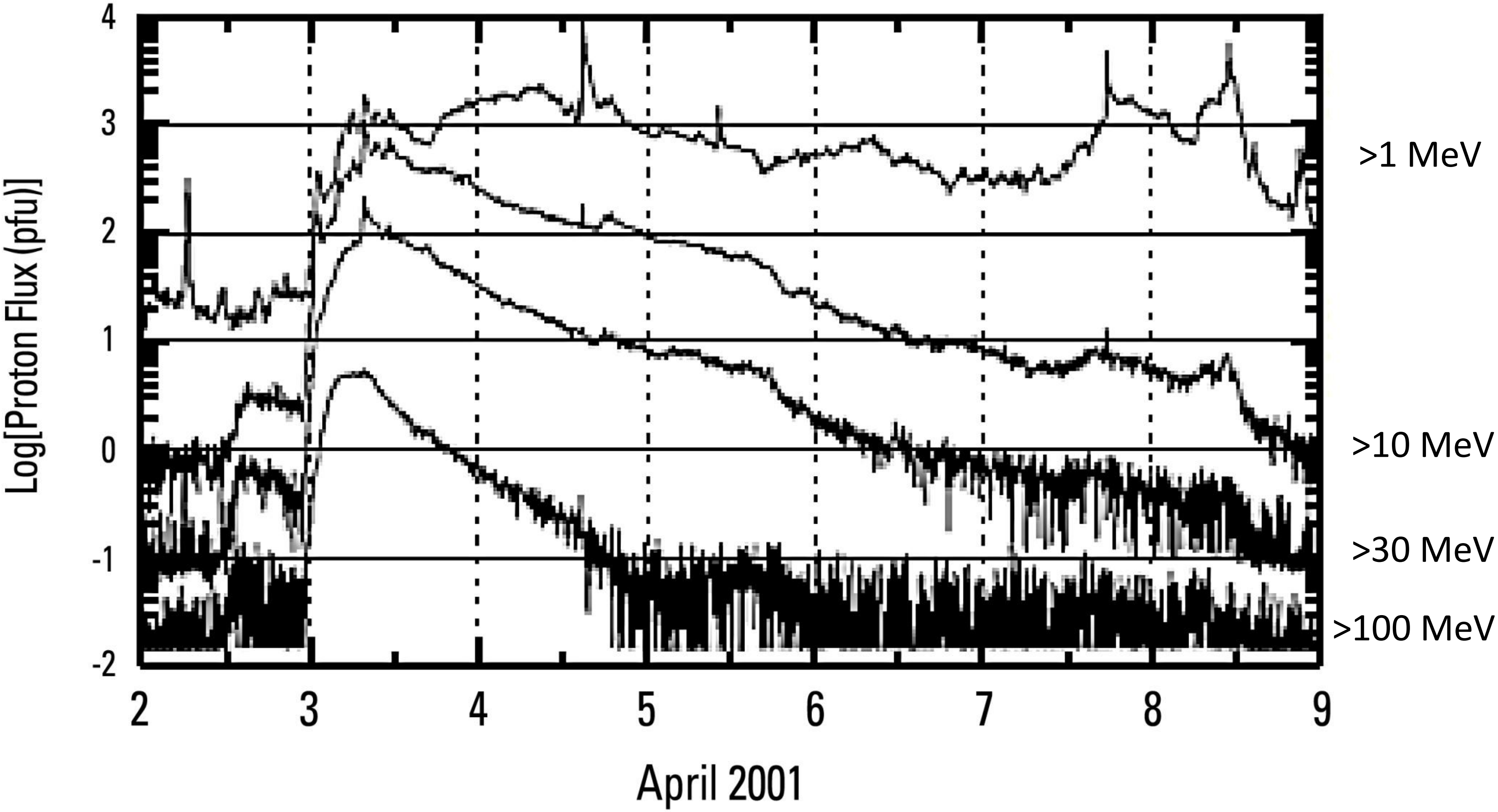
Largest SEP Event Ever Recorded

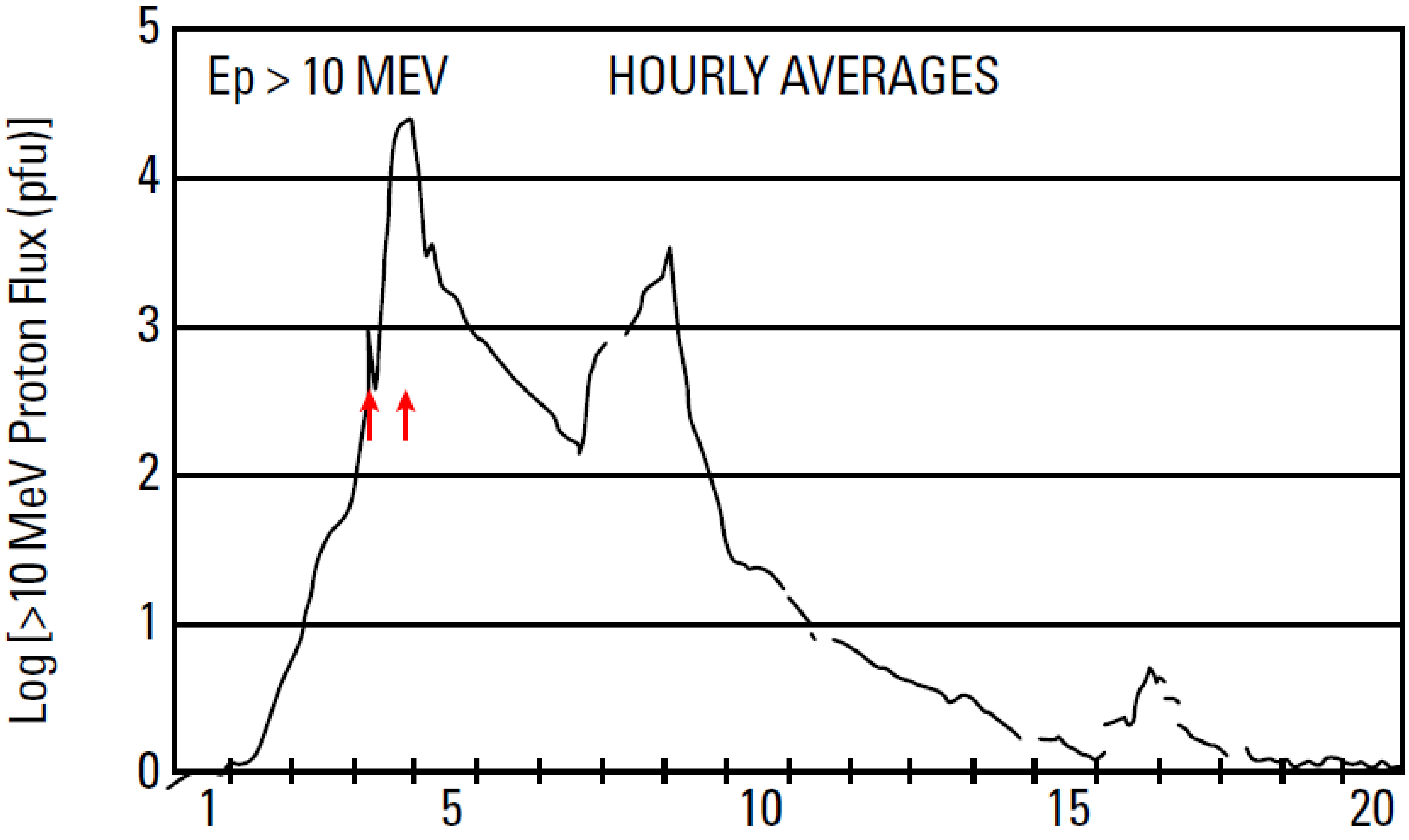


