Extreme Relativistic Electron Fluxes at Geosynchronous Orbit

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Motivation

- Satellite operators, designers and insurers are interested in extreme space weather events to help them better understand the satellite environment and assess the impacts of an extreme event

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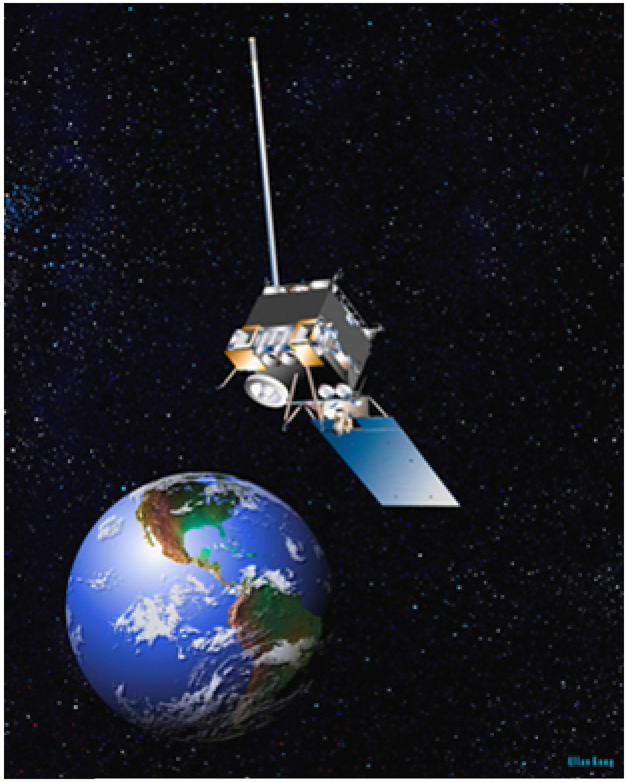
- The objective of this study is to calculate the electron flux for the 1 in 10, 1 in 50, and 1 in 100 year space weather event at geosynchronous orbit

Data Analysis

- Use GOES E > 2 MeV electron data from 1st January 1995 to 30th June 2014
- Study uses data from GOES 8, 9, 10, 11, 12, 13 and 15
- Use 5 minute resolution E > 2 MeV electron data from NOAA

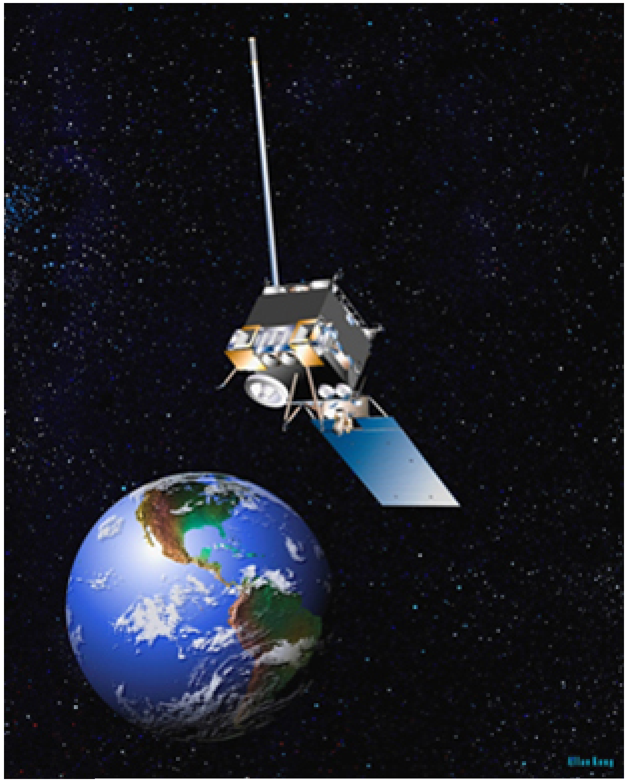


credit: NOAA

Typical Orbital Parameters
Altitude: 35,800 km
Inclination: 0°

Data Analysis

- Electron data
  - have been corrected for proton contamination
  - for the first time the data have been corrected for dead time
  - dead time correction ranges from a factor of 1.0-1.15 for fluxes around 5000 $cm^{-2}s^{-1}sr^{-1}$ to ~2 for the largest fluxes observed



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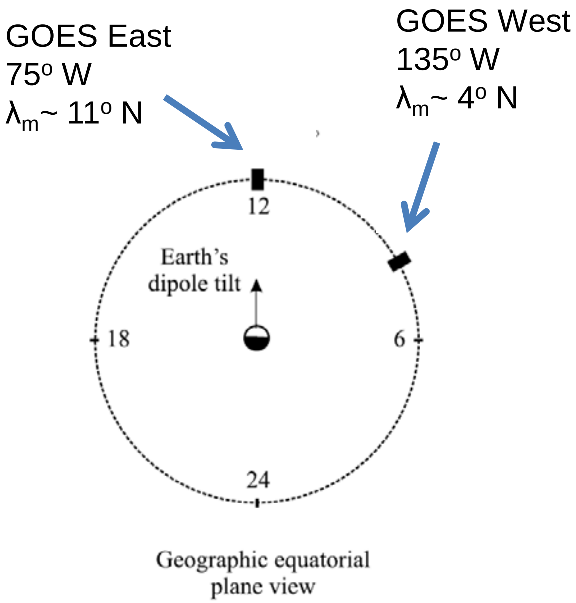
Exclude Solar Proton Events

- The E > 2 MeV electron data may be contaminated during solar proton events
- We adopt the NOAA SWPC definition of a solar proton event and exclude the electron data whenever the flux of E > 10 MeV protons is greater than 10 $cm^{-2}s^{-1}sr^{-1}$
- Calculate daily average when > 90% of the day has good quality data in the absence of contamination from solar protons

Primary Geographic Longitudes

- GOES satellites operate at two primary geographic longitudes, GOES East at 75º and GOES West at 135º W
- The satellites are at different magnetic latitudes with GOES East at 11º N and GOES West at 4º N
- GOES East and GOES West are at different L shells
- Since the flux of energetic electrons generally decreases with L near geosynchronous orbit we conduct our analysis for GOES East and West separately



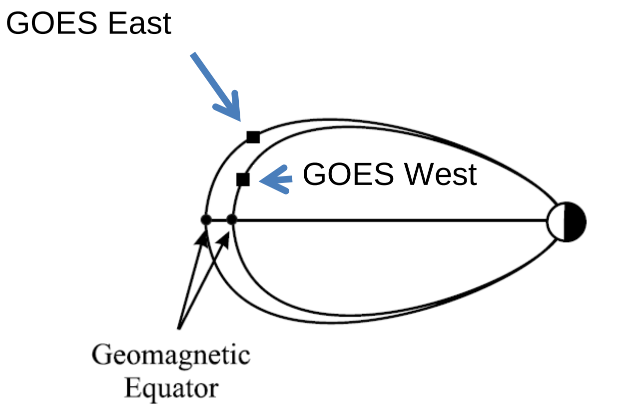


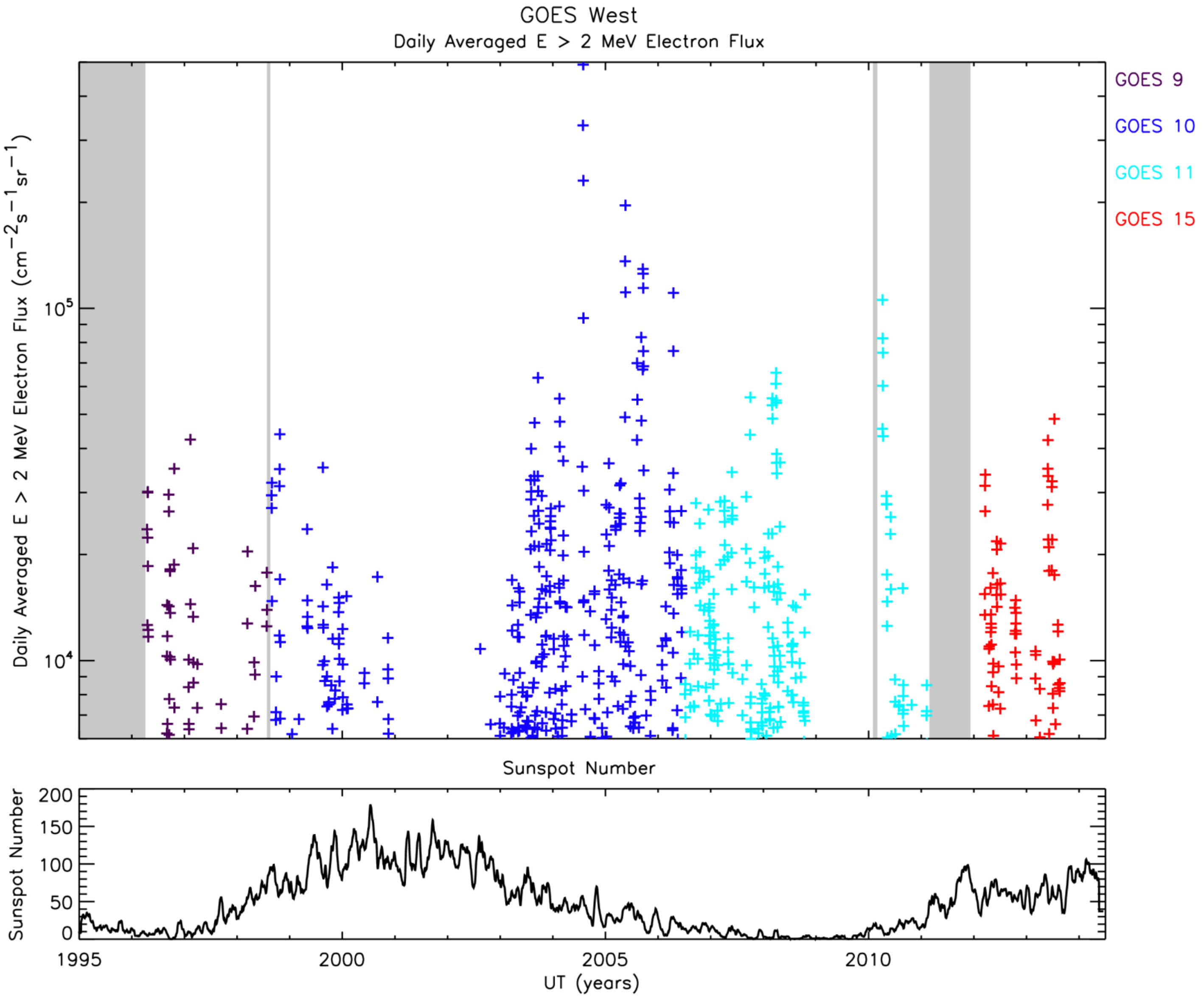
Figure adapted from Onsager *et al*., 2004

