Extreme Solar Eruptions and their Space Weather Consequences

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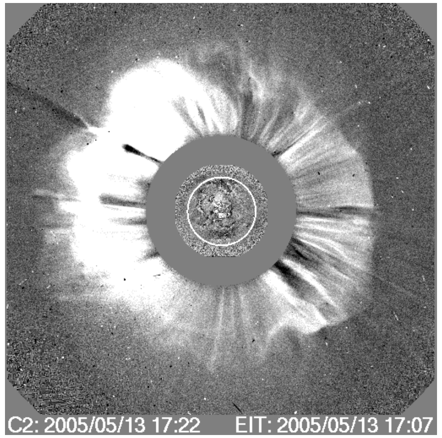
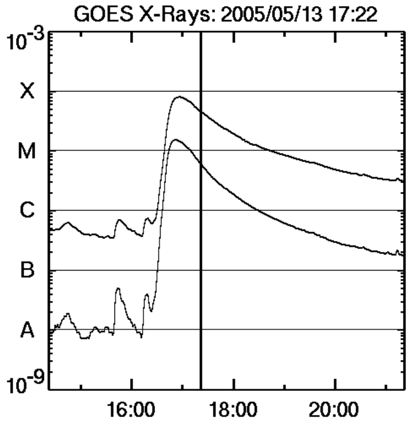
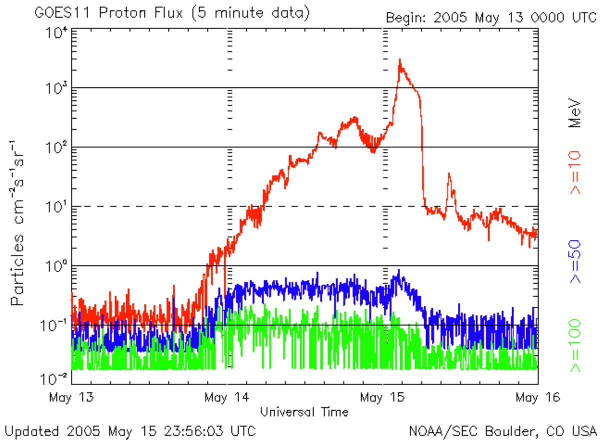
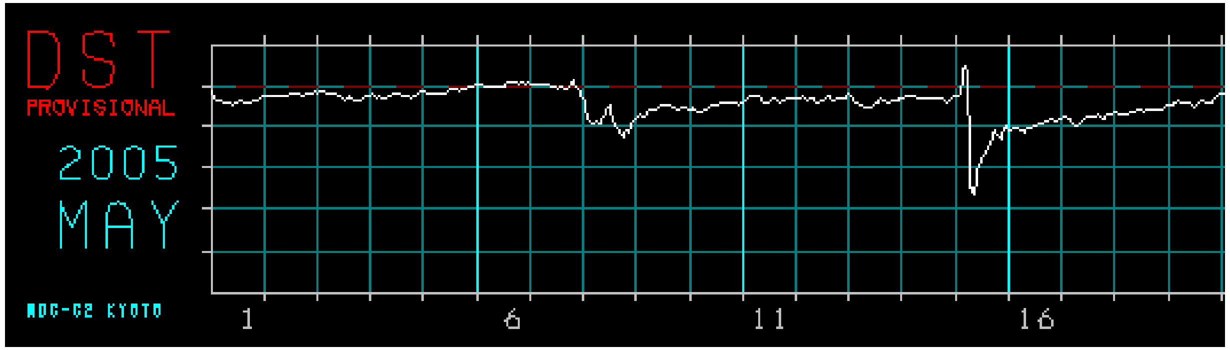








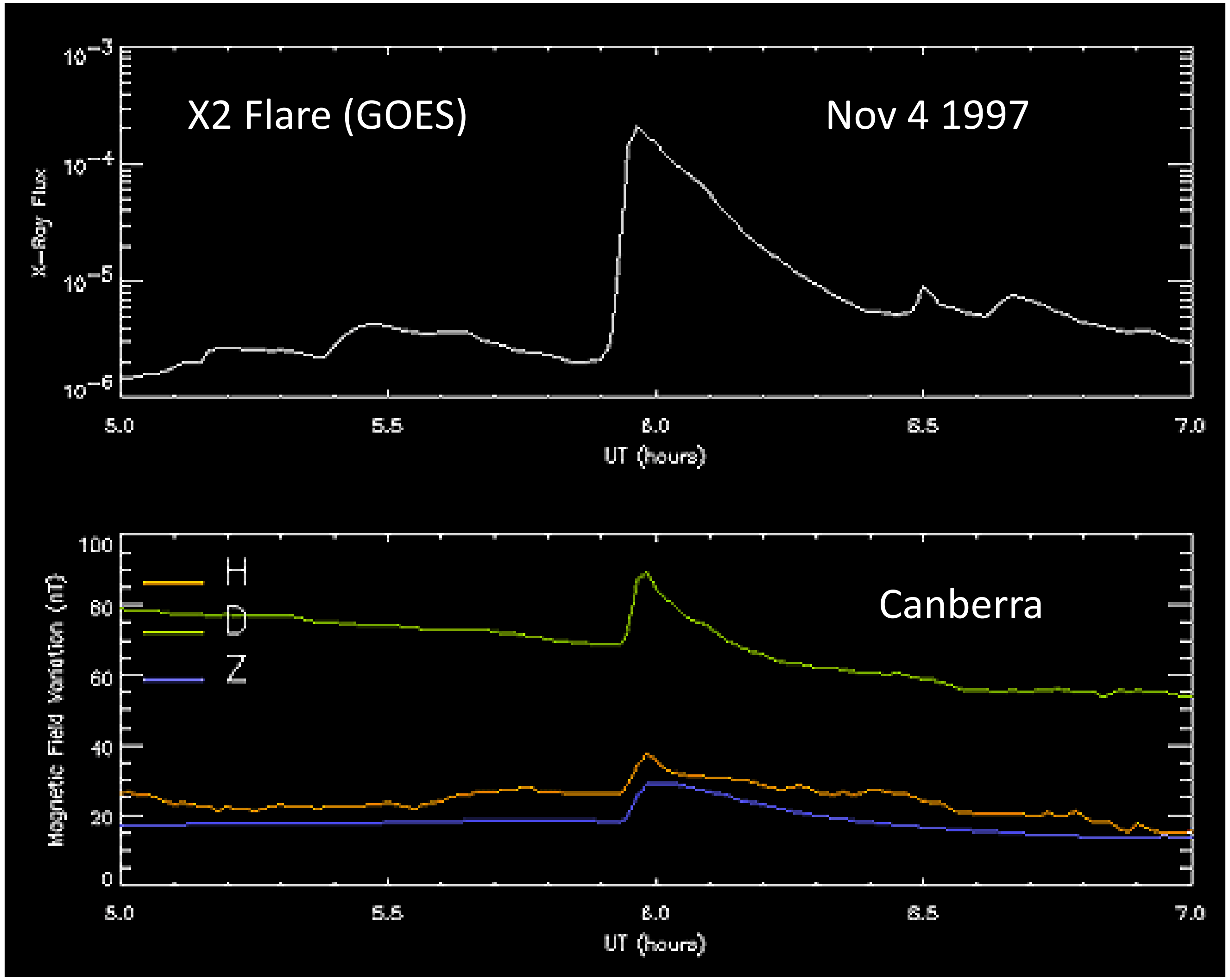
ISWI Workshop Nov 2-4, 2021

What is an Extreme Event?

- Event on the tail of a distribution
- An occurrence singularly unique either in the occurrence itself or in terms of its consequences
- Occurrence: CME, flare (active region size, magnetic content)
- Consequences: SEP events, Magnetic storms
- Tail: The mechanism does not change; consider 100- and 1000-year events
- Black Swans (outlier, **extreme impact**, hindsight bias) & Dragon Kings (outlier, extreme impact, different mechanism in tail)

Familiar extreme events: earthquakes, volcanic eruptions, wildfires, landslides, floods

Magnetic Crochet: Solar Flare Effect on Earth's Magnetic Field

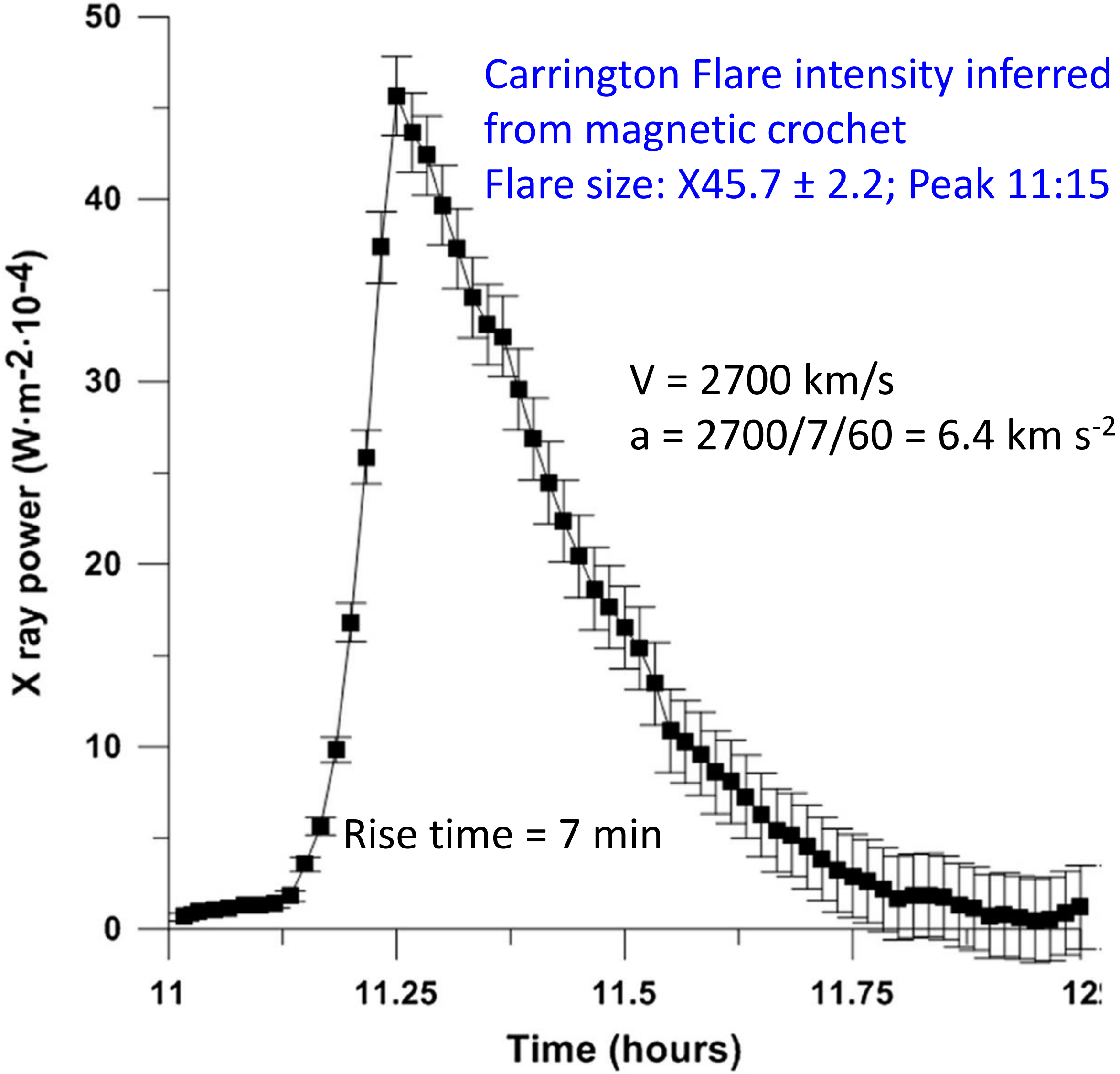


- Flares: increased ionization in the D and E layers
- Enhanced conductivity → enhanced current resulting in the new magnetic field
- Only observed during large flares, especially when the rise time is short

Flares can be also be detected by
- GNSS receivers (Curto et al. 2020)
- VLF receivers (Raulin et al. 2010)