SEP event profiles at Earth depend on the source flare/CME location

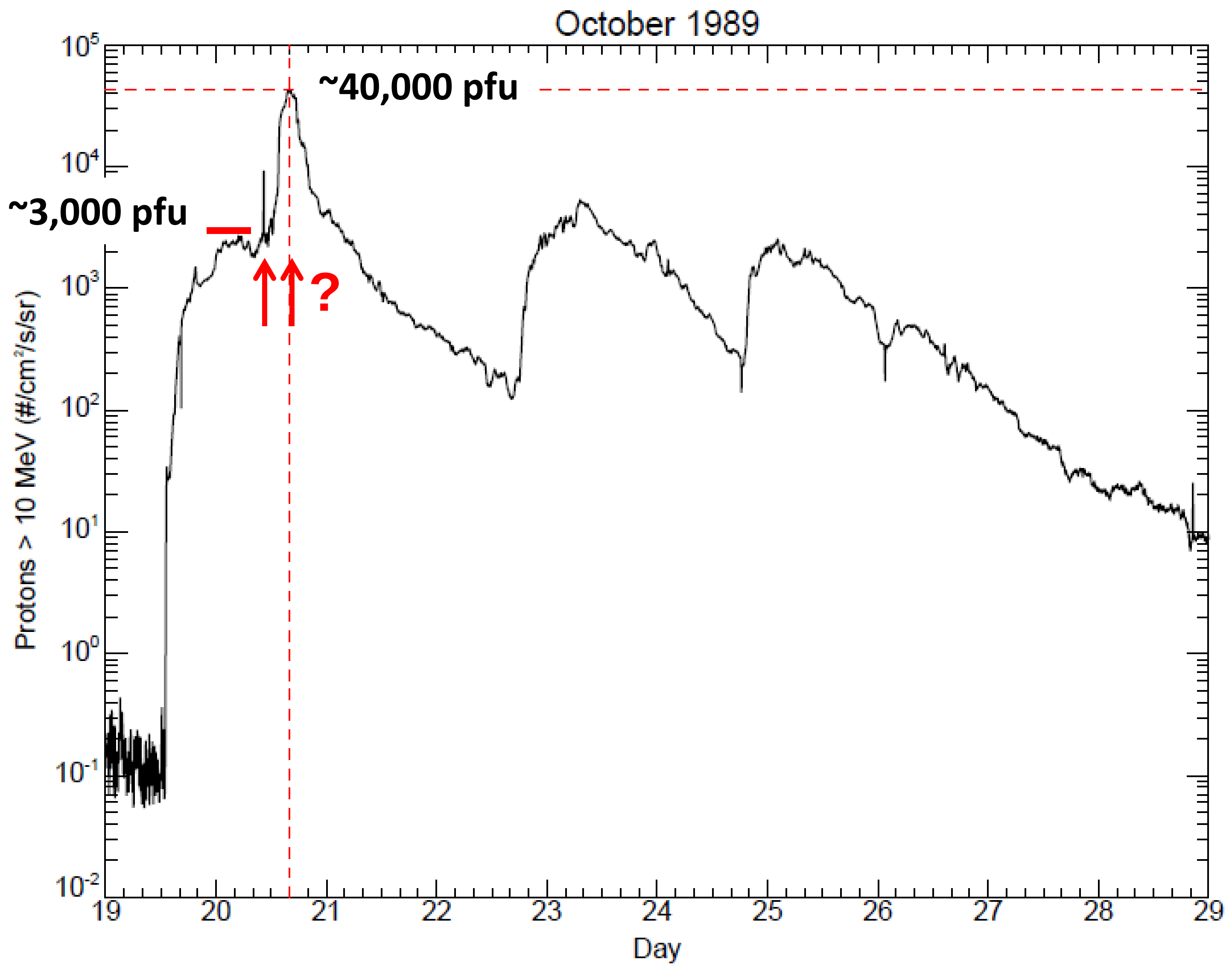
Cane & Reames (1988)