Good Quality Data Points

- In total there are 5844 good quality data points at GOES West, corresponding to approximately 16 years of operational data

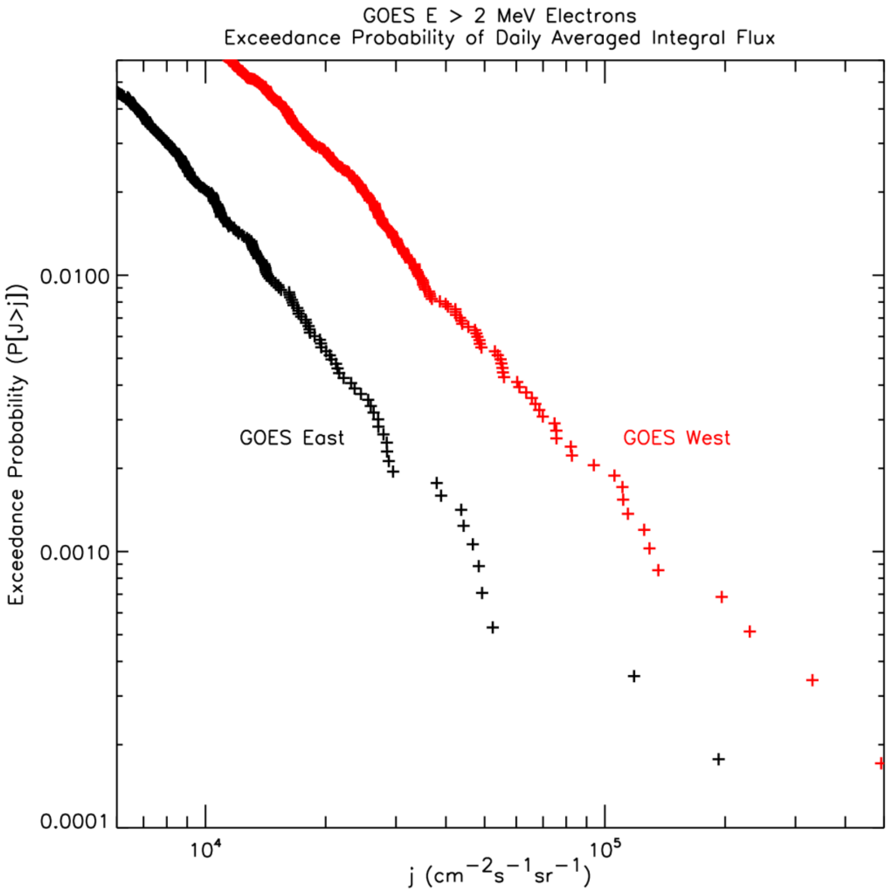
- There are 5649 good quality data points at GOES East corresponding to approximately 15.5 years of operational data

GOES West: E > 2 MeV Electrons



Exceedance Probability

- Probability that an individual sample J is greater than j (P[J>j])

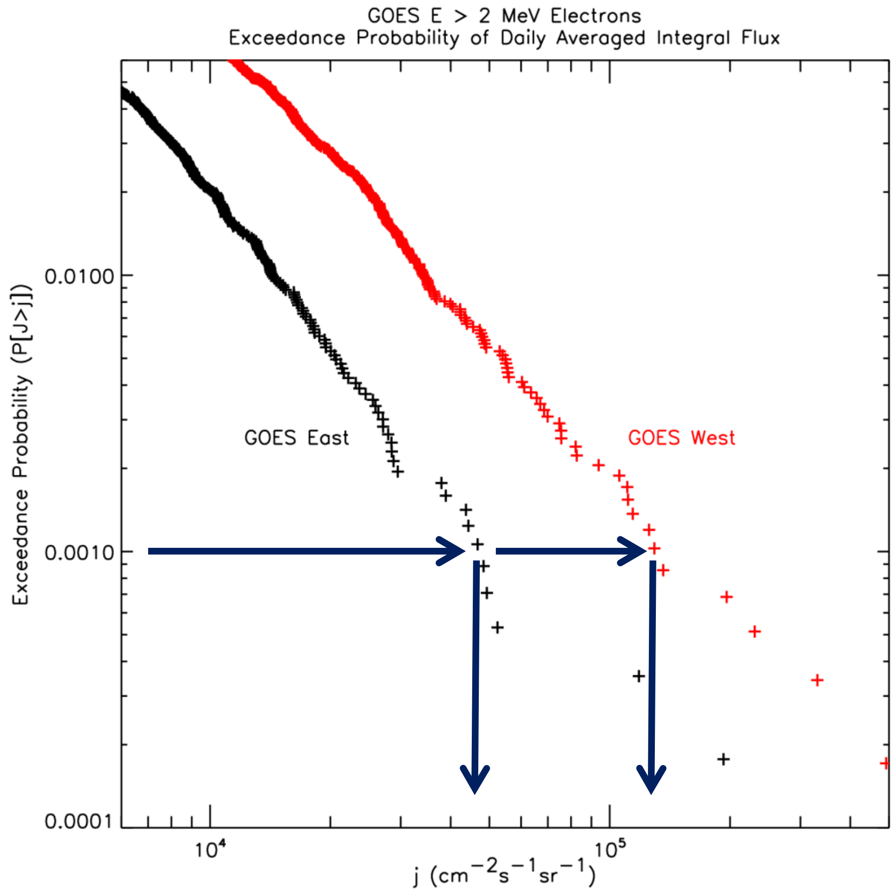


Exceedance Probability

- Probability that an individual sample J is greater than j (P[J>j])

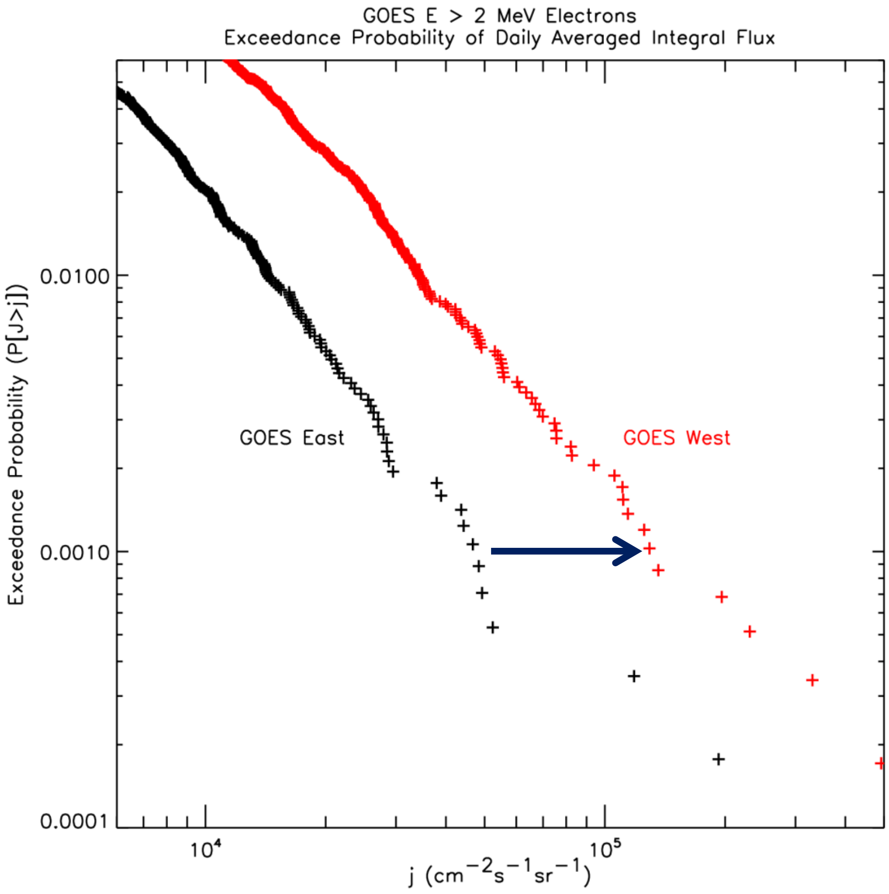
- Flux that is exceeded 0.1% of the time is