R. Thompson, IPS

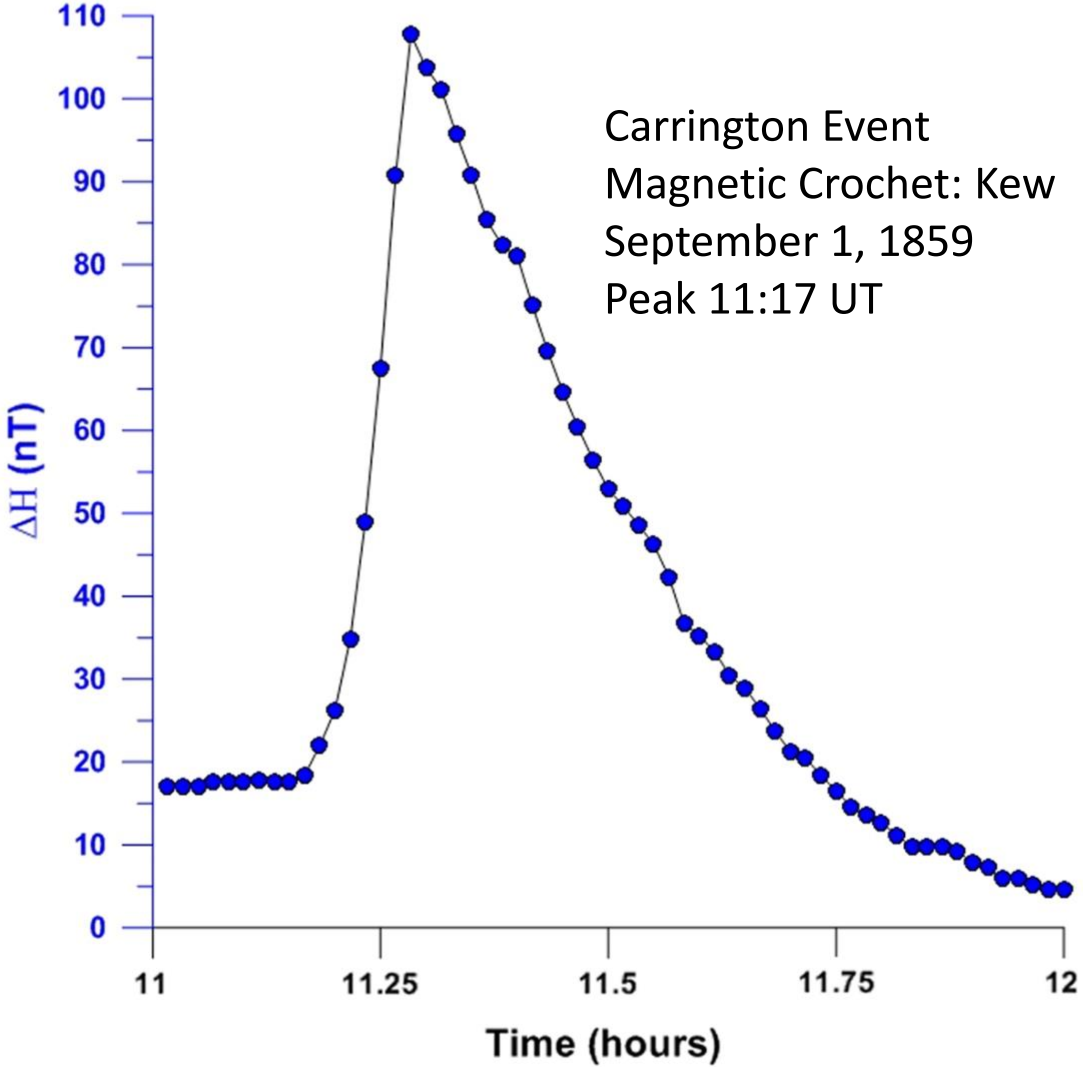
$$\frac{\mathrm{d}B(t)}{\mathrm{d}t} = \alpha \frac{\mathrm{d}X(t-a)}{\mathrm{d}t} + \beta \frac{\mathrm{d}U(t-b)}{\mathrm{d}t} + \sigma.$$



Carrington Flare intensity inferred from magnetic crochet
Flare size: X45.7 ± 2.2; Peak 11:15 UT

V = 2700 km/s
a = 2700/7/60 = 6.4 km s^{-2}

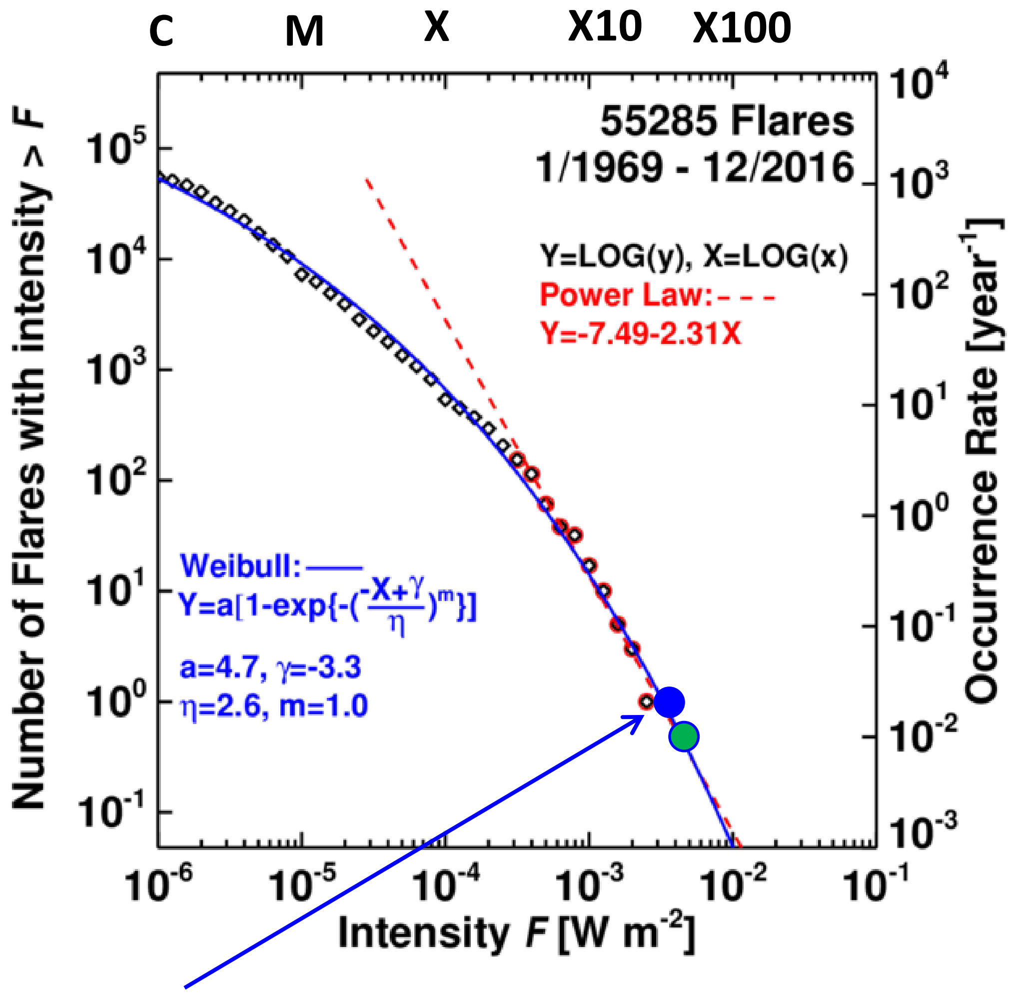
Rise time = 7 min



Carrington Event
Magnetic Crochet: Kew
September 1, 1859
Peak 11:17 UT

Curto et al. 2016

Flare Intensity in X-rays (1 – 8 Å)



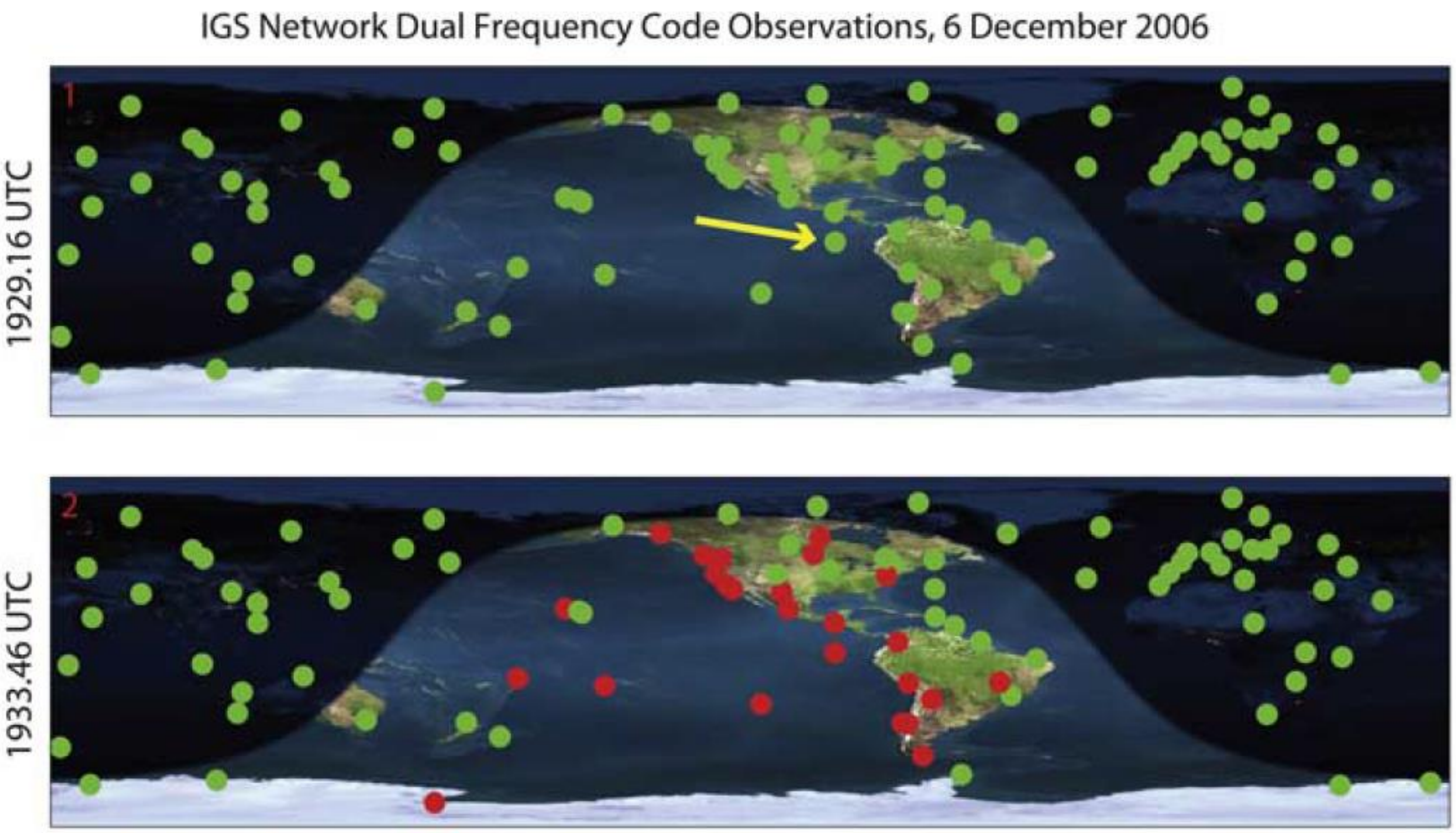
- SOLRAD, GOES Data since 1969
- The corrected size of the 2003/11/04 Flare: X34–X48, average ~ X40 (Brodrick et al. 2005)
- Carrington flare size: X42 – X48, nominal value of X45 (Cliver and Dietrich 2013)
- Weibull distribution: X43.9 (100-year); X101 (1000-year)
- Power law distribution: similar flare sizes: X42 and X115
- X100 → 10^{33} erg (super-flare threshold)
- A 10^{34} erg flare can occur once in 125,000 yr

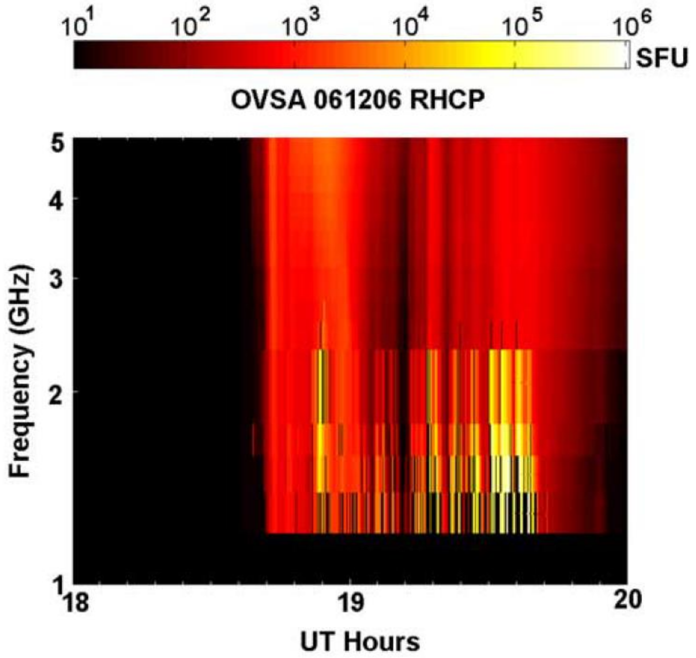
The 4 November 2003 flare at 19:29 UT has the highest intensity of 2.8×10^{-3} W m^{-2} (X28); corrected intensity ~ X40