Typical large (well-connected; solar western hemisphere) SEP event

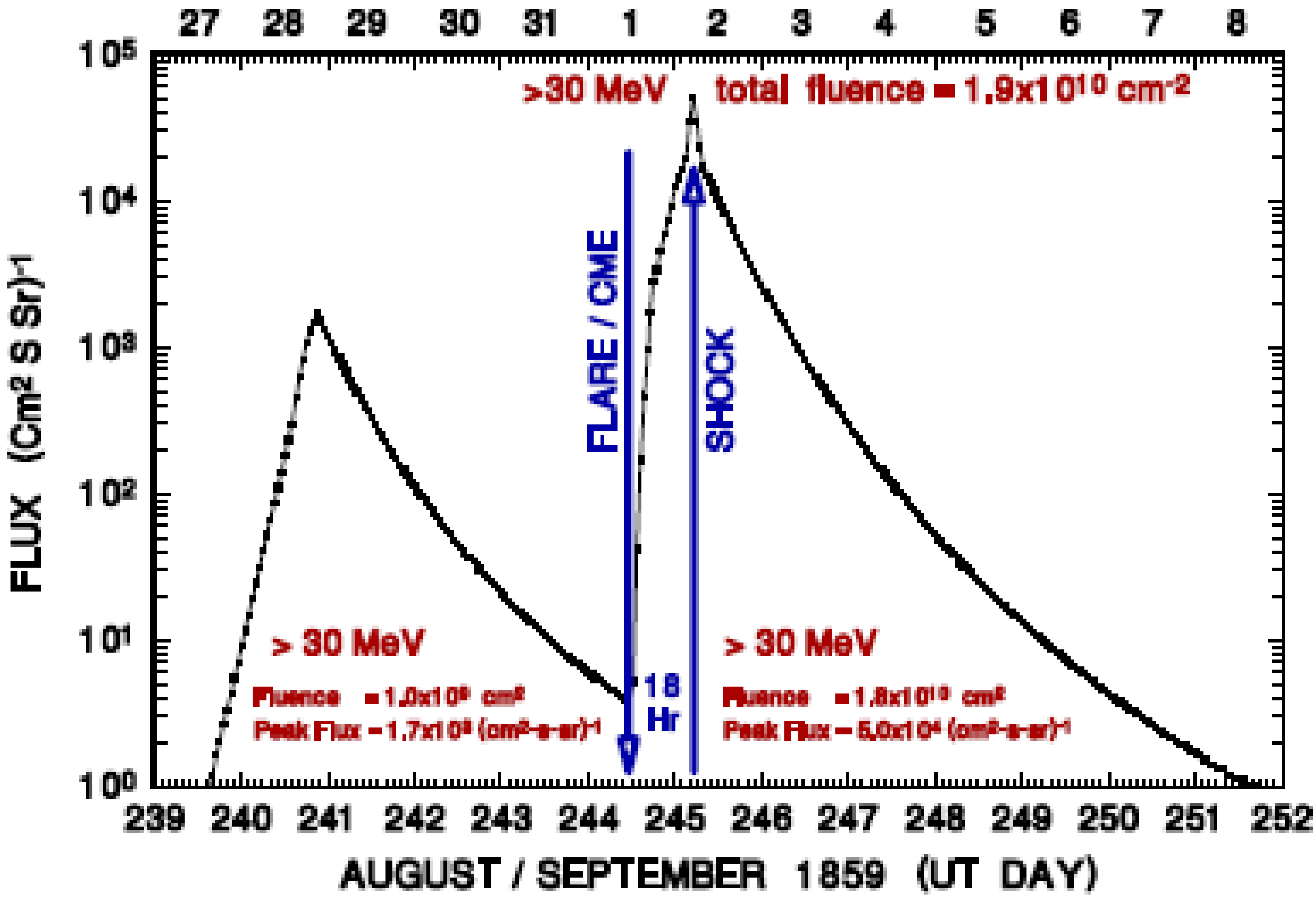




SEP profile (1st large peak) for a large flare at central meridian; the SEP peaks near the geomagnetic storm SC (2nd red arrow)