  - $4.5 \times 10^4\ cm^{-2}s^{-1}sr^{-1}$ at GOES East
  - $1.35 \times 10^5\ cm^{-2}s^{-1}sr^{-1}$ at GOES West



Exceedance Probability

- Fluxes at GOES West are typically a factor of 2.5 higher than those at GOES East
- This is largely due to the fact that the satellite at GOES West is at a lower magnetic latitude and hence L shell



Extreme Value Analysis

- Two main methods for extreme value analysis
  - block maxima
  - exceedances over a high threshold

- For comparison with earlier work (e.g., Koons [2001]) we use the exceedances over a high threshold method

- For this approach the appropriate distribution function is the Generalised Pareto Distribution (GPD)

Generalised Pareto Distribution

- The GPD may be written in the form

$$G(x-u) = 1 - (1+ \xi(x-u)/\sigma)^{-1/\xi}$$

where: x are the data values above the chosen threshold u

ξ is the shape parameter which controls the behaviour of the tail

σ is the scale parameter which determines the dispersion or spread of the distribution

- The GPD is a distribution function

- 1-G(x-u) representing the probability that a random variable X exceeds some value x given that it already exceeds a threshold u

Declustering

- Values can exceed the threshold on consecutive days
- The statistical analysis assumes that the individual exceedances are independent
- Technique to deal with this is known as declustering

Declustering

- Use an empirical rule to define clusters of exceedances and consider cluster to be active until 3 consecutive daily averages fall below the threshold

- Identify the maximum excess in each cluster and assume cluster maxima to be independent, with conditional excess given by the GPD

- Fit the GPD to the cluster maxima

Quality Checks

- We may assess the quality of a fitted GPD model by comparing the empirical and modelled probabilities and quantiles

- If the GPD model is a good method for modelling the exceeedances then both the probability and quantile plots should be linear

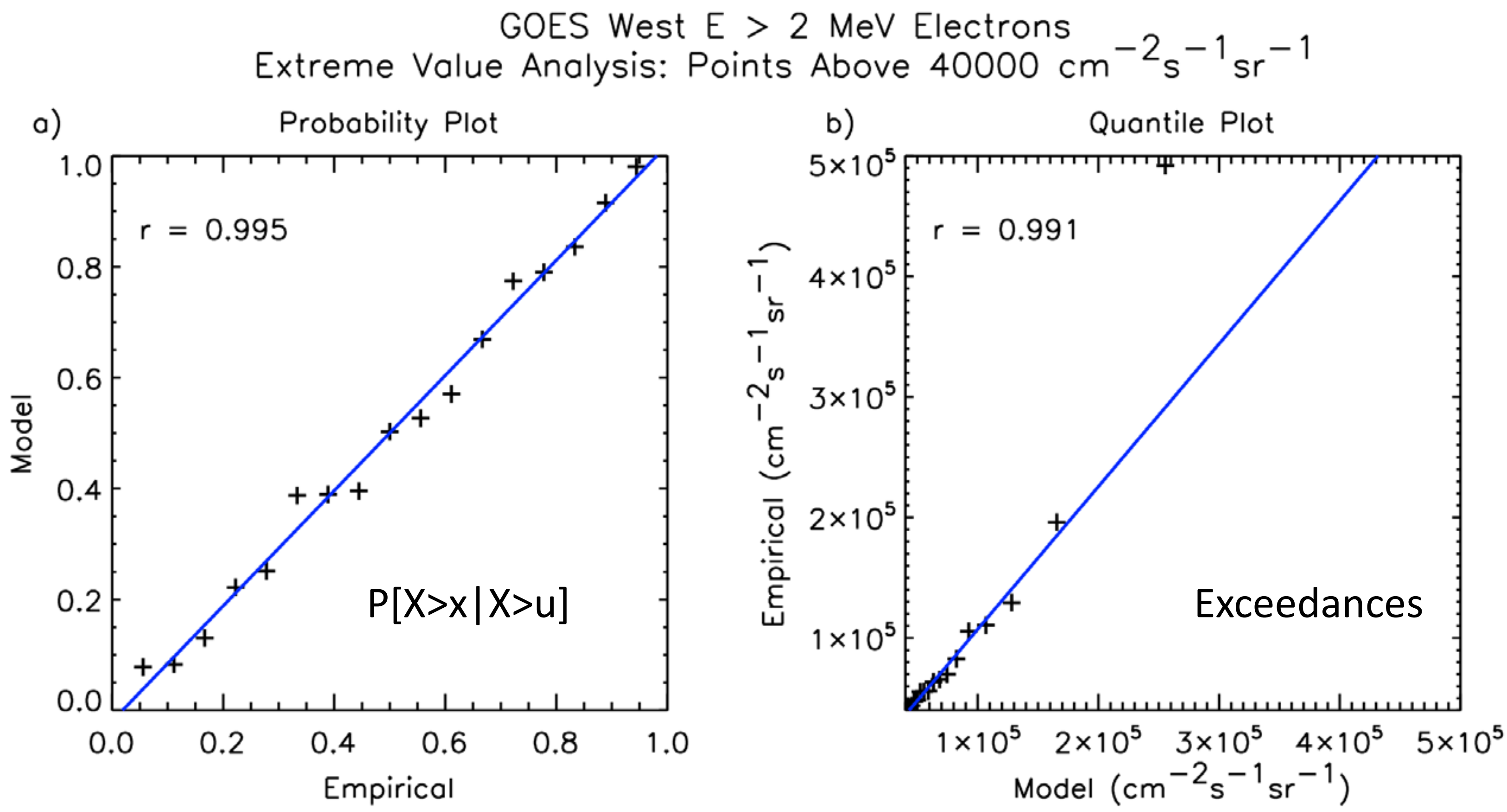
Return Levels

- The return level, x_N, which is exceeded on average once every N years can be expressed in terms of the fitted parameters σ and ξ as:

$$x_N = u + (\sigma/\xi)(Nn_d\zeta)^{\xi} - 1))$$

where $\zeta = n_c/n_{tot}$, the number of cluster maxima divided by the total number of data points and n_d = is the average number of data points in any given year

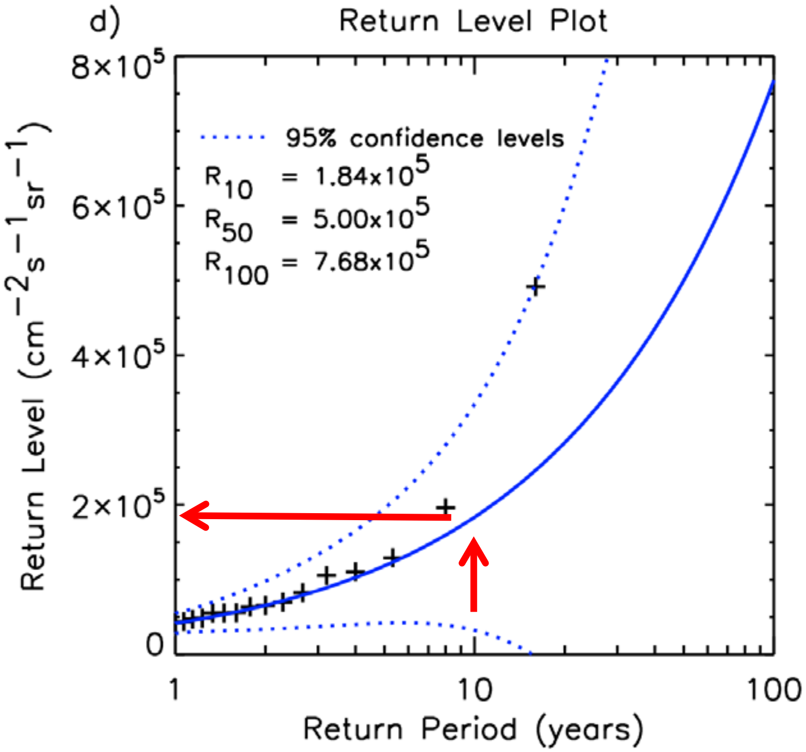
GOES West: Extreme Value Analysis



- The probability and quantile plots are both approximately linear showing that the GPD is a good method for modelling the exceedances