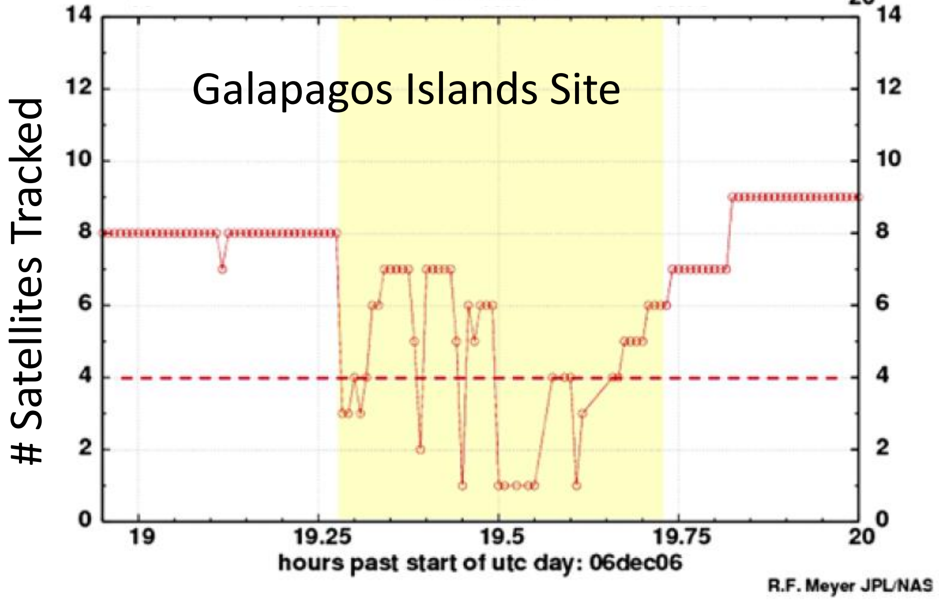
Gopalswamy 2017

Solar Radio Burst Affecting GPS

Microwave bursts are due to electrons accelerated in flaring regions



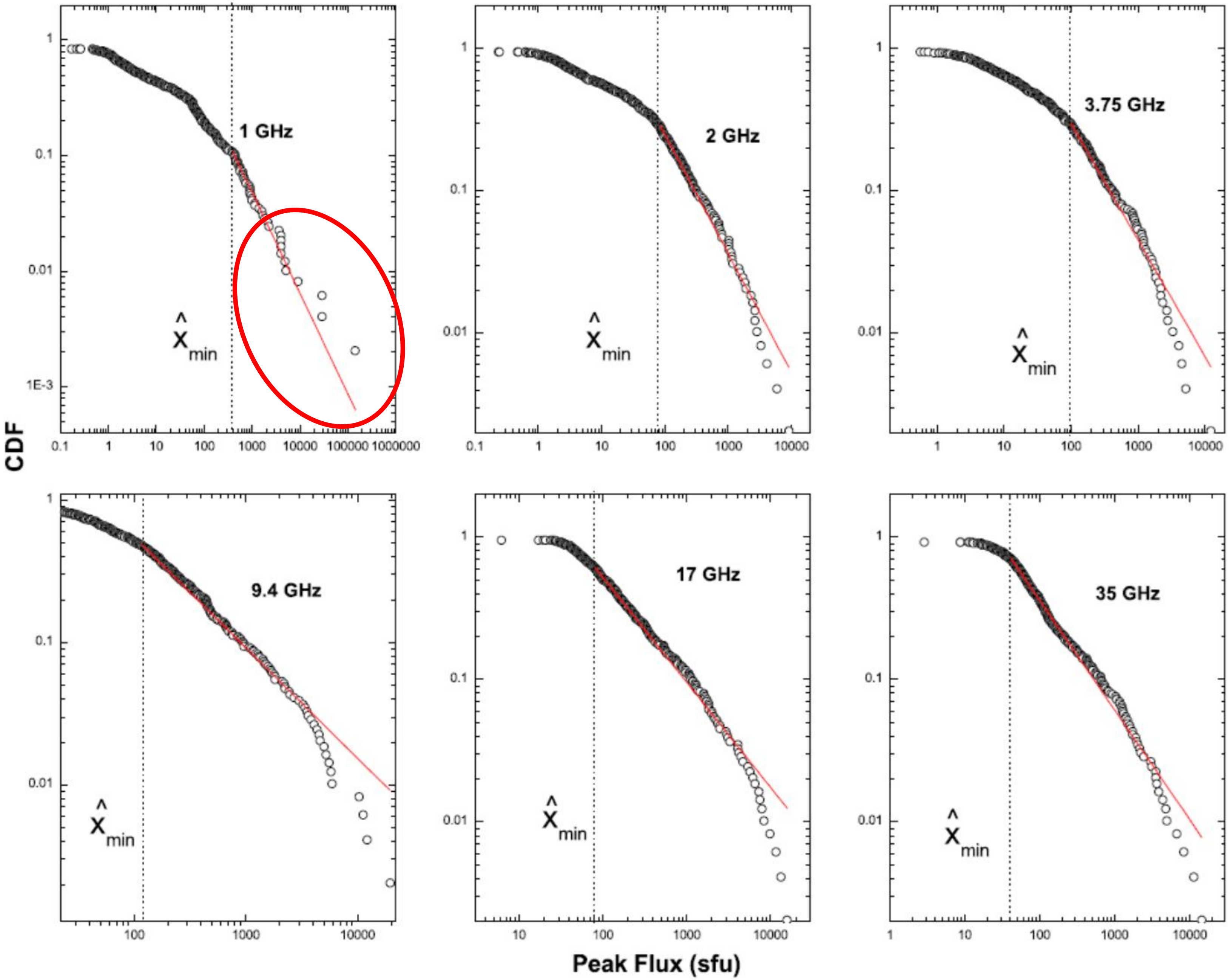




- Solar Radio Bursts affect the entire sunlit hemisphere
- Different from the frequent but localized ionospheric irregularities
- Civilian dual frequency GPS receivers were the most severely affected

Corrections require ≥4 satellites tracked

Cerruti et al. 2008 SpaWea

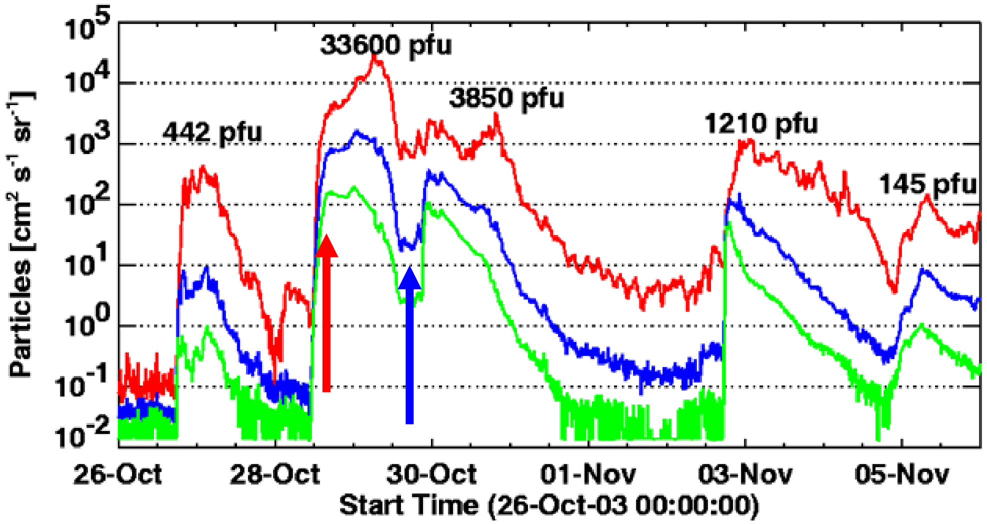


Song et al. (2012)

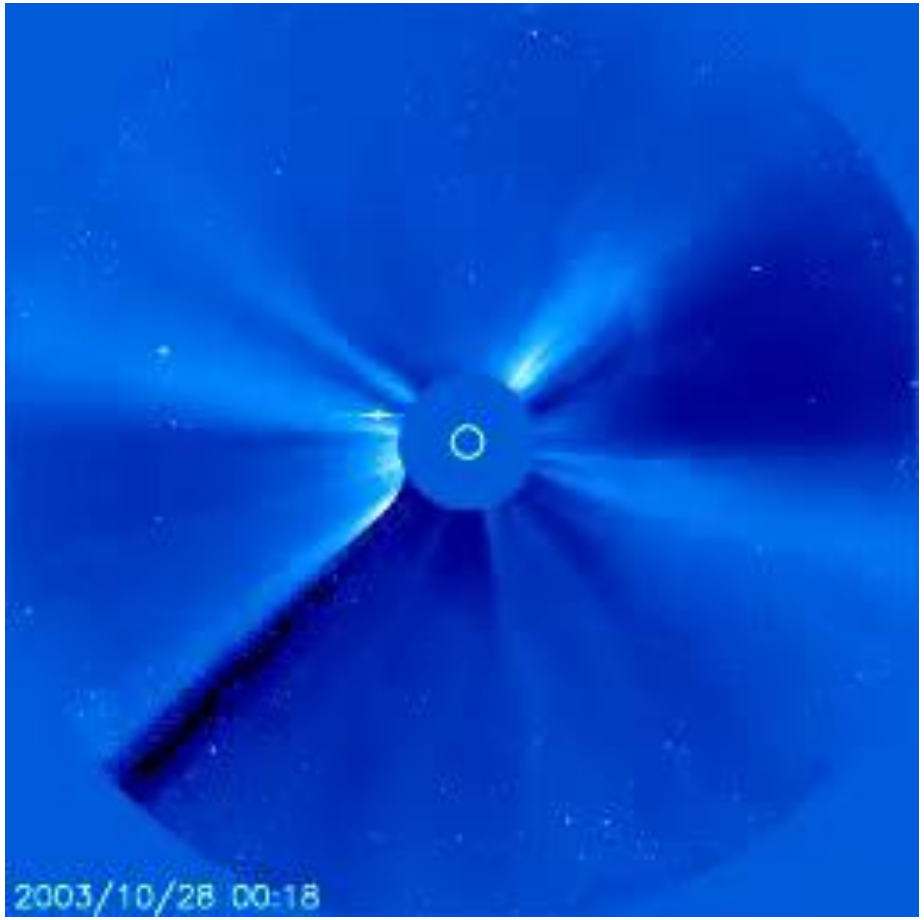
- Cliver (2021) points to the 1 GHz spectrum different from others
- There seems to be an additional mechanism different from the one that produces spectra at other frequencies (dragon king events)
- One possibility is that appropriate flare conditions (B, n) exits for electron cyclotron maser frequencies around 1 GHz

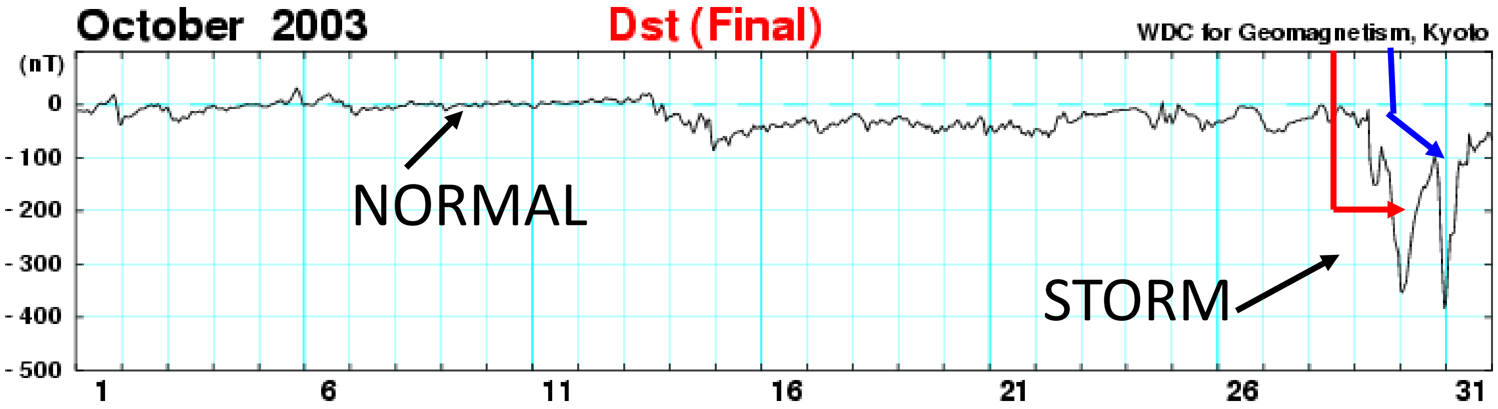
Extreme Event Examples: Halloween Storms