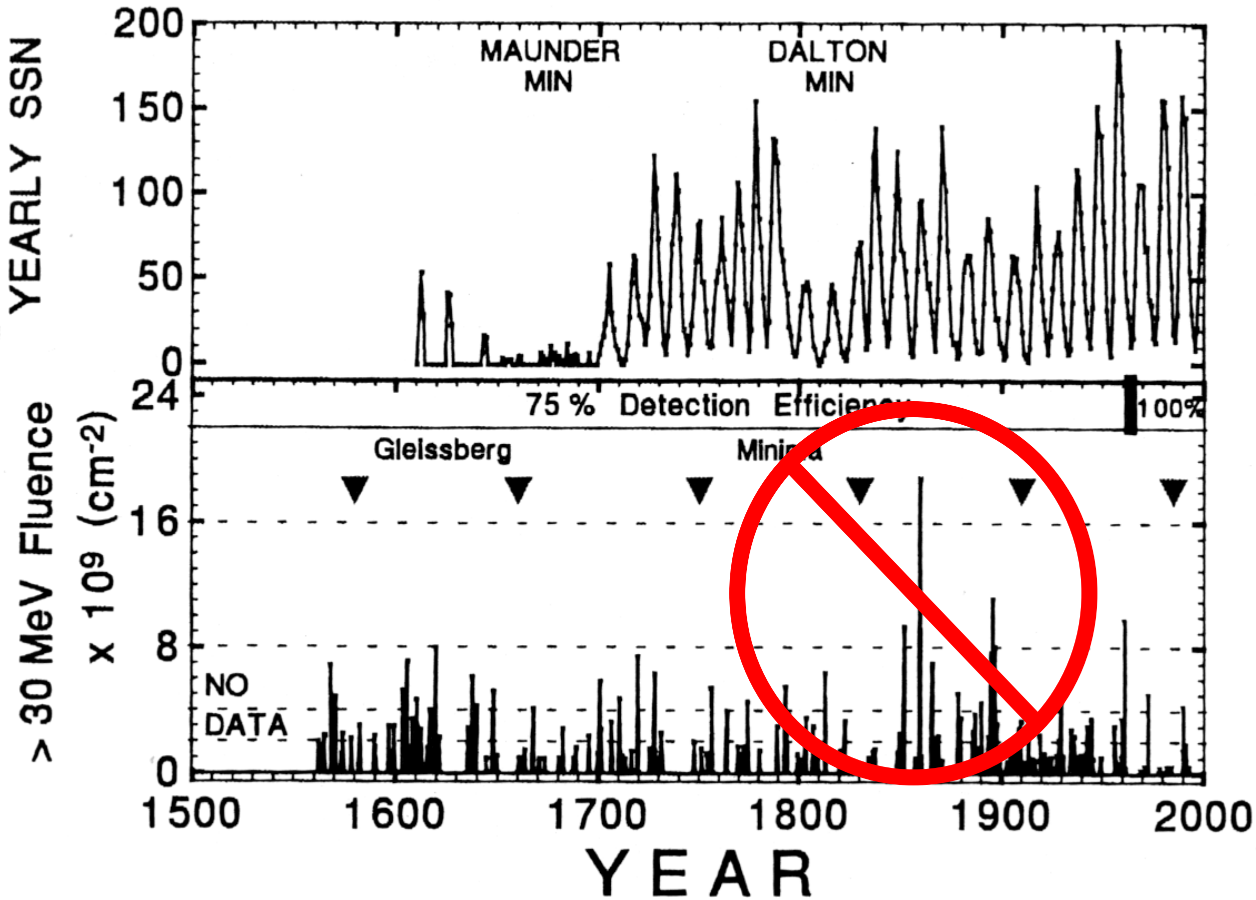
Such shock-associated peaks can dominate SEP events associated with central meridian flares



Reconstruction of the time profile 1859 SEP event

Smart et al. (2006)