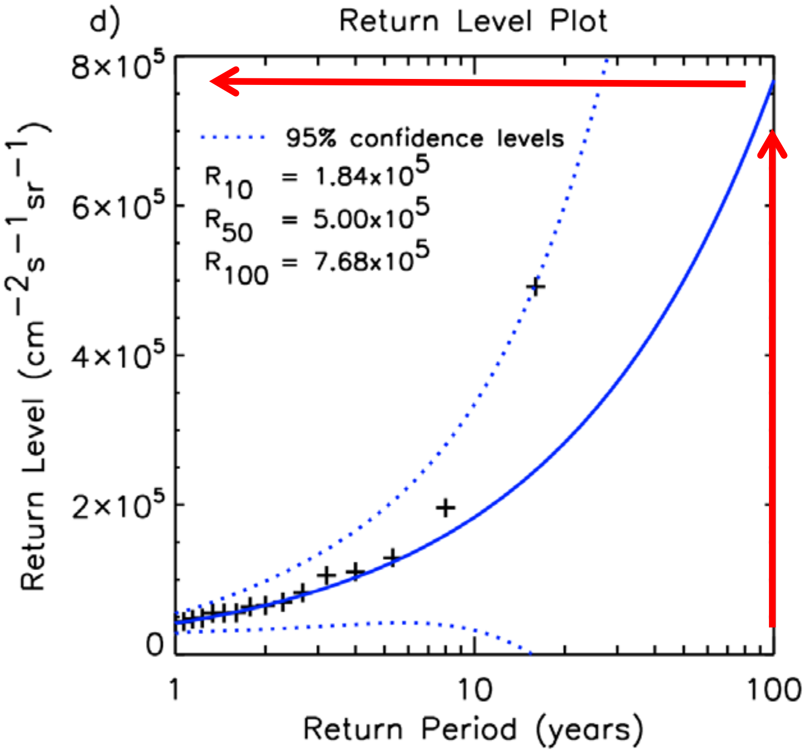
GOES West: Return Level Plot

- One in Ten Year Flux
  - $1.84x10^5$ $cm^{-2}s^{-1}sr^{-1}$



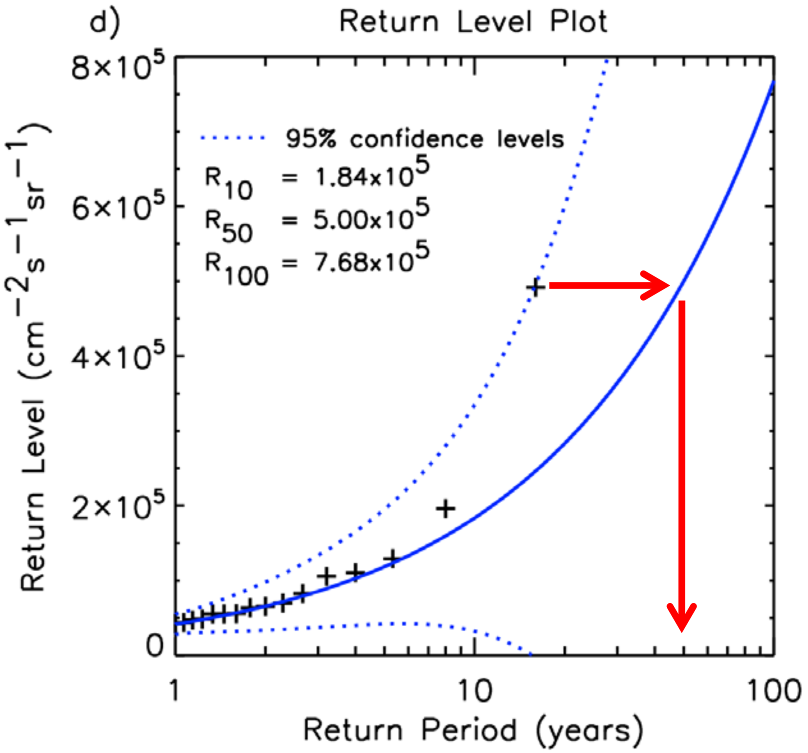
GOES West: Return Level Plot

- One in Ten Year Flux
  - $1.84x10^5$ $cm^{-2}s^{-1}sr^{-1}$
- One in One Hundred Year Flux
  - $7.68x10^5$ $cm^{-2}s^{-1}sr^{-1}$

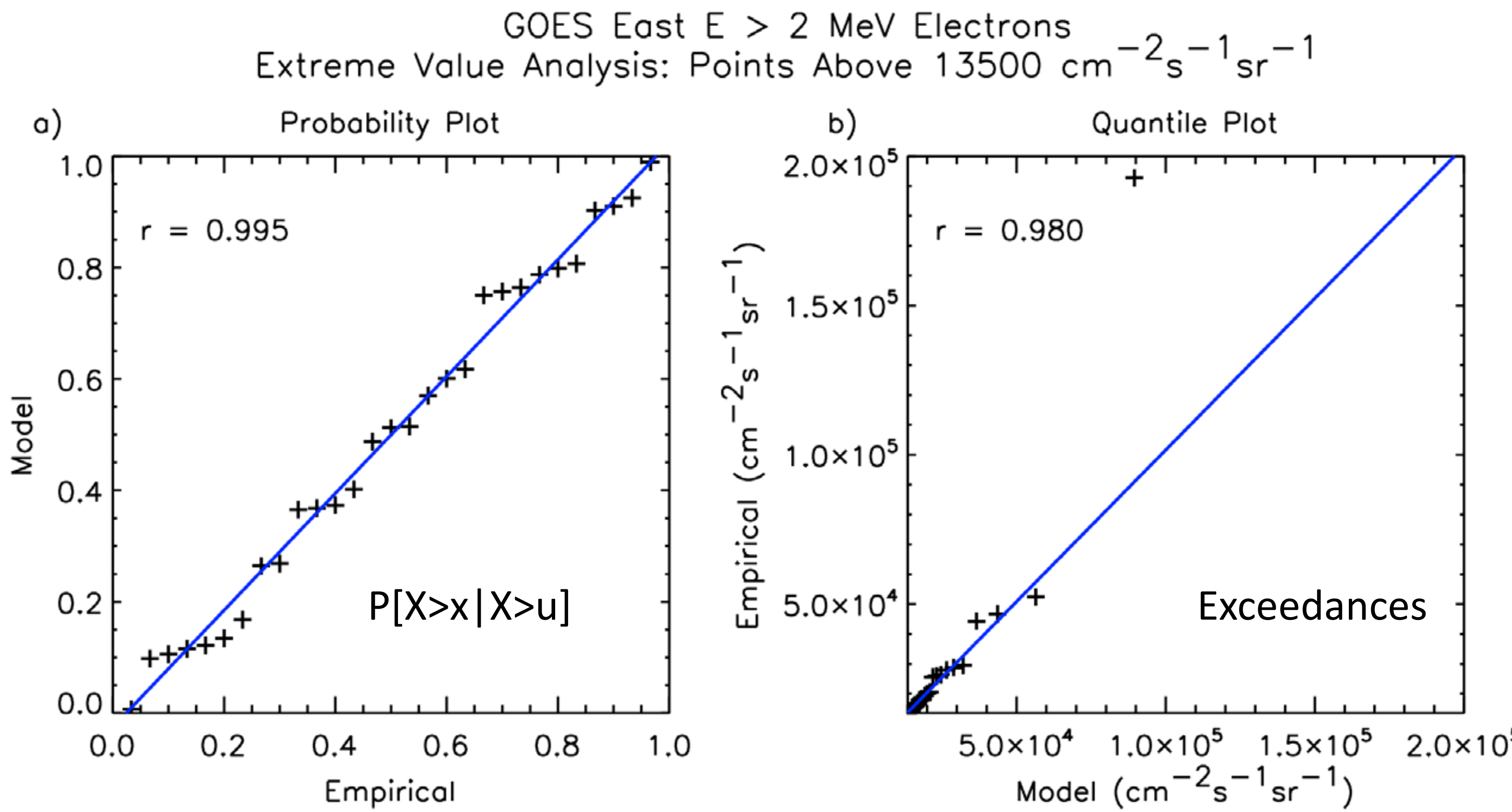


GOES West: Return Level Plot

- Largest observed flux is a one in fifty year event



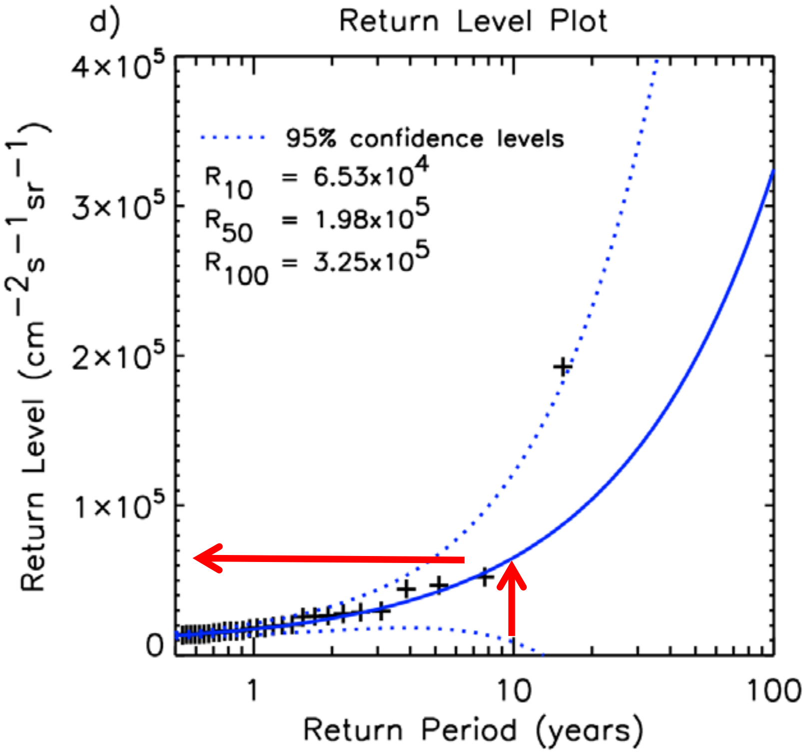
GOES East: Extreme Value Analysis



- The probability and quantile plots are both approximately linear showing that the GPD is a good method for modelling the exceedances