- Fast transit
- Double whammy
- Intensity of historical proportions



Two halo CMEs: 10/28 and 10/29 2003





NORMAL

STORM

http://wdc.kugi.kyoto-u.ac.jp/dstdir/

Movie from https://cdaw.gsfc.nasa.gov/CME_list

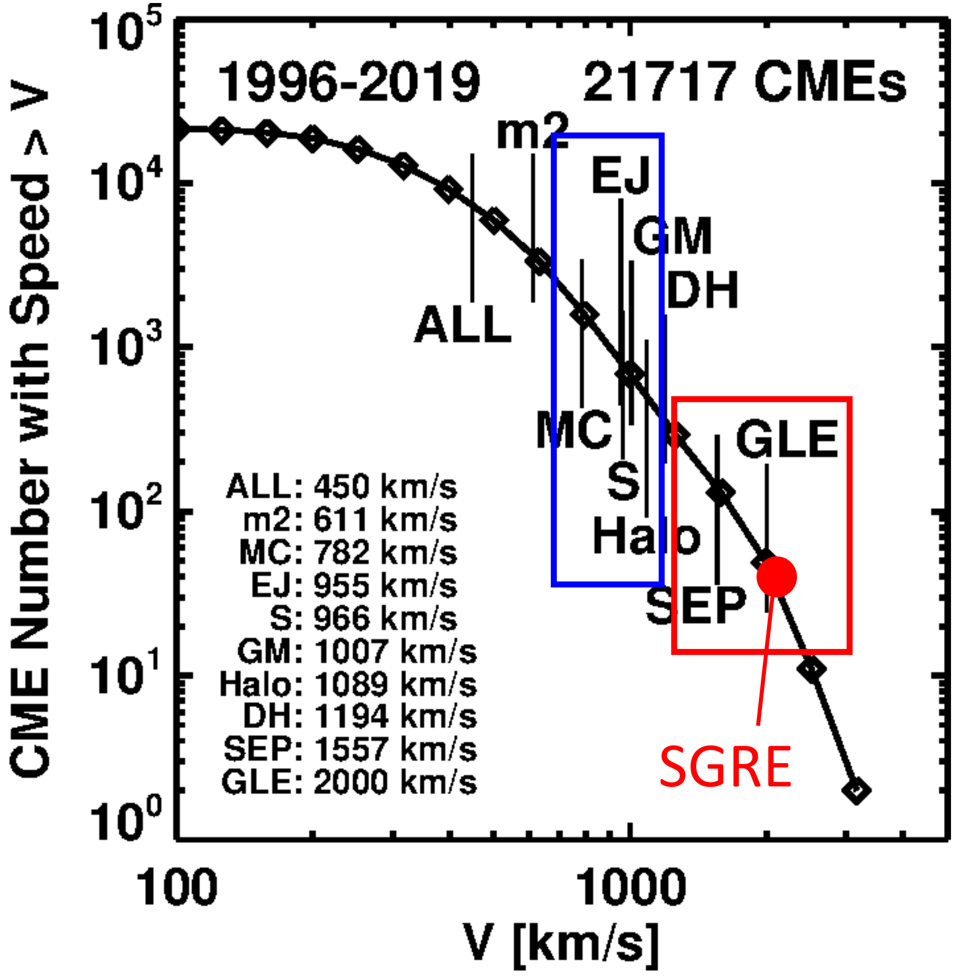
SOHO/LASCO

Significant CMEs & their Consequences

Cycle 23 – 24 CMEs from SOHO/LASCO

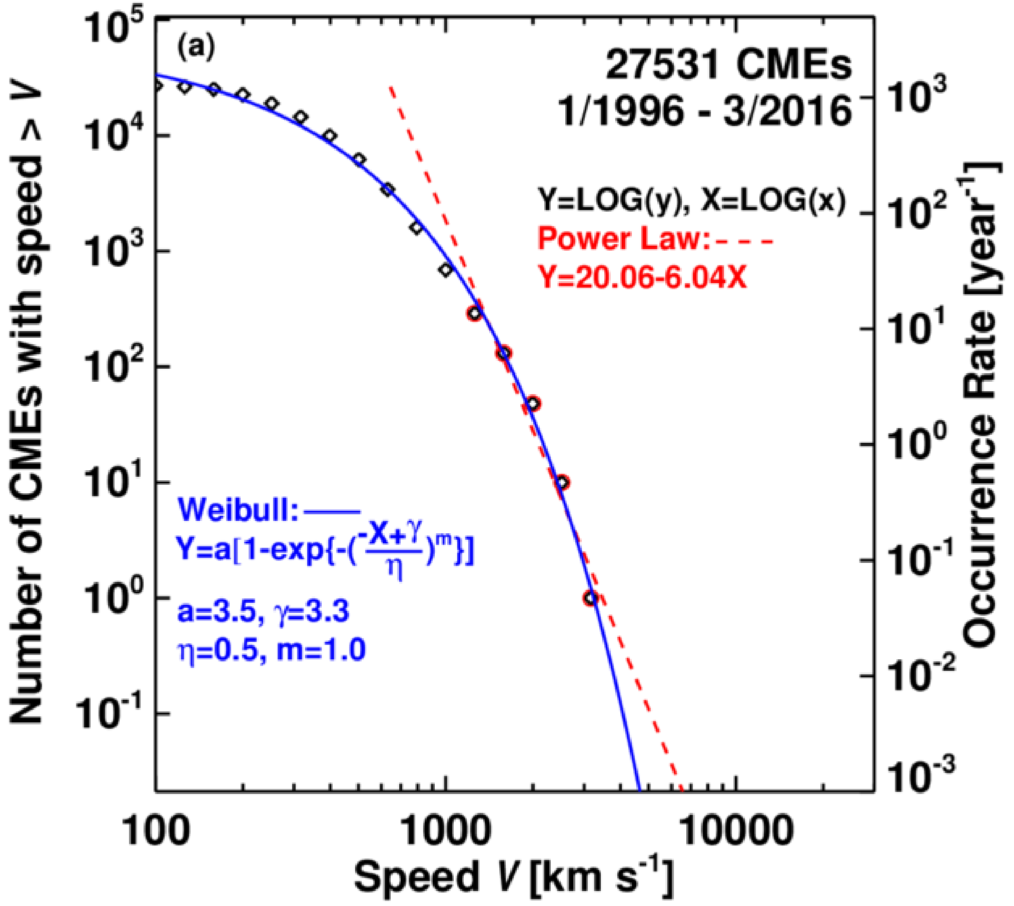
m2 – Metric type II
MC – Magnetic Cloud
EJ – Non-cloud Ejecta
S – Interplanetary shock
GM – Geomagnetic storm ↙
Halo – Halo CMEs
DH – Type II at λ 10-100 meters
SEP – Solar Energetic Particles ↙
GLE – Ground Level Enhancement
SGRE – Sustained γ-Ray Emission

Gopalswamy, 2006; 2010 (updated)

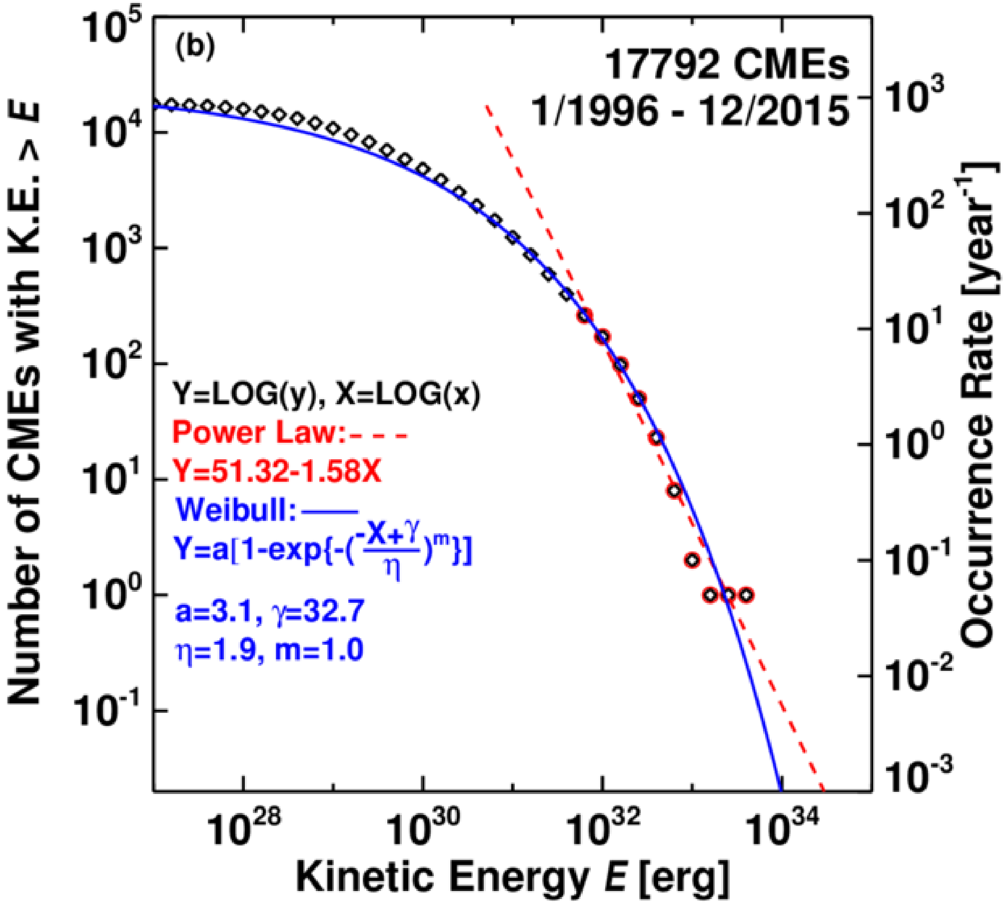


Plasma impact   Energetic particles

CME Speed and Kinetic Energy



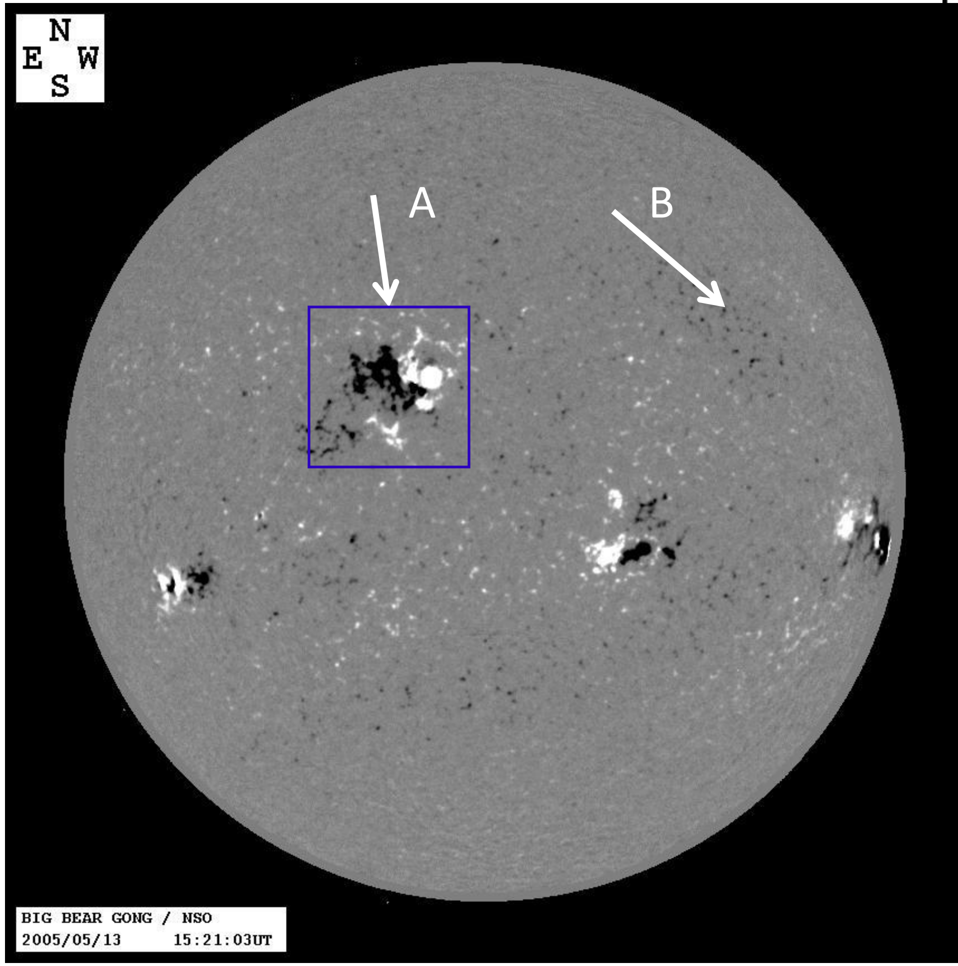
100-year: 3800 km/s
1000-year: 4700 km/s