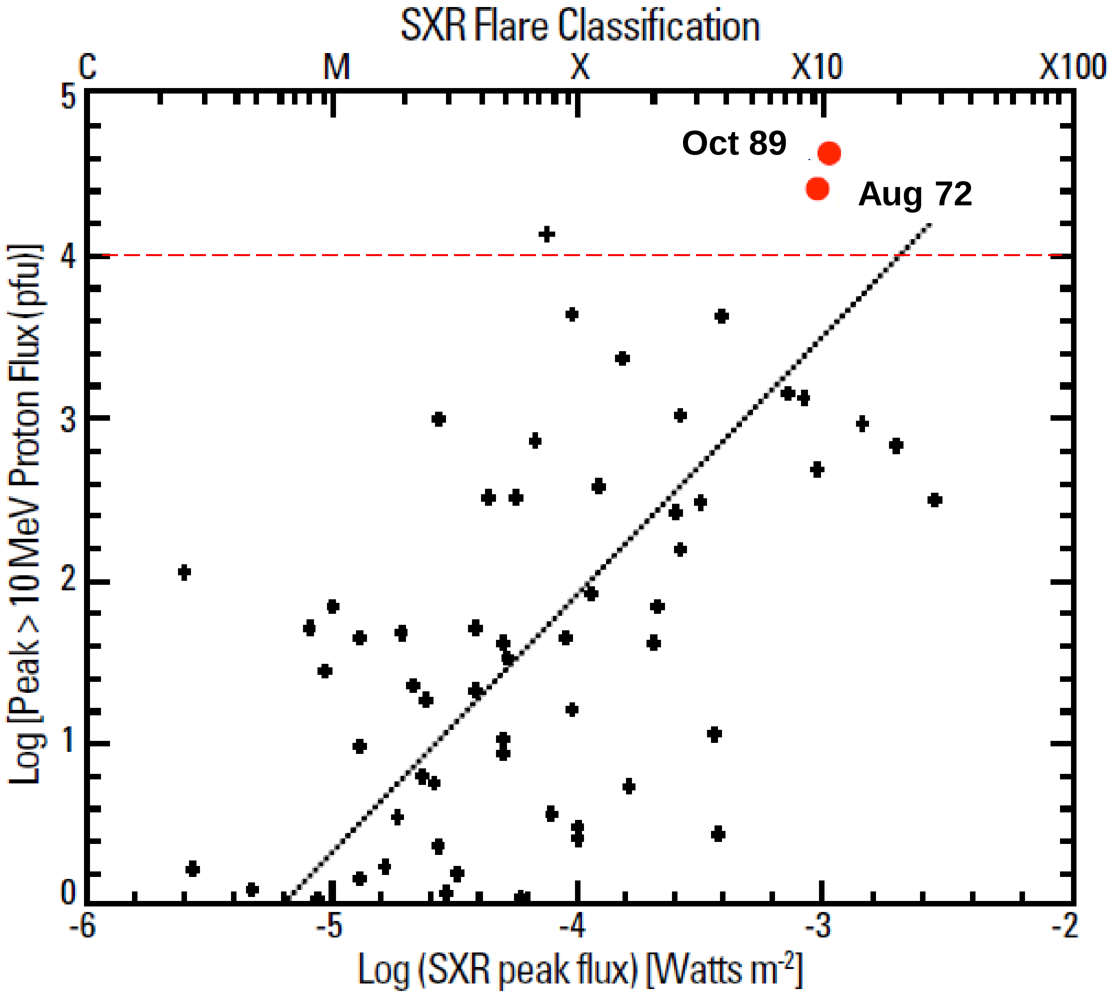
Solar Energetic Particle Events, 1560-2000 (from nitrate measurements in ice cores)



Date	> 30 MeV 10^9 pr cm^{-2}
1859	18.8
1895	11.1
1960	9.7
1851	9.3
1896	8.0
1619	8.0
1894	7.7
1719	7.4
1605	7.1
1864	7.0
1972	5.0

Wolff et al. (2012) provided evidence against technique

McCracken et al. (2001)



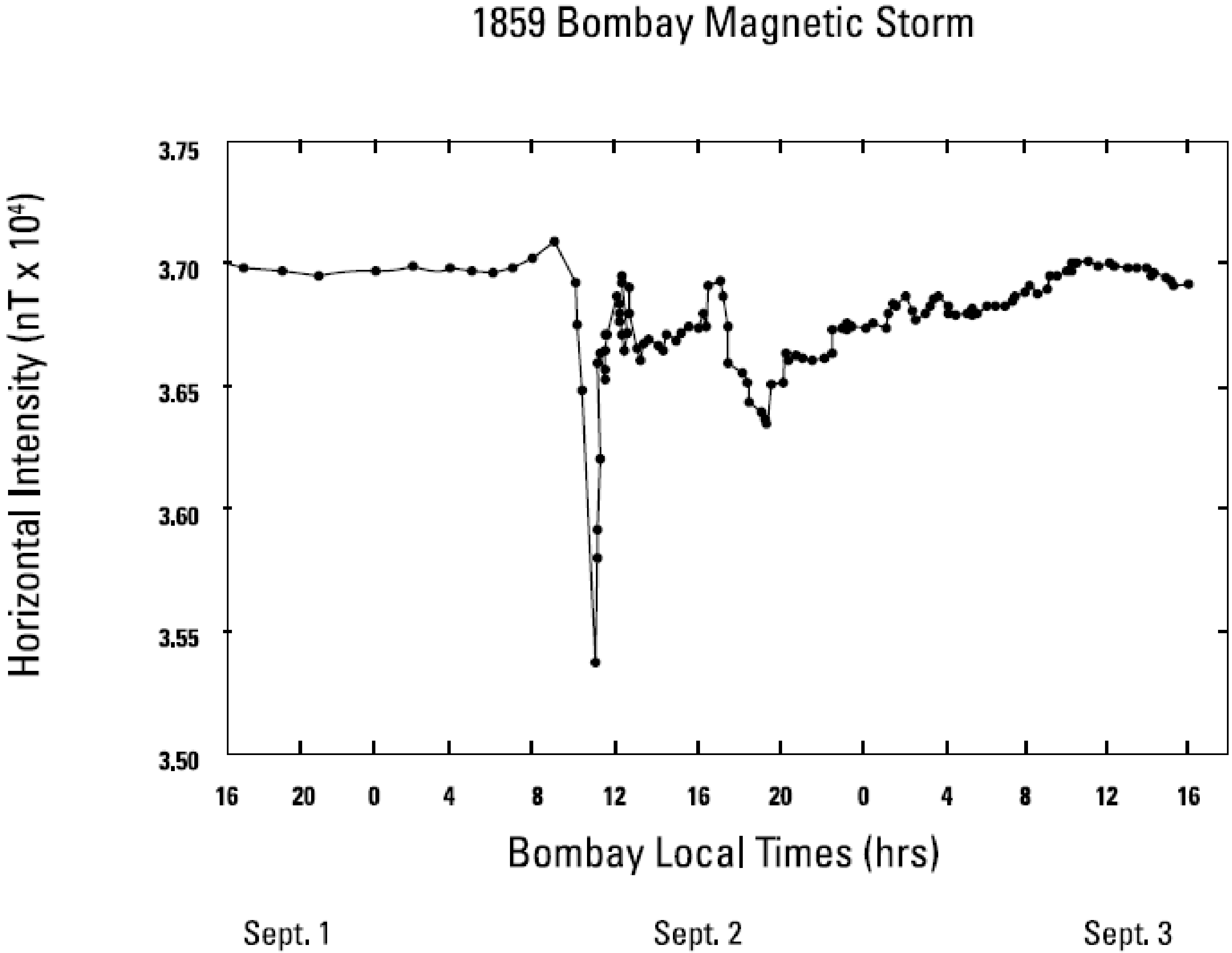
X40 flare => Peak Intensity (> 10 MeV) ~ 1-3 x 10^5 pfu