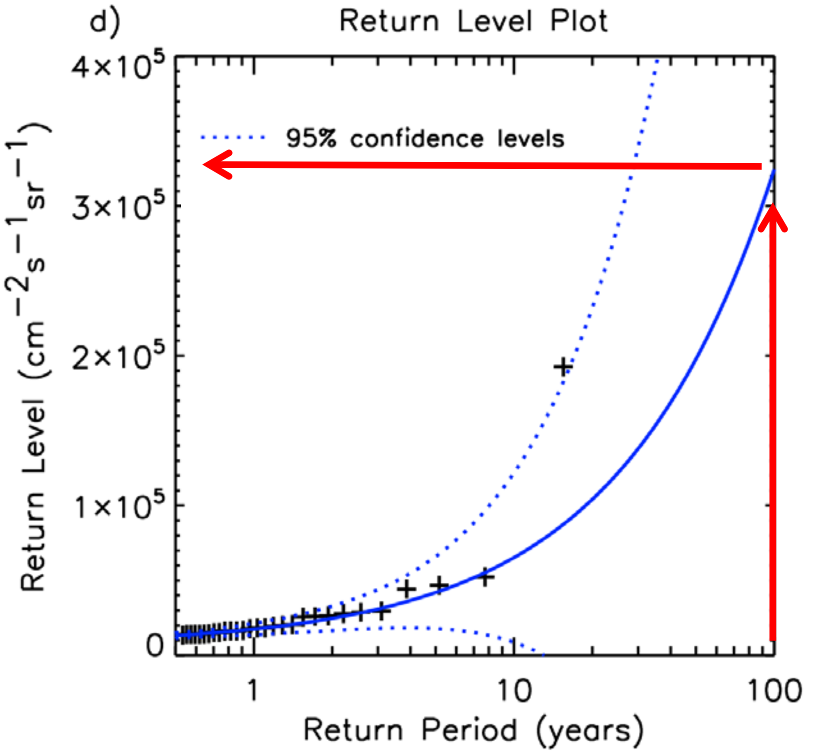
GOES East: Return Level Plot

- One in Ten Year Flux
  - 6.53×10^4 $cm^{-2}s^{-1}sr^{-1}$



GOES East: Return Level Plot

- One in Ten Year Flux
  - 6.53×10^4 $cm^{-2}s^{-1}sr^{-1}$
- One in One Hundred Year Flux
  - 3.25×10^5 $cm^{-2}s^{-1}sr^{-1}$



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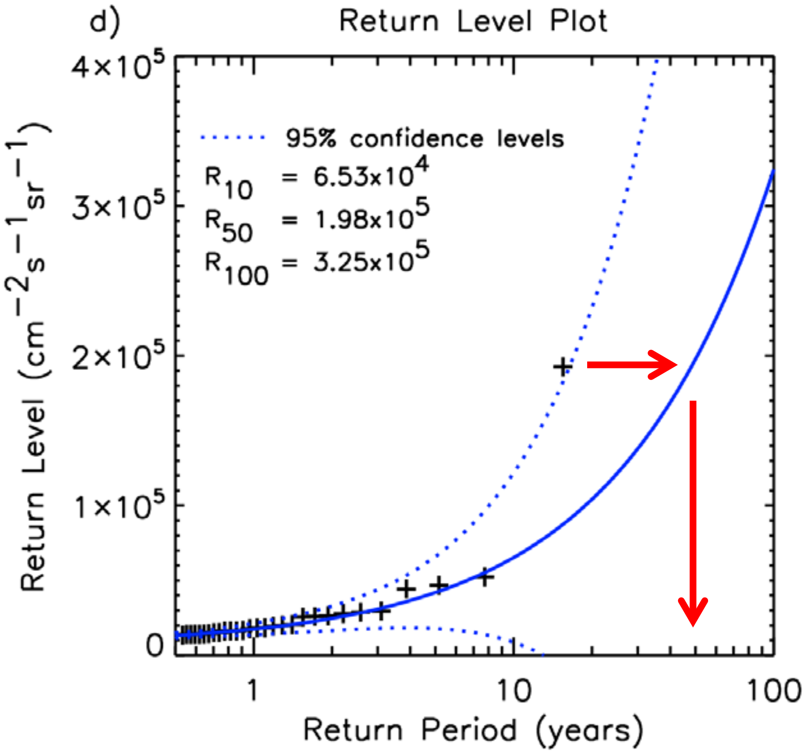


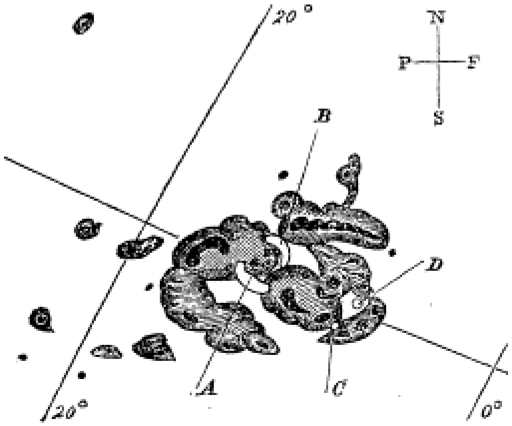
Return Levels for Event with same Frequency as the Carrington Event

- Largest space weather event of the last 200 years is widely regarded to be the Carrington event of 1859

- When ranked by 5 different space weather effects it is the only event to appear at or near the top of each ranking [Clilver and Svalgaard, 2004]

- Historical auroral records suggest the return period of a Carrington type event is 150 years [Lloyds, 2013]

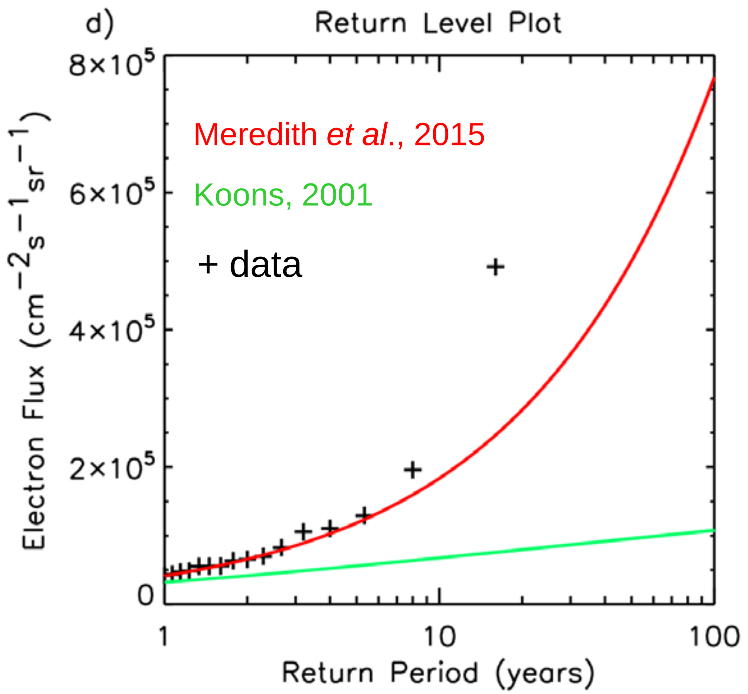
- The return levels for a 150 year event are 9.86×10^5 and 4.35×10^5 $cm^{-2}s^{-1}$ sr^{-1} at GOES West and GOES East respectively