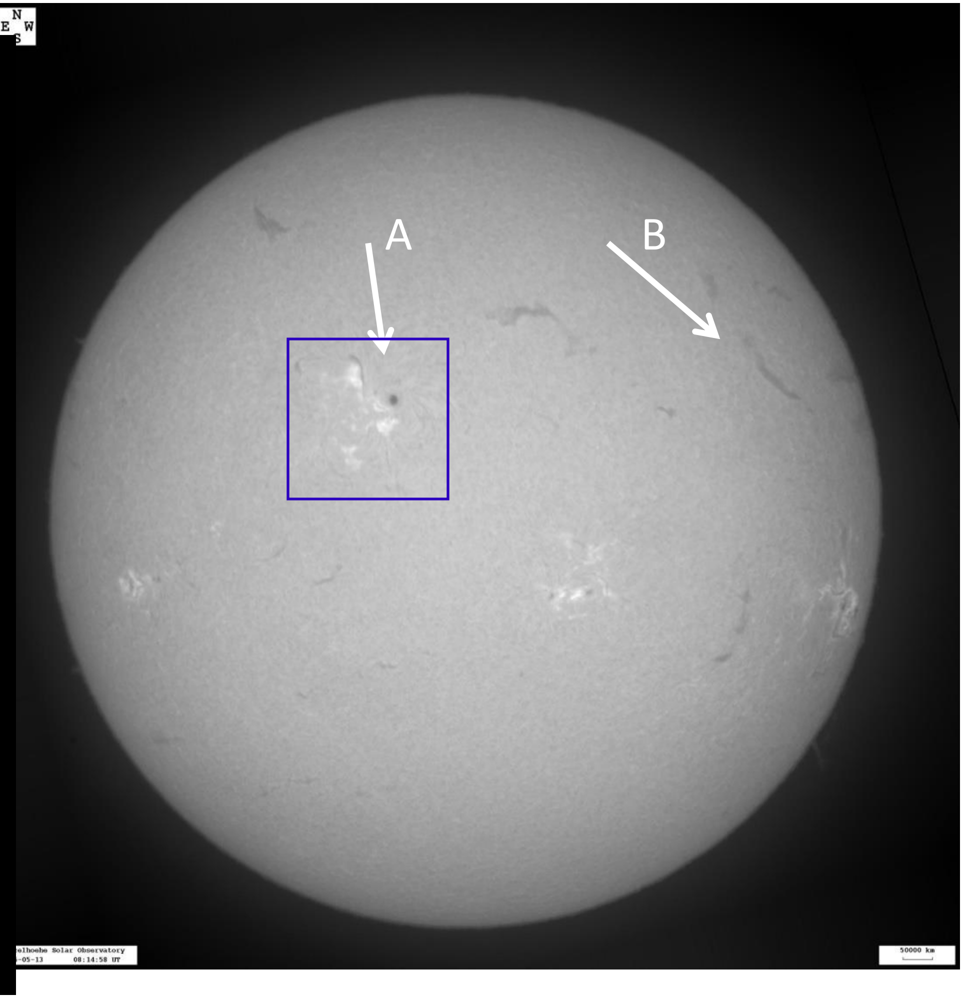
100-year: 4.4×10^{33} erg
1000-year: 9.8×10^{33} erg

CME Source Regions

Photospheric Magnetogram



Chromosphere (H-alpha)

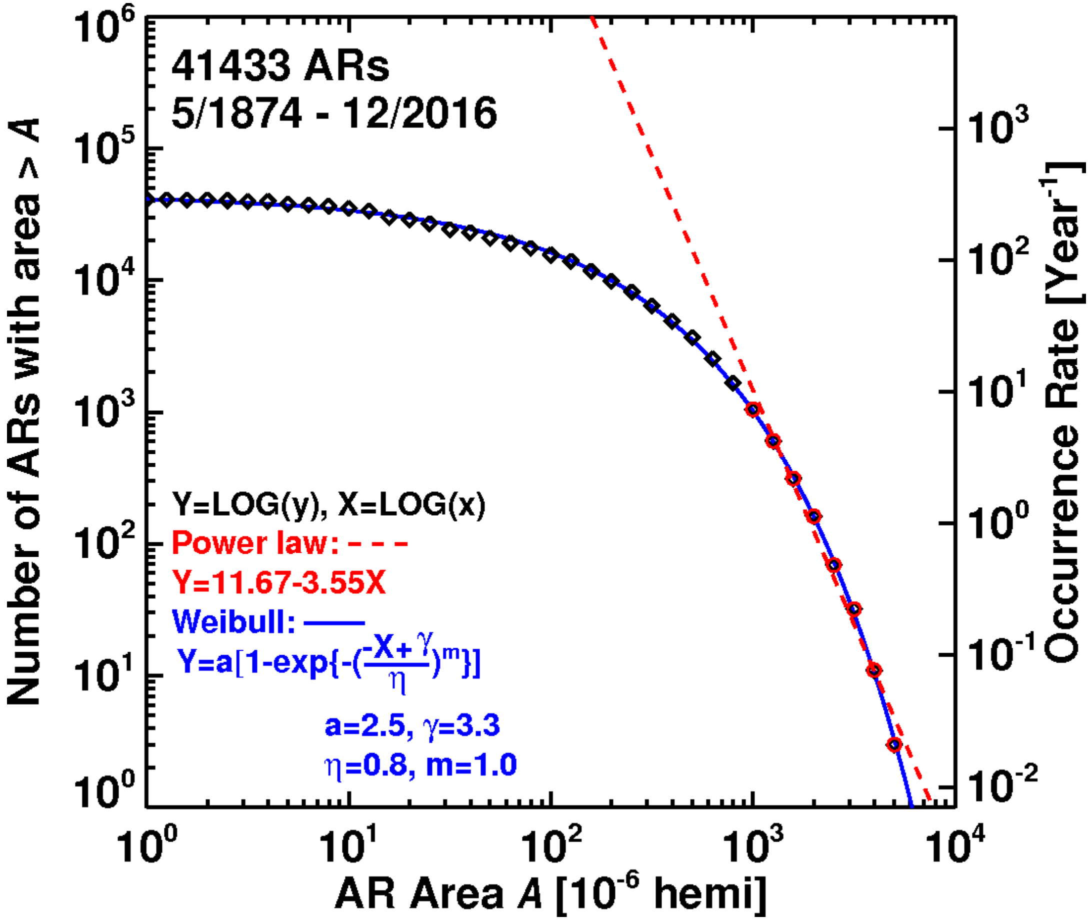


A: active region

B: Filament region (also bipolar, but no sunspots)

Both regions have filaments along the polarity inversion line

Sunspot Group Area

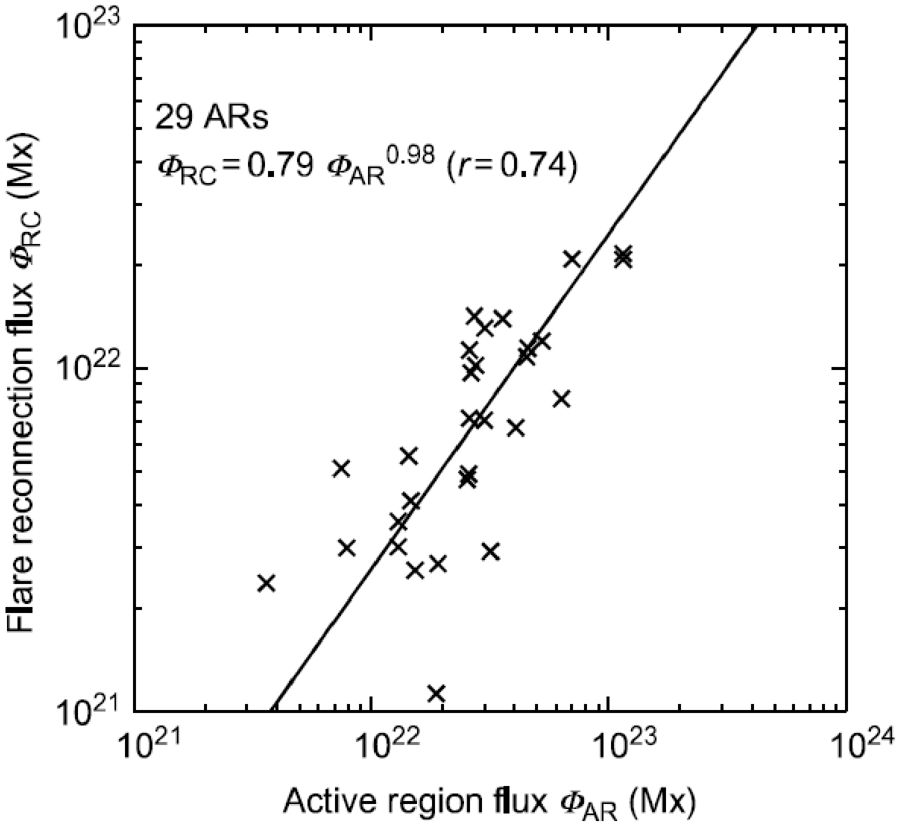


- A 100-year AR has an area of ~7000 msh (power law) and ~5900 msh (Weibull function)
- The area of April 1947 AR (6132 msh) is similar to a 100-year event
- Max field strength ~6100 G (Livingston et al. 2006)
- Max Potential energy ~ $(B^2/8\pi)A^{1.5}$ = 3.8 ×10^{36} erg
- AR Flux = 1.2 ×10^{24} Mx
- Free energy ~0.3 MPE ~ 1.2×10^{36} erg

Maximum observed area was 6132 msh (SC 18) in 143 yr

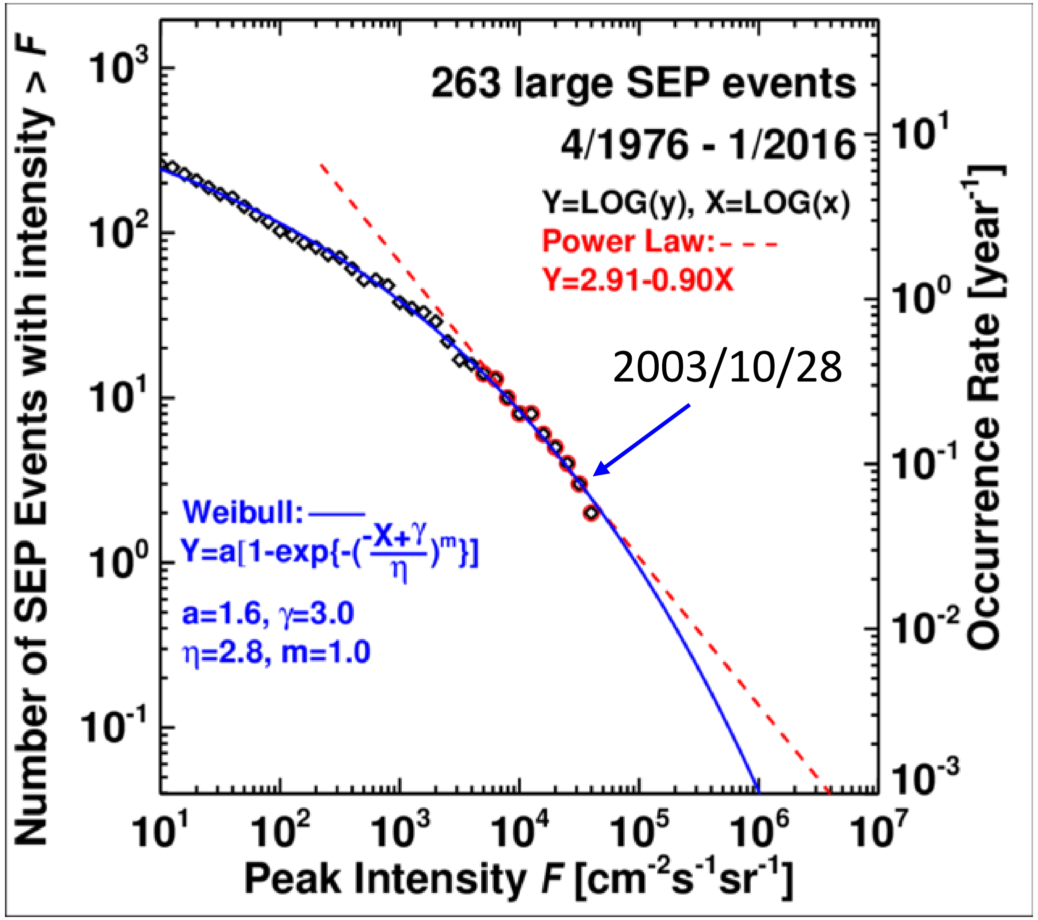
1 msh = 3.077x 10^{16} cm^2

AR Flux vs. Reconnected Flux



- B = 6100 G, A = 6132 msh (6132x3.07×10^{16} cm^2).
- AR flux Φ_{AR} is ~1.2×10^{24} Mx.
- $\Phi_{RC} = 0.79\Phi_{AR}^{0.98}$ gives (plot)
- Φ_{RC} ~3.0×10^{23} Mx,
- CME KE = $0.19(\Phi_{RC})^{1.87}$ (Gopalswamy et al. 2017); Φ_{RC} in 10^{21} Mx; KE in 10^{31} erg
- KE = 8.2×10^{34} erg (not the maximum)
- An order of magnitude larger than a 1000-year event