or Fluence (> 30 MeV) ~ 2-6 x 10^{10} pfu cm^{-2}

(scaled up by a factor of 10 for effect of shock)

Usoskin & Kovaltsov (2012): F(>30 MeV) ~ 2 x 10^{10} pfu cm^{-2}

Largest Geomagnetic Storm Ever Recorded



High-time resolution records for the 1859 event are only available from Bombay. These data indicated a Dst value -1760 nT …

Tsurutani et al. (2003)

Severe Geomagnetic Storms

D_{ST}
1957-1998

Date	D_{ST}
02 Sep 1859	-1760
13 Mar 1989	-589
15 Jul 1959	-429
13 Sep 1957	-427
11 Feb 1958	-426
25 May 1967	-387
08 Nov 1991	-354
13 Nov 1960	-339
08 Jul 1958	-330
01 Apr 1960	-327
14 Jul 1982	-325
30 Apr 1960	-325
13 Apr 1981	-311
08 Feb 1986	-307
23 Sep 1957	-303
04 Sep 1958	-302

aa_m*
(1868-1998)

Date	aa_m*
13 Mar 1989	450
18 Sep 1941	429
24 Mar 1940	382
15 May 1921	378
13 Nov 1960	372
17 Nov 1882	371
08 Jul 1928	344
15 Jul 1959	336
28 Mar 1946	325
31 Oct 1903	321
01 Apr 1960	314
25 Sep 1909	314
20 Nov 1882	309
17 Apr 1882	305
04 Aug 1972	302

… a value ~ 3 X less than that of the next greatest storm.

Cliver & Svalgaard (2004)

Critiques of the Bombay-based Dst estimate of -1760 nT for the 1859 storm

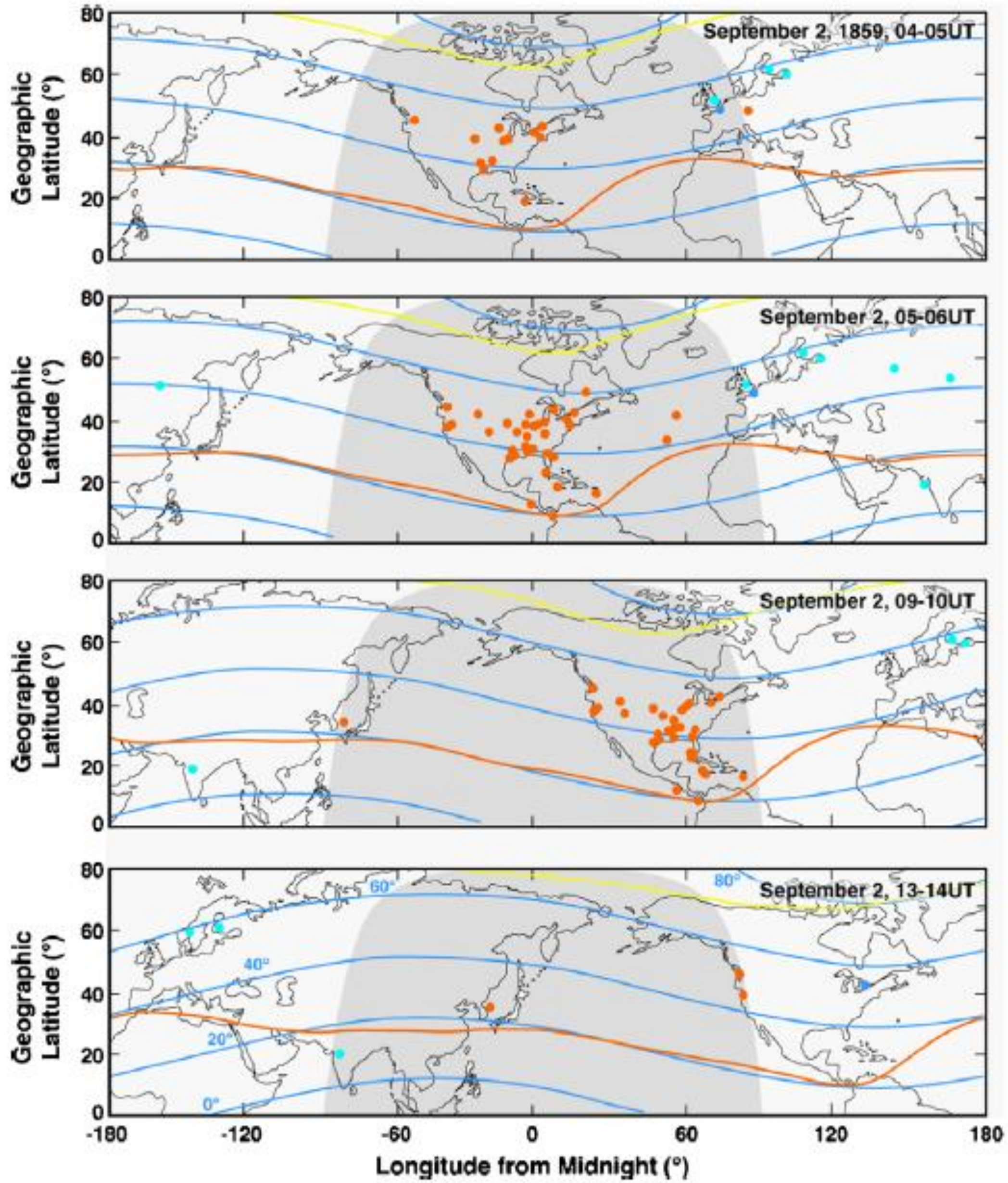
Kamide & Akasofu (2005): Single station, Rapid Recovery of storm