Carrington, 1859

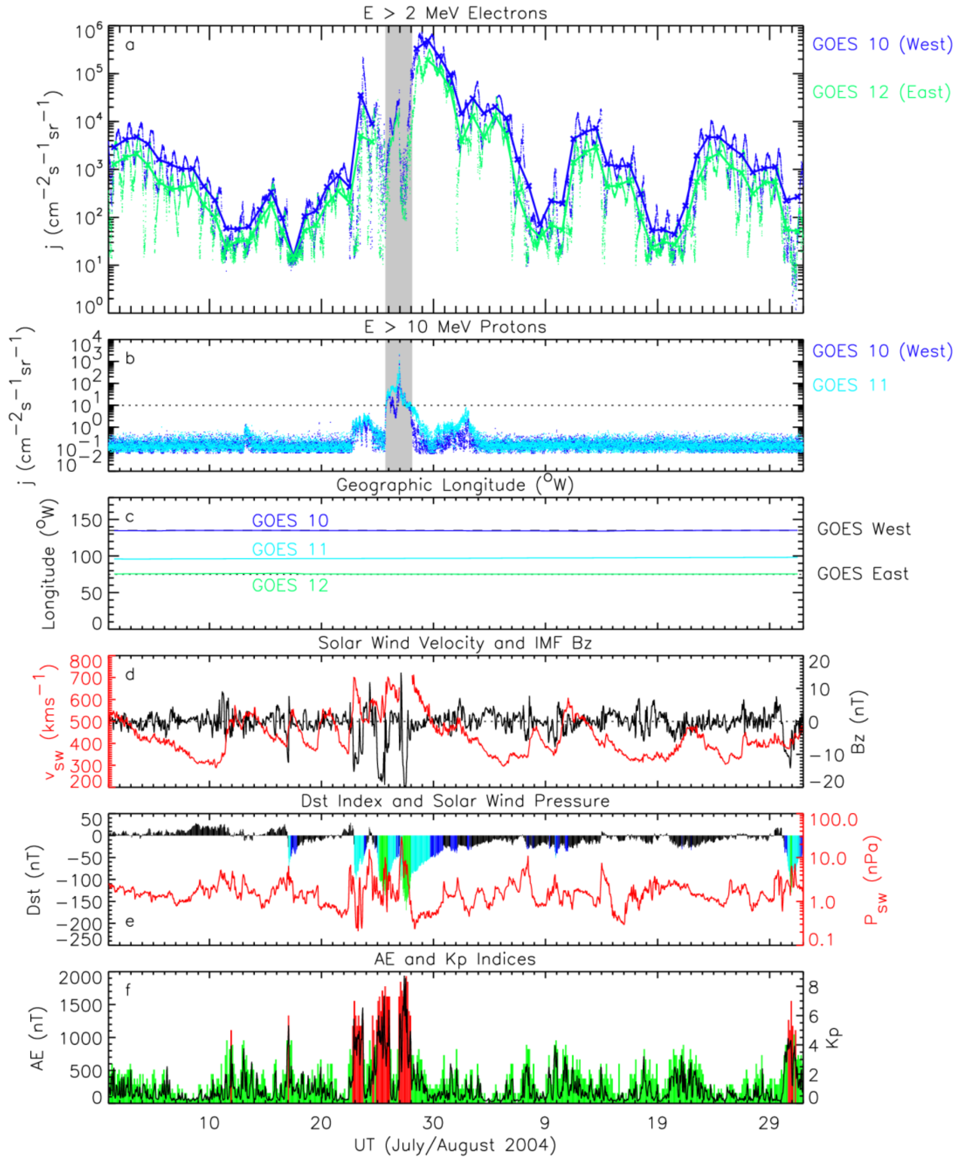
Comparison with Koons [2001] Study

- Our results are significantly larger than those presented in Koons [2001]
- The 1 in 10 year event at GOES West is about a factor of 2.7 times that estimated by Koons [2001]
- For more extreme events, the 1 in 100 year event at GOES West is about a factor of 7 times that estimated by Koons [2001]



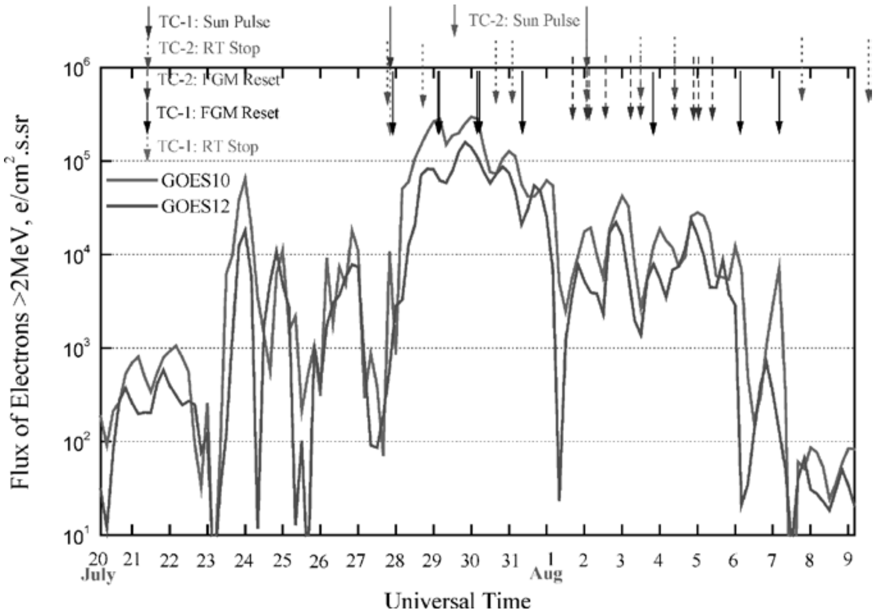
July/August 2004

- Largest E > 2 MeV flux of 4.91×10^5 $cm^{-2}s^{-1}sr^{-1}$ observed at GOES-West on 29th July 2004
- Coincided with the largest E > 2 MeV flux of 1.93×10^5 $cm^{-2}s^{-1}sr^{-1}$ at GOES-East
- Independent measurements of this extreme flux event suggests the flux event is real
- GOES-West flux exceeded 10,000 $cm^{-2}s^{-1}sr^{-1}$ for nine consecutive days from 28th July to 5th August



July/August 2004

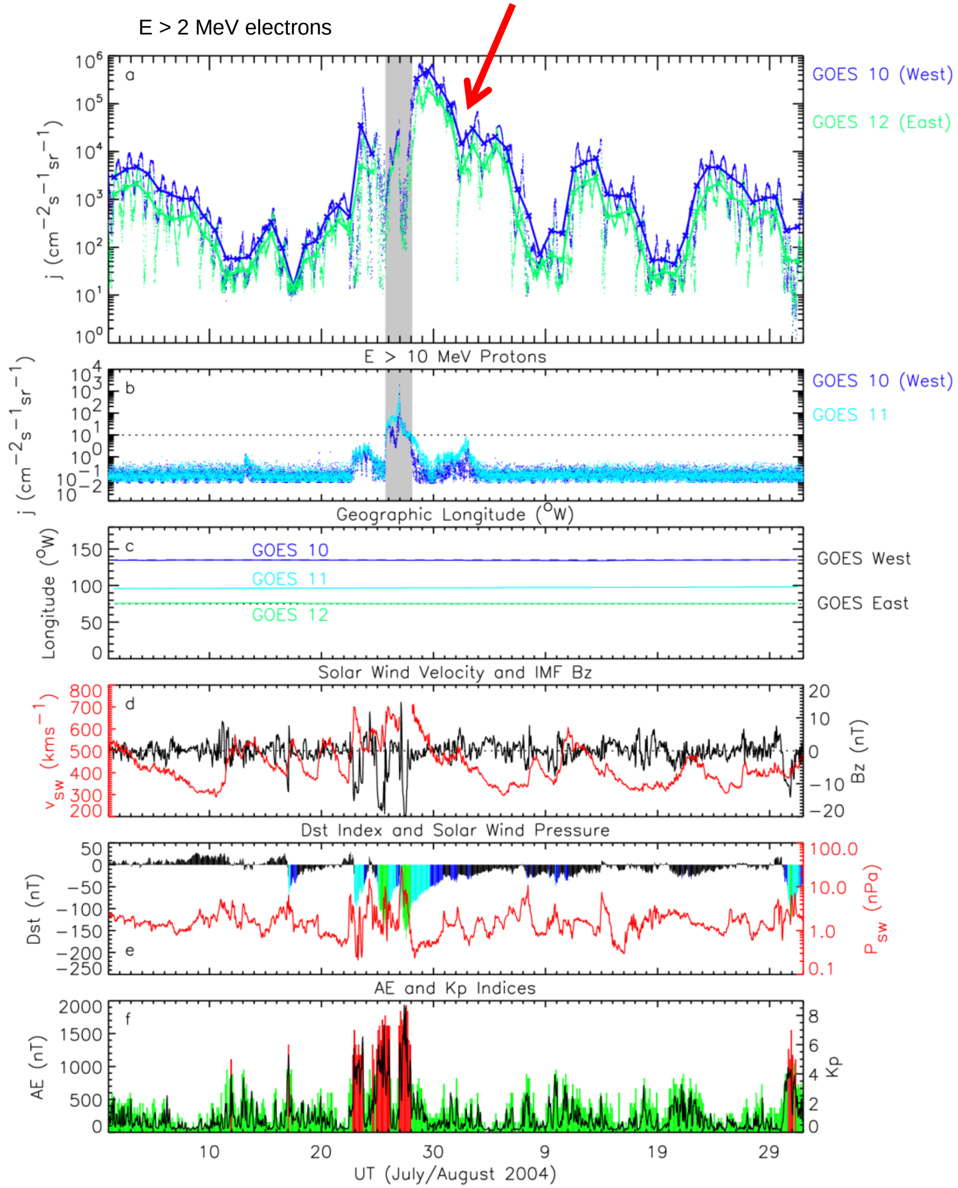
- Double Star TC1 and TC2 reported over 30 anomalies during the period from 27 July to 10 August [Han *et al*., 2005]
- These anomalies largely occurred in the Earth's radiation belt and were attributed to internal charging [Han *et al*., 2005]