Peak SEP Intensity

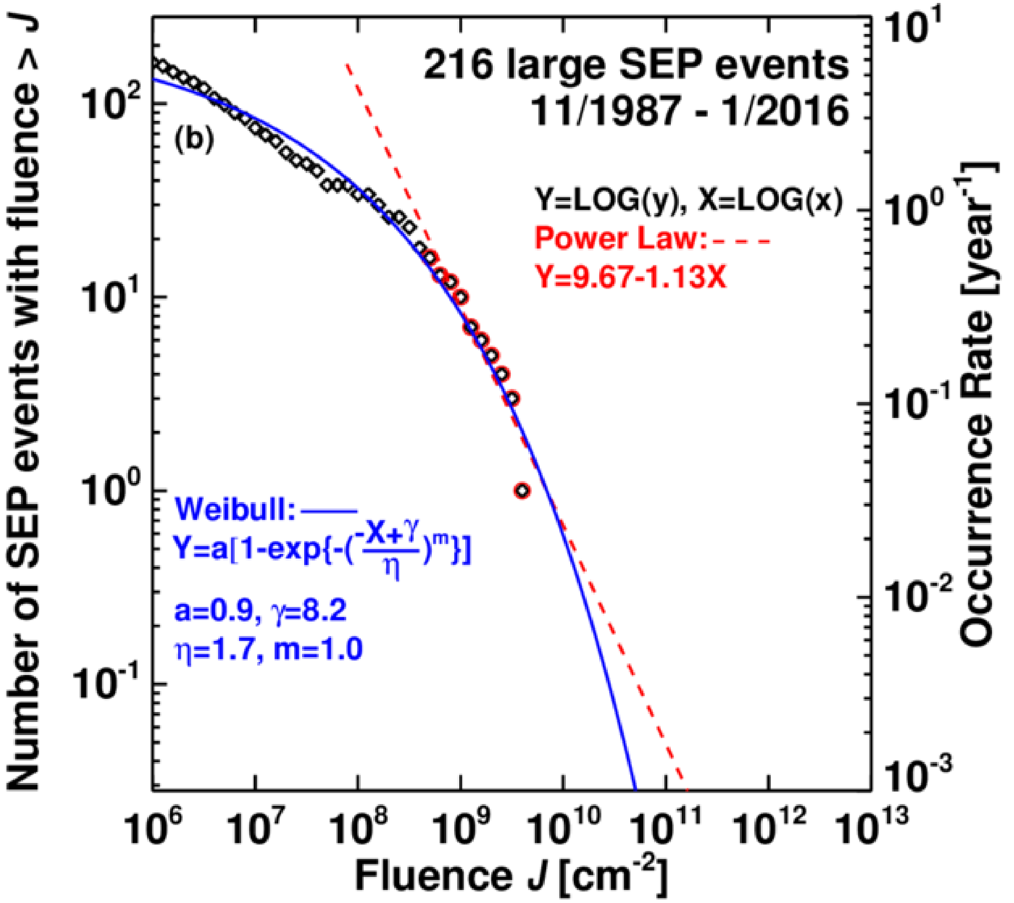


100-year: 2.04×10^5 pfu; 1000-year: 1.02×10^6 pfu

The 23 March 1991 SEP event has the highest peak intensity of 4.3×10^4 cm^{-2} s^{-1} sr^{-1}.
The 100-year event is 5 times larger than this event

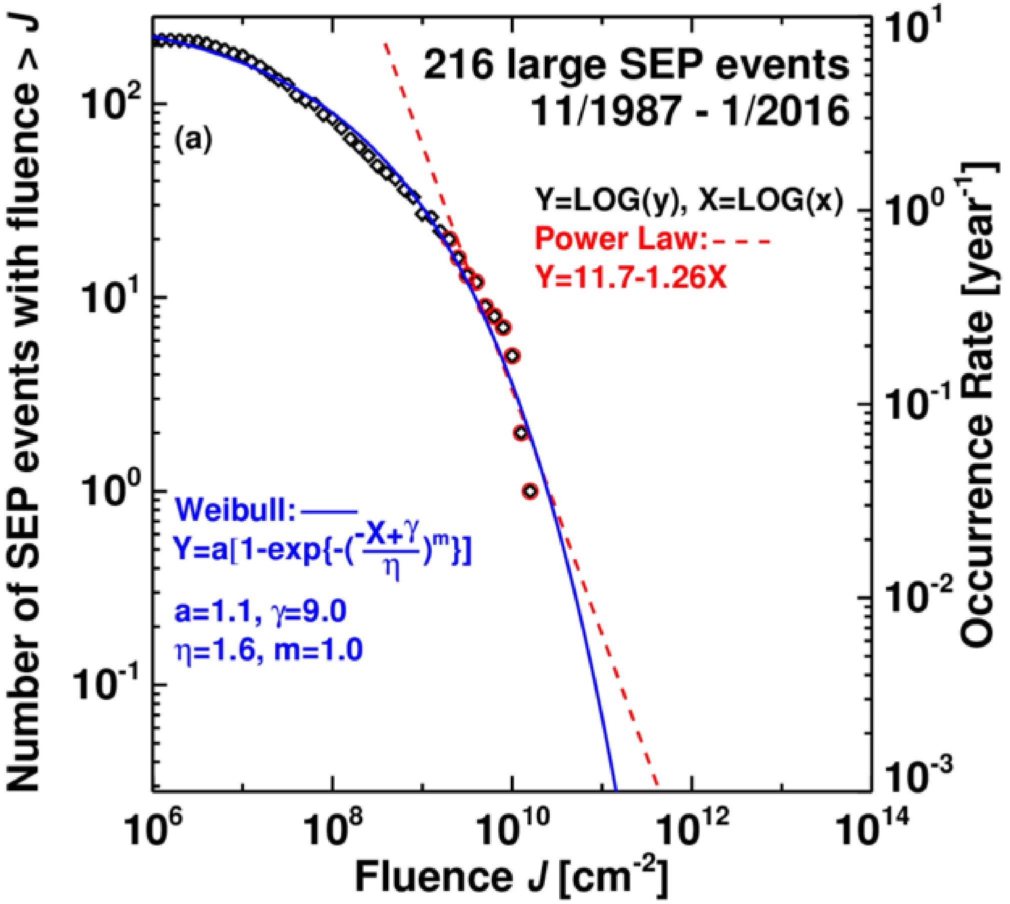
Fluence

>30 MeV



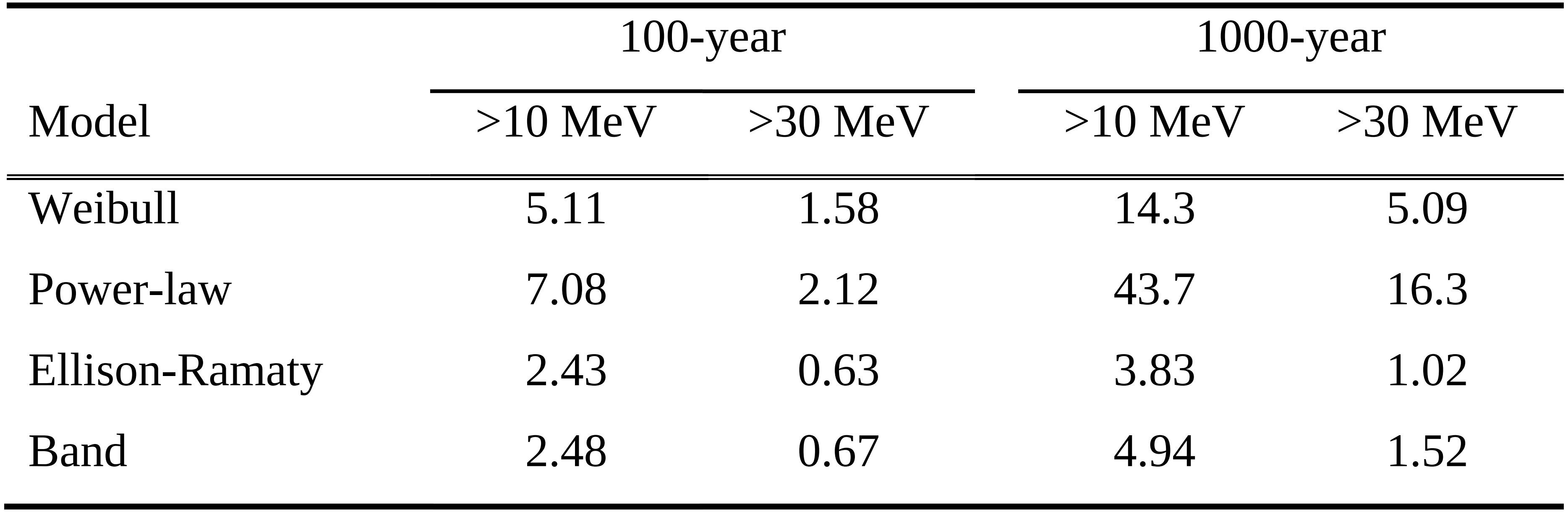
100-year: 1.6×10^{10} p cm^{-2}; 1000-year: 5.9×10^{10} p cm^{-2}

>10 MeV



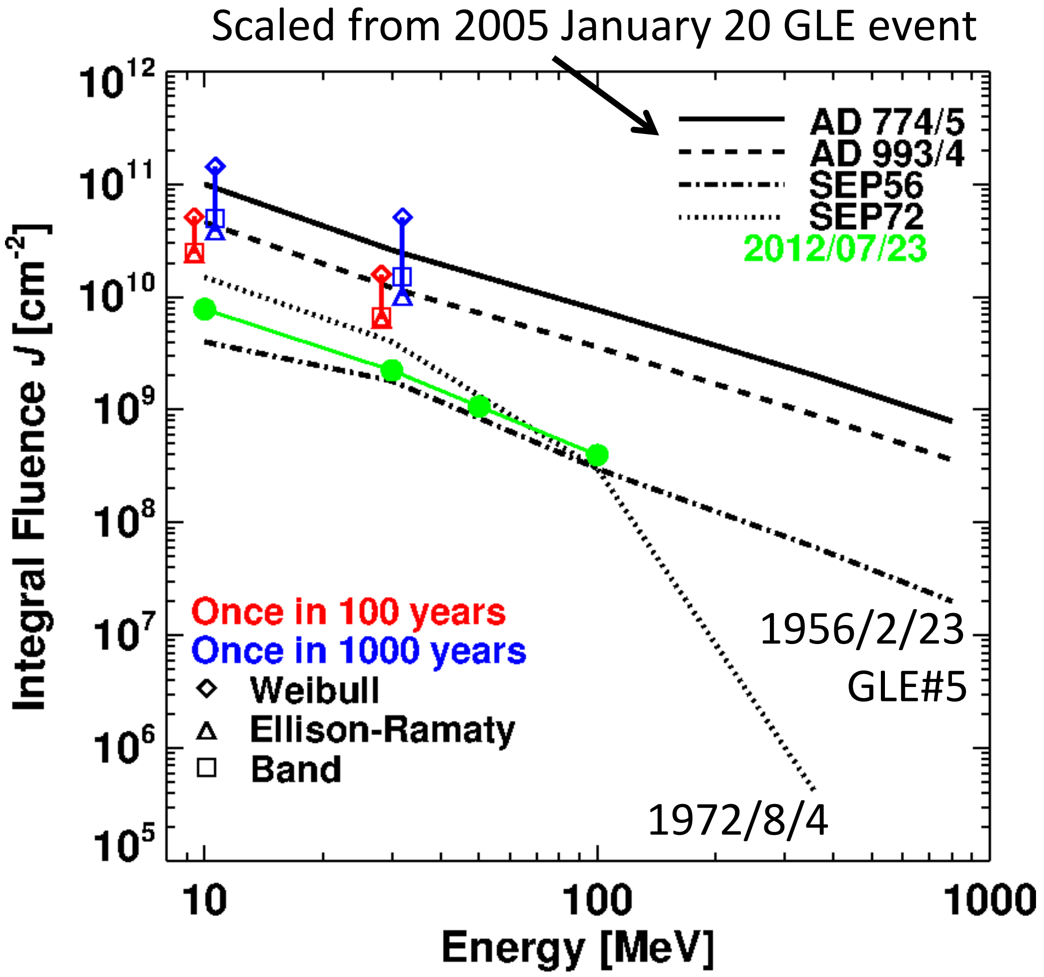
100-year: 5.1×10^{10} p cm^{-2}; 1000-year: 1.4×10^{11} p cm^{-2}

Integral Fluences for Different Model Fits (in units of 10^{10} p cm^{-2})



	100-year		1000-year	
Model	>10 MeV	>30 MeV	>10 MeV	>30 MeV
Weibull	5.11	1.58	14.3	5.09
Power-law	7.08	2.12	43.7	16.3
Ellison-Ramaty	2.43	0.63	3.83	1.02
Band	2.48	0.67	4.94	1.52