Siscoe et al. (2006): Not hourly-averaged; Ionospheric effect?

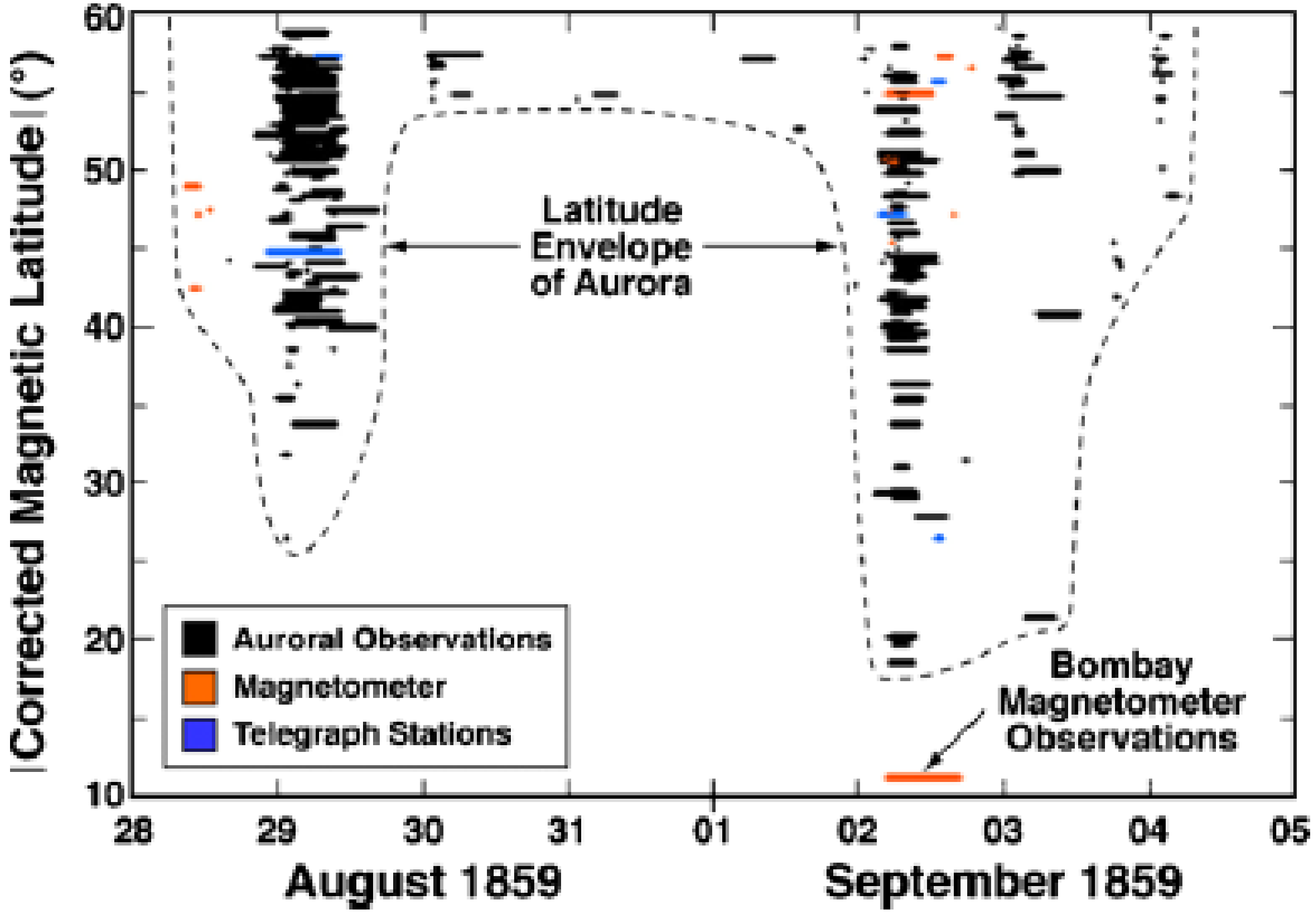
Green & Boardsen (2006): Auroral electrojet effect?

Aurora Australis 2 September 1859 $10^h\,26^m$ p.m.