Han *et al*., JSR, 2005

July/August 2004

Galaxy 10 R secondary
XIPS failure

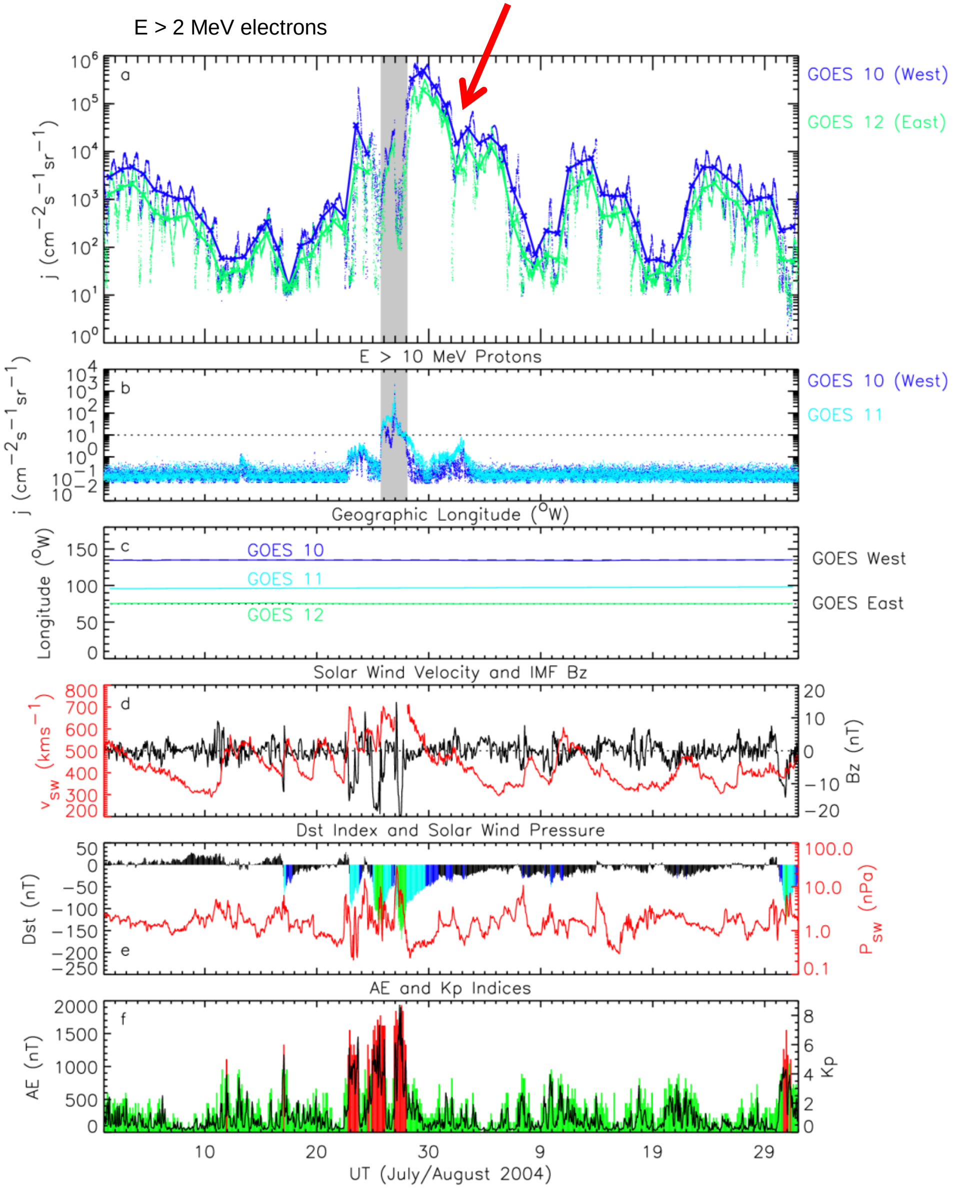


- On 3 August, during the extended period of enhanced E > 2 MeV electron fluxes, Galaxy 10R lost its secondary xenon ion propulsion system [Choi *et al*., 2011]
- This reduced its lifetime significantly resulting in an insurance payout of US $75.3 M

What Caused the Extreme Event ?

- Three consecutive storms
- IMF Bz remained southward for significant periods during recovery phase of each storm
- Average value of AE index around 900 nT for first 10 hours of each recovery phase
- Such high and sustained levels of AE are likely to be associated with
  - strong and sustained levels of whistler mode chorus
  - elevated seed electrons
  - strong acceleration of electrons to relativistic energies

Galaxy 10 R secondary XIPS failure



Conclusions

- The daily average flux of E > 2 MeV electrons measured at GOES West is typically a factor of 2.5 higher than that measured at GOES East

- The 1 in 10, 1in 50 and 1 in 100 year event at GOES West are $1.84\text{x}10^5$ $5.00\ \text{x}10^5$ and $7.68\text{x}10^5$ $cm^{-2}s^{-1}sr^{-1}$ respectively

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- These flux levels can serve as “yardsticks” or “benchmarks” to compare against current or previous space weather conditions

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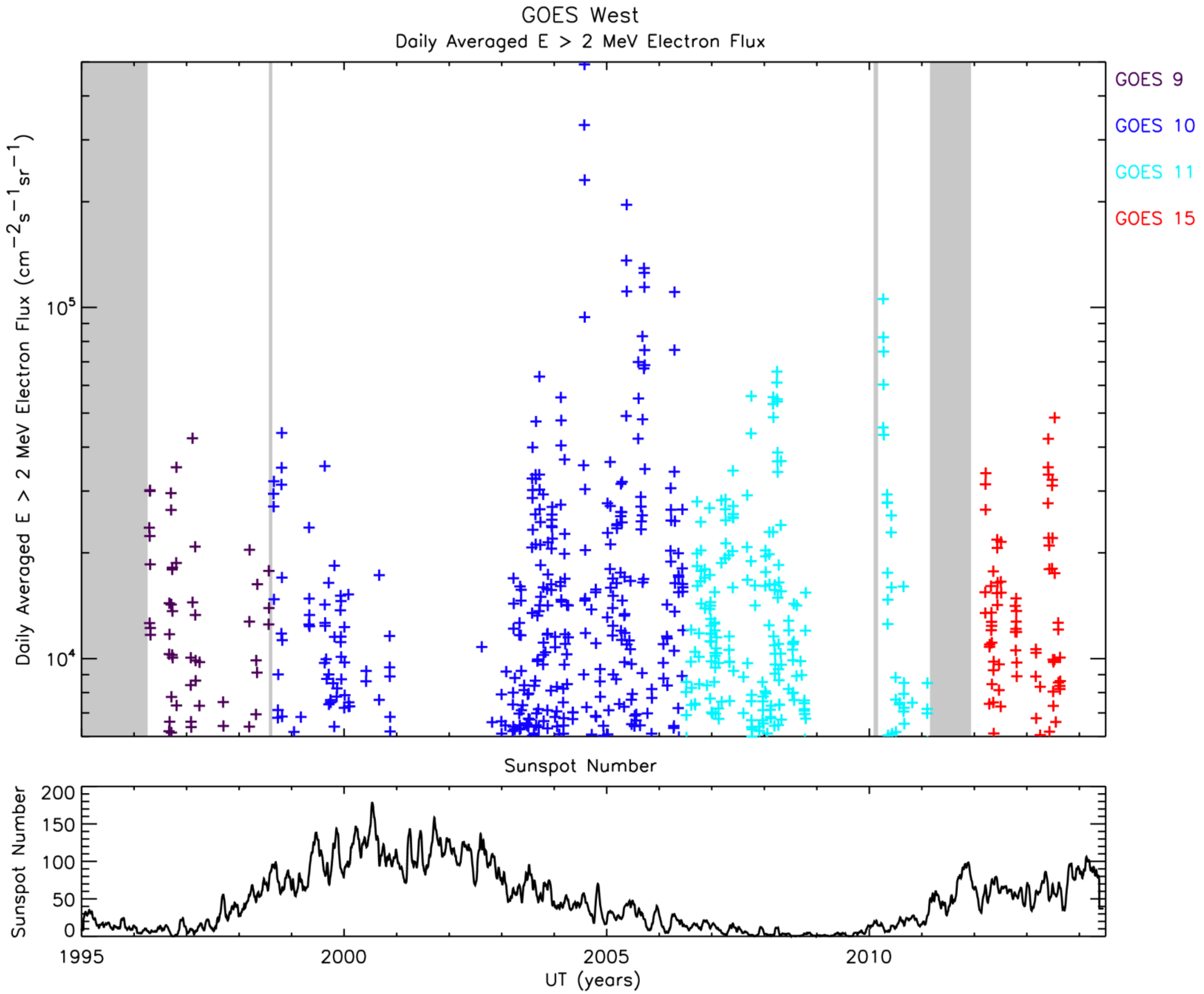
- These flux levels can serve as “yardsticks” or “benchmarks” to compare against current or previous space weather conditions
- The results can be used to determine the return period of any given event
  - our results suggest that the largest event seen during the study period was a one in fifty year event

Acknowledgements

- The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreements number 606716 (SPACESTORM) and is also supported in part by the UK Natural Environment Research Council