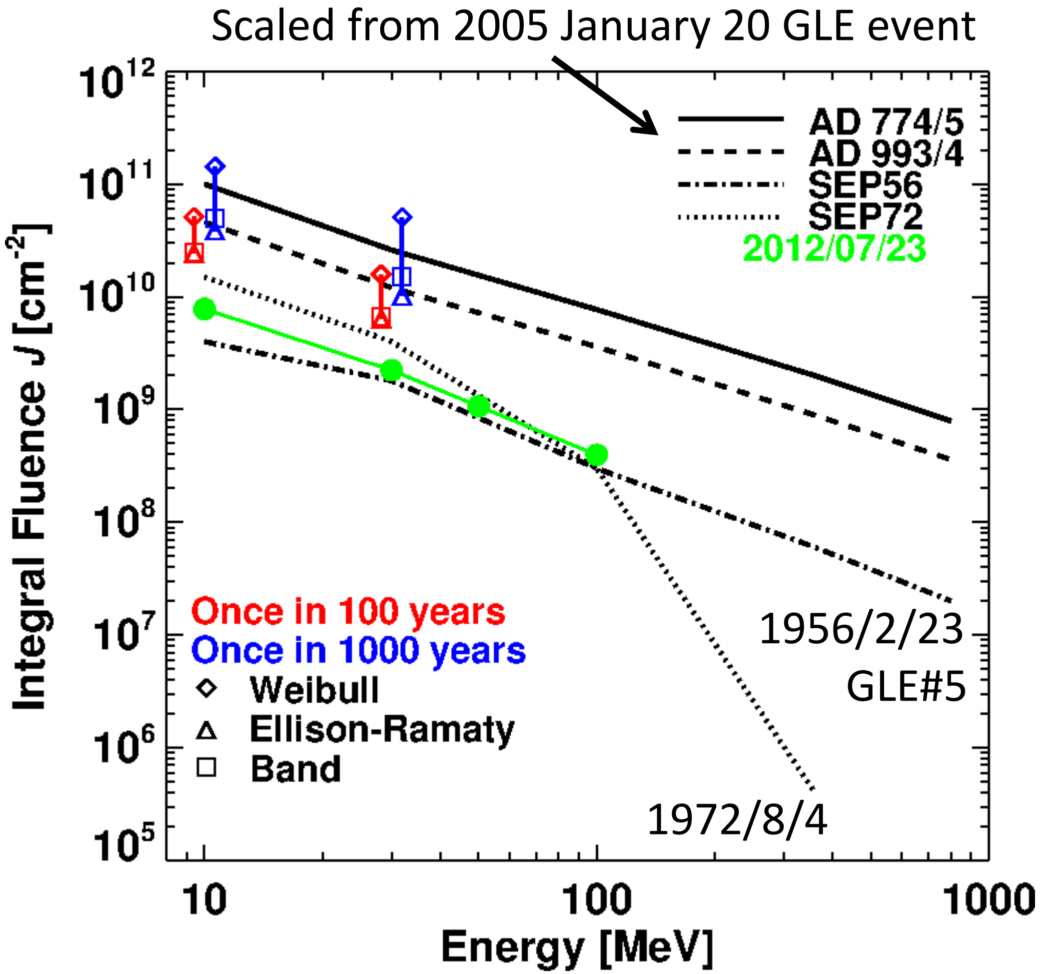
Fluence Spectra of Miyake Particle Events

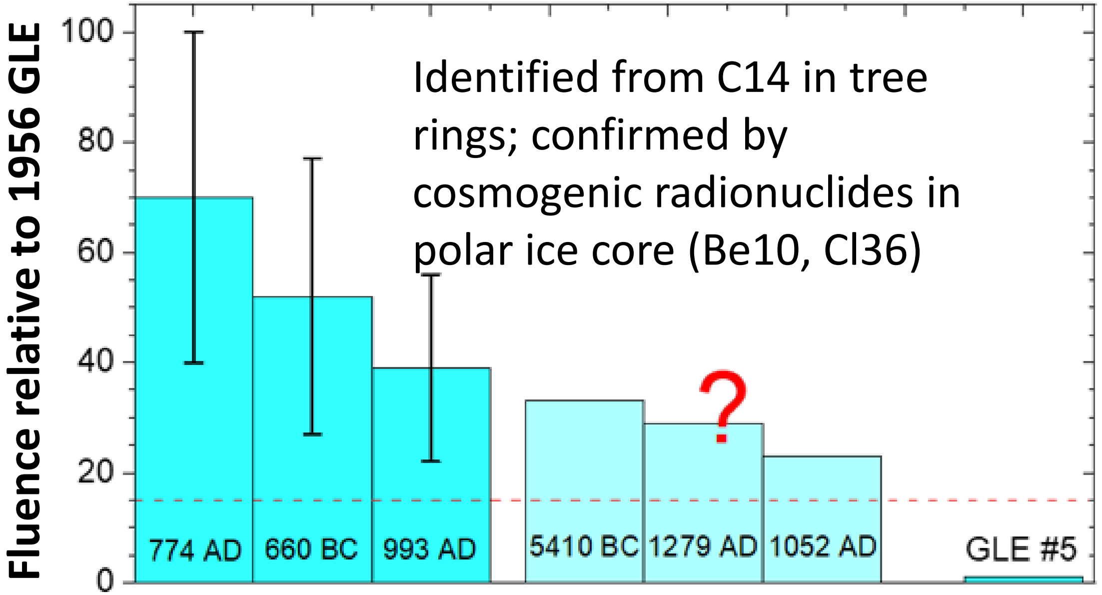

Scaled from 2005 January 20 GLE event

- Large SEP events were identified from CEDAR tree rings that occurred in AD 774/5 and AD 992/3 (Miyake et al. 2013)
- 1000-year fluences in the >10 MeV and >30 MeV ranges from Weibull distribution cover the AD774/5 and AD 992/3 events
- Two-point slopes are consistent with the spectra pf known SEP events
- AD774/5 and AD 992/3 events are consequences of SEP events
- The 2012 July 23 Backside Event at STEREO-A shows that extreme events can occur in weak sunspot cycles

Miyake et al. 2013; Mekhaldi et al. 2015; Usoskin 2017; Gopalswamy et al. 2016

SEP peak flux (>10 MeV) can be much higher


Scaled from 2005 January 20 GLE event


Identified from C14 in tree rings; confirmed by cosmogenic radionuclides in polar ice core (Be10, Cl36)

SEP event hypothesis bolstered by recent identification of five new candidate historical events, including two 774-class events (5259 BC, 7176 BC; Brehm et al., 2021)

Cliver 2021
Miyake et al. 2012
Mekhaldi et al. 2015

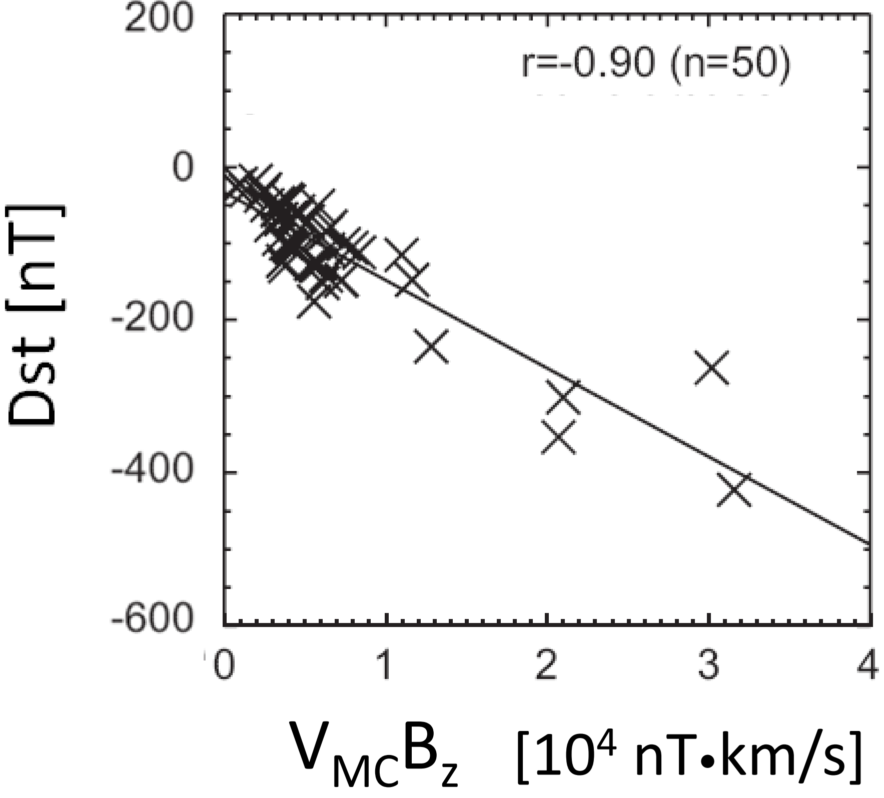
Geomagnetic Storm and CME parameters

$$Dst = -0.01VB_z - 32 \ \text{nT}$$

The high correlation suggests
That V and Bz are the most
Important parameters
(- Bz is absolutely necessary)

V and Bz in the IP medium are
related to the CME speed and
magnetic content

Gopalswamy 2008

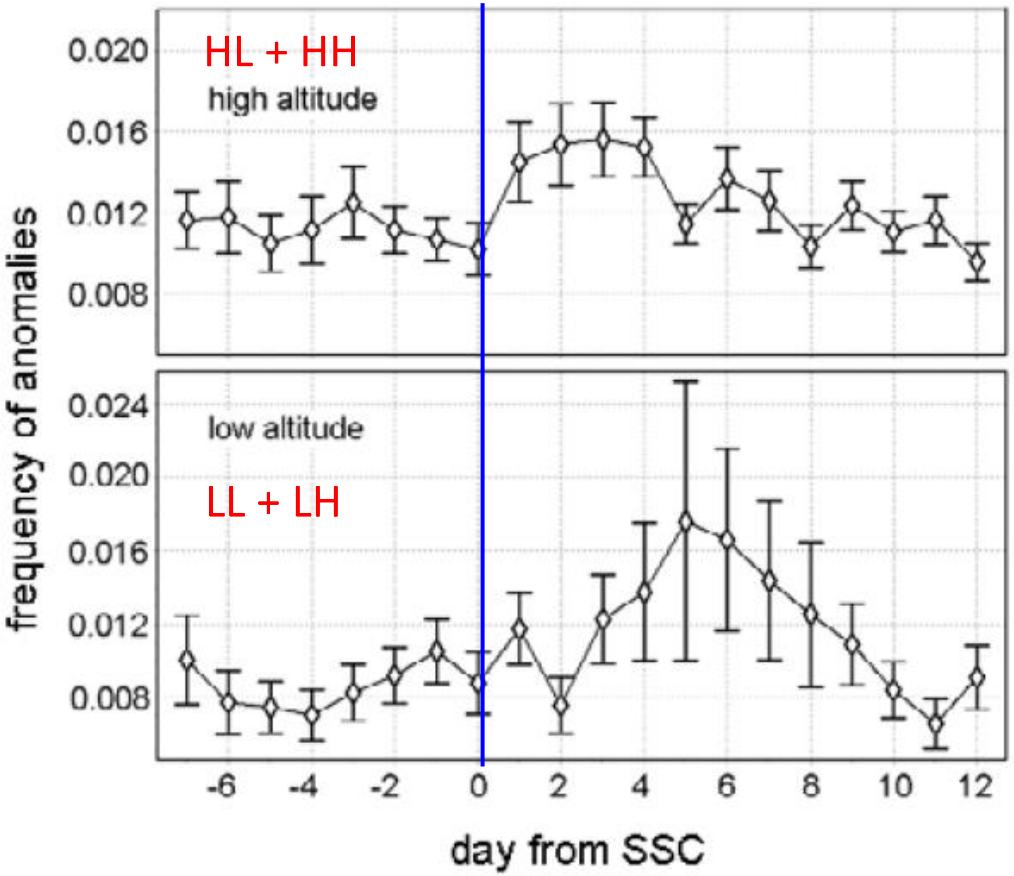


Carrington Event: VBz = 1.6 10^5 nT•km/s

V = 2000 km/s, Dst = -1650 nT → Bz = -81 nT

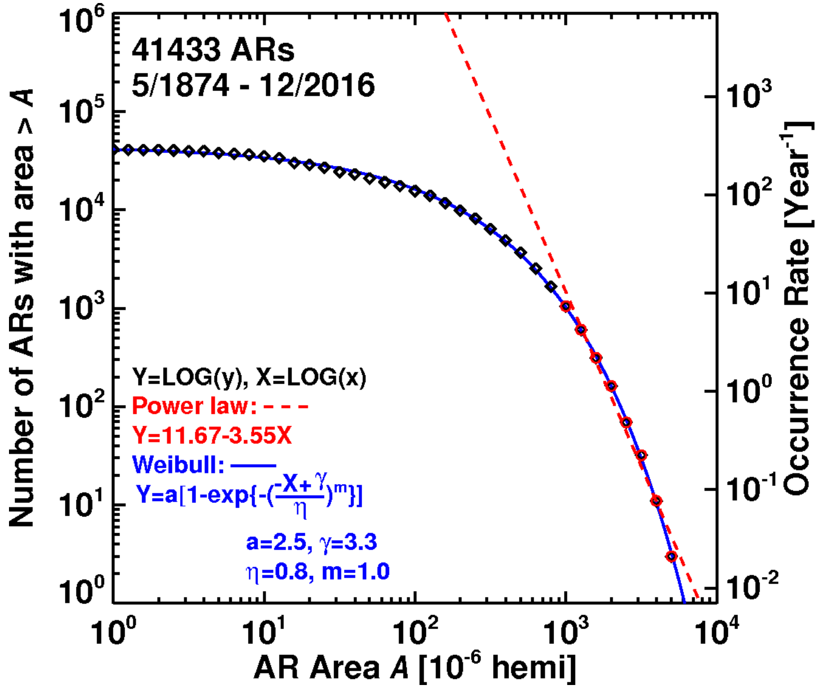
Satellite Anomalies Following Storm Sudden Commencement