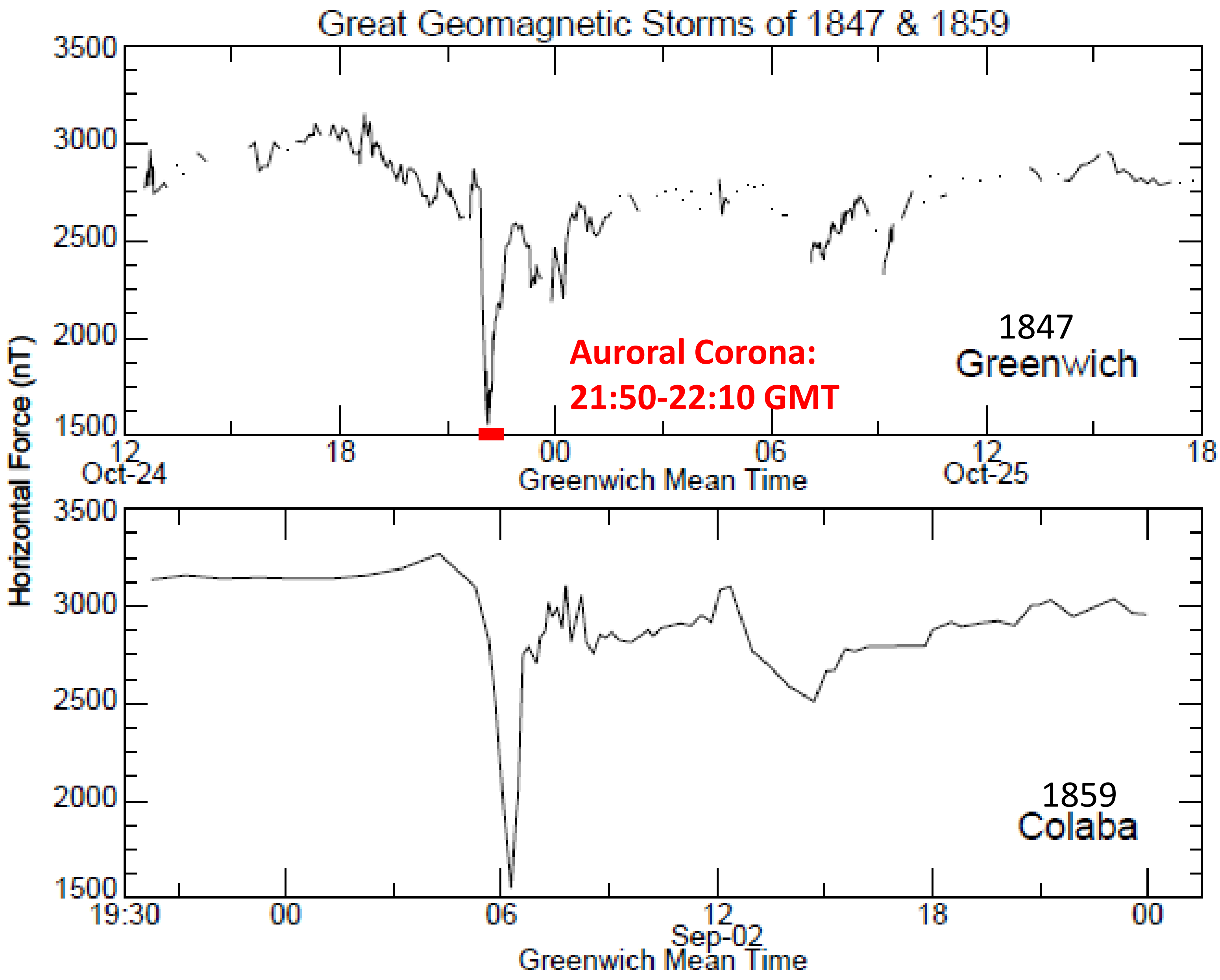
Extent of aurora in northern hemisphere for 1859 storm



Green & Boardsen (2006)



Green & Boardsen (2006)



The rapid recovery of the 1859 storm at Colaba is similar to the auroral effect observed for a great storm at Greenwich in 1847

Recent Estimates of Minimum Dst for the 1859 Storm

Peak Dst (nT)	Technique/Basis	Reference
-625	Modified Burton Equation[1,2]	Siscoe et al. (2006)
-850	Colaba Magnetogram	Siscoe et al. (2006)
~ -700	Temerin and Li Dst Model[3]	Li et al. (2006)
-1050	Colaba Magnetogram	Gonzalez et al. (2011)
-1160	Burton Equation	Gonzalez et al. (2011)
~-950	Average of empirical values	Working estimate

Notes: 1 = Burton et al. (1975); 2 = O'Brien and McPherron (2000); 3 = Temerin and Li (2002)

Vasyliunas (2012) estimate of largest possible storm: ~-2500 nT

Observed & Estimated Limits of Space Weather Activity

	Observed	**Estimated**
Flare	~X30 (~X40)	~X40
Minimum Transit Time	~14 hrs	?
> 10 MeV SEP Flux	~4 x 10^4 pfu	~1-3 x 10^5 pfu
> 30 MeV SEP Fluence	~5 x 10^9 pfu	2-6 x 10^{10} pfu cm^{-2}
Minimum Dst	-950 nT	~-1000 / ~-2500 nT