- Anomalies of High-altitude (low & high inclination) satellites peak in 2-4 days after the SSC
- Anomalies of Low-altitude (low & high inclination) satellites peak in 5 days after the SSC



Iucci et al. 2005

Origin of V and B



$$Dst = -0.01VB_z - 32 \text{ nT}$$

Solar Wind speed
CIR Speed
CME speed

Active Region
Free energy

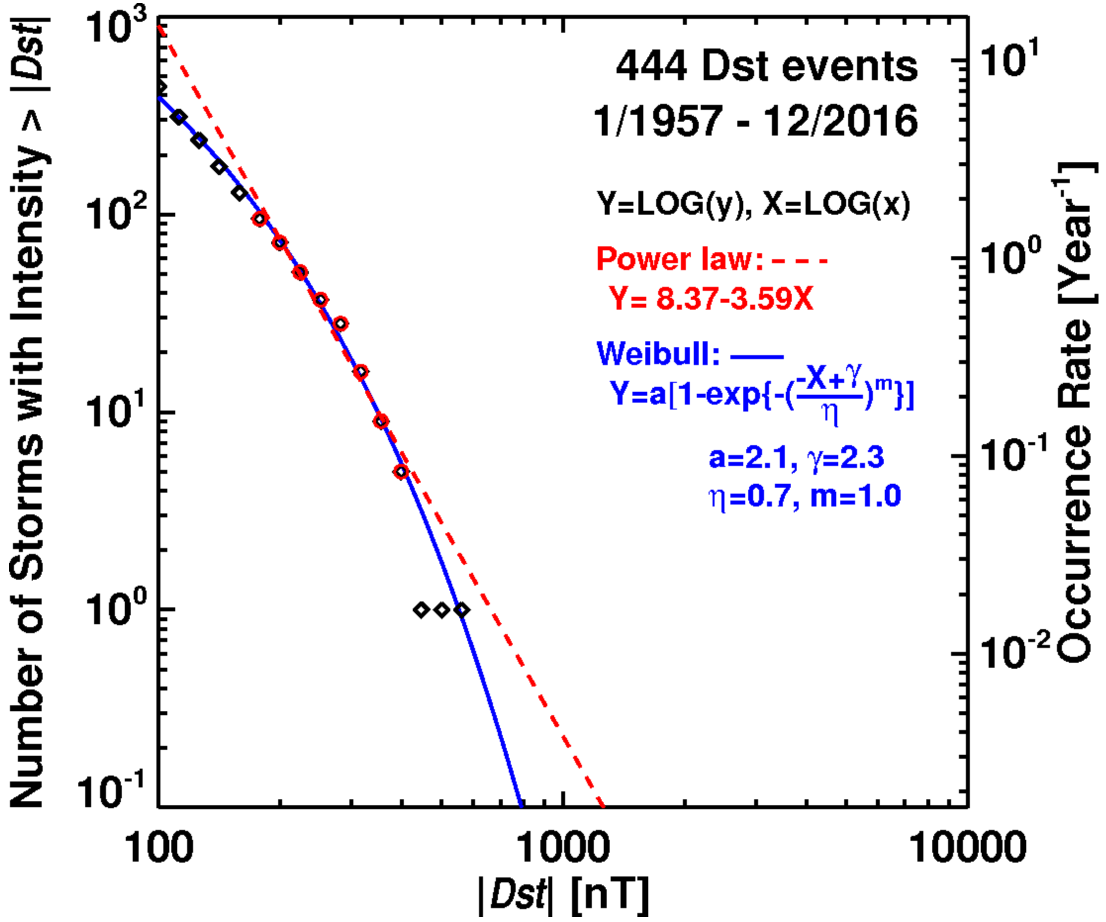
Alfven waves
CIR: Amplified Alfven waves
ICME: Sheath & Flux rope

Heliospheric
Mag Field

Active Region
Mag Field

Gopalswamy 2010

Magnetic Storms



100-year: -603 nT; 1000-year: -845 nT

- The Weibull distribution fits all the data points.
- A 100-year event has a size of -603 nT, consistent with the March 1989 event
- A 1000-year event has a size of -845 nT, consistent with some estimates of the Carrington storm:
- -1600 nT (Tsurutani et al. 2003)
- -850 nT (Siscoe 2006)
- -1160 nT (Gonzalez et al. 2011)
- -900 nT (Cliver and Dietrich 2013)

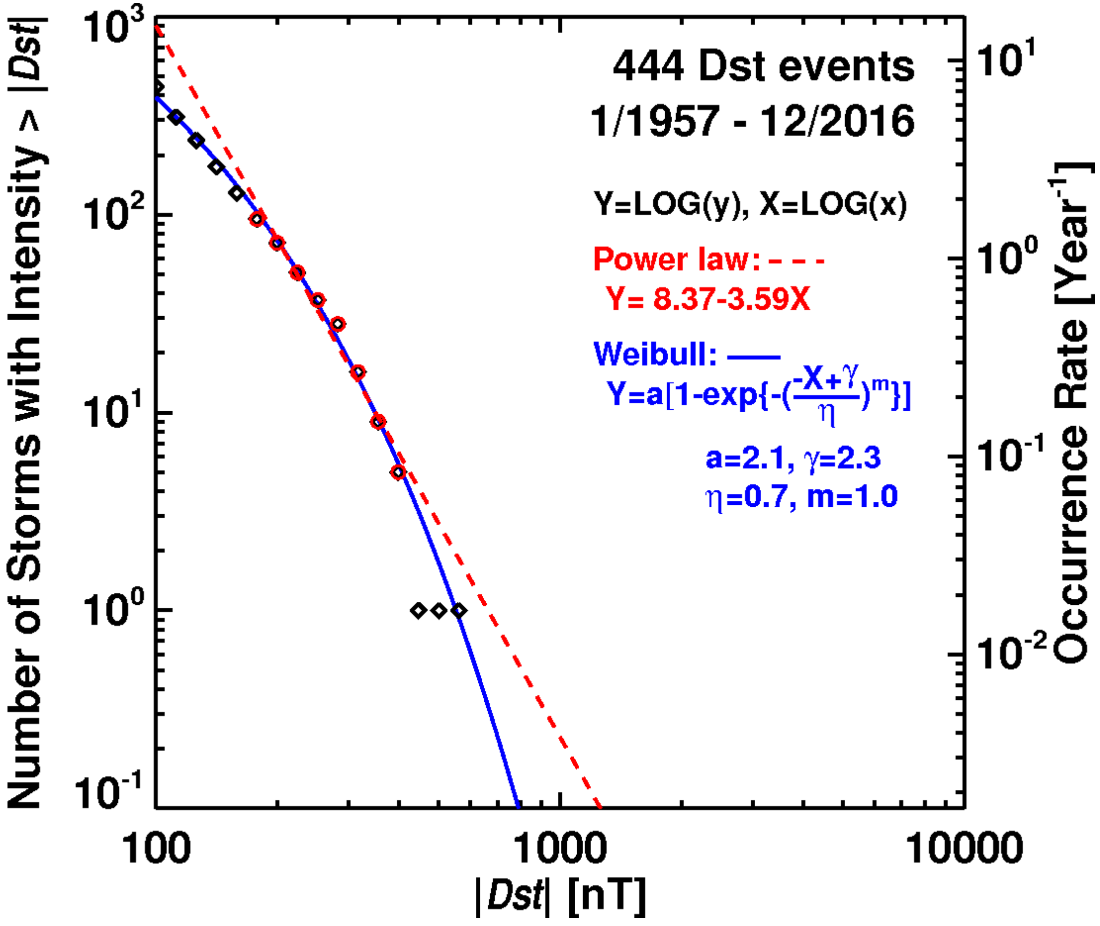
The empirical relation,
Dst = -0.01VBz – 32 nT
can explain –1160 nT if V = 2000 km/s and Bz = -78 nT
Using
$Bt = 0.06\, V_{ICME} - 13.58$ nT (Gopalswamy et al. 2017)
And
|Bz| = 0.74 Bt , it is possible to get Bt =106 nT and Bz = -78 nT

Geomagnetic Storms

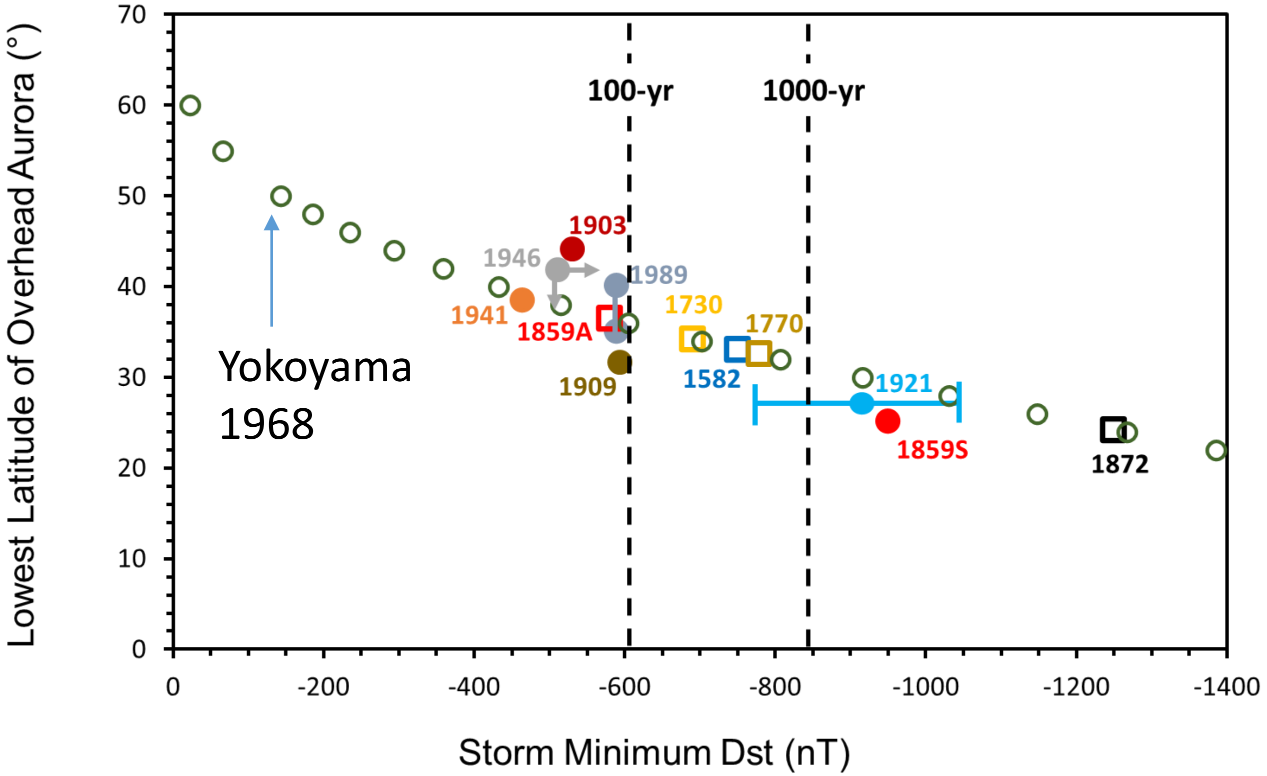
Six 100-yr storms (Dst ≤ -600 nT) in ~450 years (1582, 1730, 1770, 1859S, 1872, 1921)

Three 1000-yr storms (Dst ≤ -845 nT) in ~450 years (1859S, 1872, 1921)

Potential storms of -1200 nT (July 2012; Li et al., 2013) and -1400 nT (August 1972; Gonzales et al., 2011)



Gopalswamy 2018



Cliver 2021

Summary

- Assuming extreme events to be events on the tails of cumulative distributions, we estimated one-in-100 and one-in-1000 yr sizes
- Weibull function is used as the baseline in extrapolating the distributions of AR size, flares, CMEs, SEP events, and geomagnetic storms.
- Power-law distributions appear to yield overestimates
- This approach is consistent with the historical extreme event such as the Carrington event, the AD 774/75 event, the AD 994/95 event, and the recent 2012 July 23 backside event
- The simple relation Dst = – 0.01VBz – 32 nT is adequate to estimate extreme storms including the Carrington storm
- While most extreme events can be characterized as black swans, some events fall into the category of dragon kings

https://ui.adsabs.harvard.edu/link_gateway/2017arXiv170903165G/EPRINT_PDF

Chapter 2 in https://www.sciencedirect.com/book/9780128127001/extreme-events-in-geospace