GOES West: E > 2 MeV Electrons



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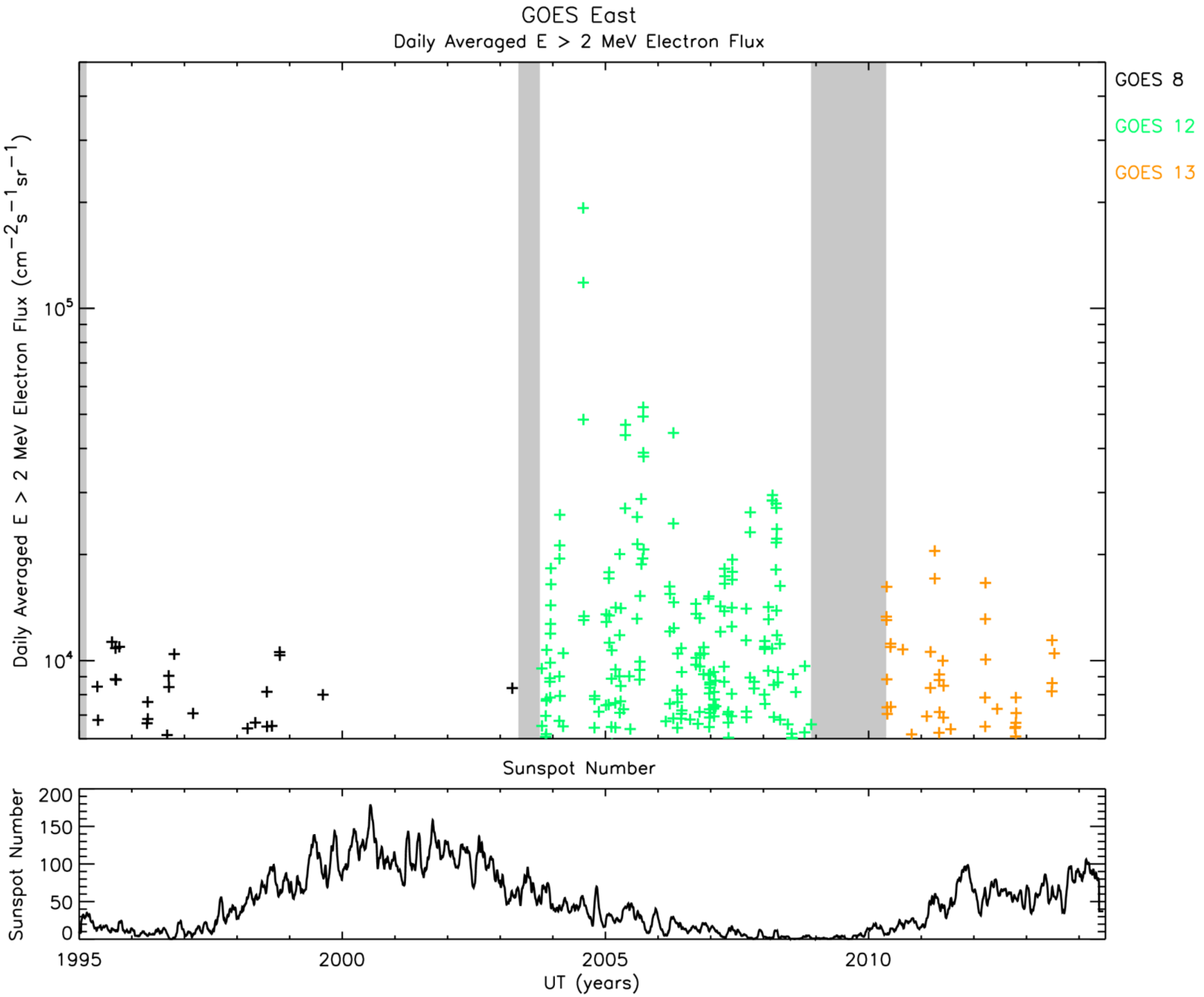


Top Ten Flux Events at GOES West

	Flux ($cm^{-2}s^{-1}sr^{-1}$)	Date
1	4.92×10^5	29th July 2004
2	3.31×10^5	28th July 2004
3	2.31×10^5	30th July 2004
4	1.96×10^5	18th May 2005
5	1.36×10^5	17th May 2005
6	1.29×10^5	17th September 2005
7	1.25×10^5	18th September 2005
8	1.14×10^5	19th September 2005
9	1.11×10^5	19th May 2005
10	1.11×10^5	17th April 2006

Top Ten Flux Events at GOES East

	Flux ($cm^{-2}s^{-1}sr^{-1}$)	Date
1	$1.93x10^5$	29th July 2004
2	$1.18x10^5$	30th July 2004
3	$5.24x10^4$	19th September 2005
4	$4.93x10^4$	18th September 2005
5	$4.83x10^4$	31st July 2004
6	$4.67x10^4$	19th May 2005
7	$4.43x10^4$	17th April 2006
8	$4.37x10^4$	18th May 2005
9	$3.89x10^4$	20th September 2005
10	$3.79x10^4$	21st September 2005

Appendix 1 - Exclusions

- The E > 2 MeV electron data may be contaminated during solar proton events
- We adopt the NOAA SWPC definition of a solar proton event and exclude the electron data whenever the flux of E > 10 MeV protons is greater than 10 $cm^{-2}s^{-1}sr^{-1}$
- Calculate daily average when > 90% of the day has good quality data in the absence of contamination from solar protons

Appendix 1 - Exclusions

- We also exclude
  - data from GOES 10 in February 2010 during a period of anomalously low fluxes attributed to count rates that had not been properly converted to fluxes [Su *et al*., 2014]
  - data from GOES 12 collected in September 2003 due to a 1.5 day offset between the 5 minute and 1 minute averages
  - data from GOES 12 after 28 November 2008 due to partial failure of the dome detector

Appendix 2 - Look Direction

- The single set of electron sensors on each of GOES 8-12 look westward with the exception of those on GOES 10 which looked eastward
- There are two sets of electron sensors on GOES-13 and GOES 15. One set looks eastward and the other looks westward.
- In orbit GOES 13 is upright and we select data from the westward facing telescope
- GOES 15 undergoes a yaw flip twice a year at the equinoxes which means the eastward looking telescope then looks westward and vice versa
  - The manoeuvre lasts approximately half an hour and is discounted from the analysis
  - We select the data from the appropriate westward facing channel for our analysis

Appendix 3 - Missing Satellite Location

- The geographic longitude of the satellite is occasionally missing in the archived files when the data are of good quality
- We inspected the data and found 20 intervals of missing geographic longitudes
- With the exception of one missing interval the satellite was parked at a particular location
- For the other missing interval, which lasted one day, GOES 15 was in the process of moving from 90 W to 135 W at about 1 degree a day
- To obtain the satellite longitude during the missing intervals we linearly interpolate between the recorded longitudes before and after the missing intervals

Appendix 4 - Yaw Flips

- GOES 15 undergoes a yaw flip twice a year at the equinoxes
- The manoeuvre lasts approximately half an hour
- Dates of yaw flips:
  - September 22, 2011 c. 1800 0 (upright)
  - March 20, 2012 c. 2100 1 (inverted)
  - September 20, 2012 c. 2100 0 (upright)
  - March 20, 2013 c. 2100 1 (inverted)
  - September 23, 2013 c. 2100 0 (upright)
  - March 20, 2014 c. 2100 1 (inverted)
- The EPEAD telemetry channels labeled ‘E’ look westward when the spacecraft is upright (yaw flip flag = 0) and eastward when the spacecraft is inverted (yaw flip flag = 1).
- The EPEAD telemetry channels labeled ‘W’ look eastward when the spacecraft is upright (yaw flip flag = 0) and westward when the spacecraft is inverted (yaw flip flag = 1).

Appendix 5 – Sensitivity to Threshold Selection

GOES West

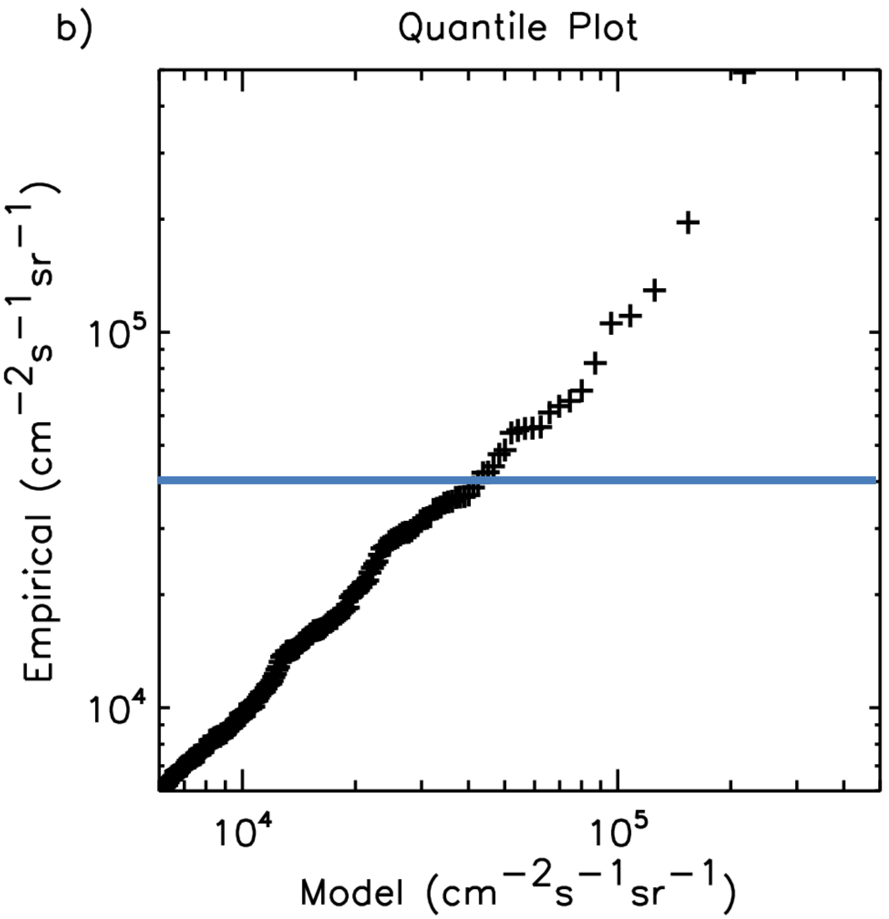
	20000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	30000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	40000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	50000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)
1 in 10 year	$1.64x10^5$	$1.88x10^5$	$1.84x10^5$	$1.84x10^4$
1 in 50 year	$3.75x10^5$	$6.26x10^5$	$5.00x10^5$	$5.01x10^5$
1 in 100 year	$5.33x10^5$	$1.06x10^6$	$7.68x10^5$	$7.67x10^5$

GOES East

	6750 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	10125 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	13500 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	16875 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)
1 in 10 year	$5.85x10^4$	$6.77x10^4$	$6.53x10^4$	$6.45x10^4$
1 in 50 year	$1.23x10^5$	$1.94x10^5$	$1.98x10^5$	$1.66x10^4$
1 in 100 year	$1.67x10^5$	$3.09x10^4$	$3.25x10^5$	$2.49x10^5$

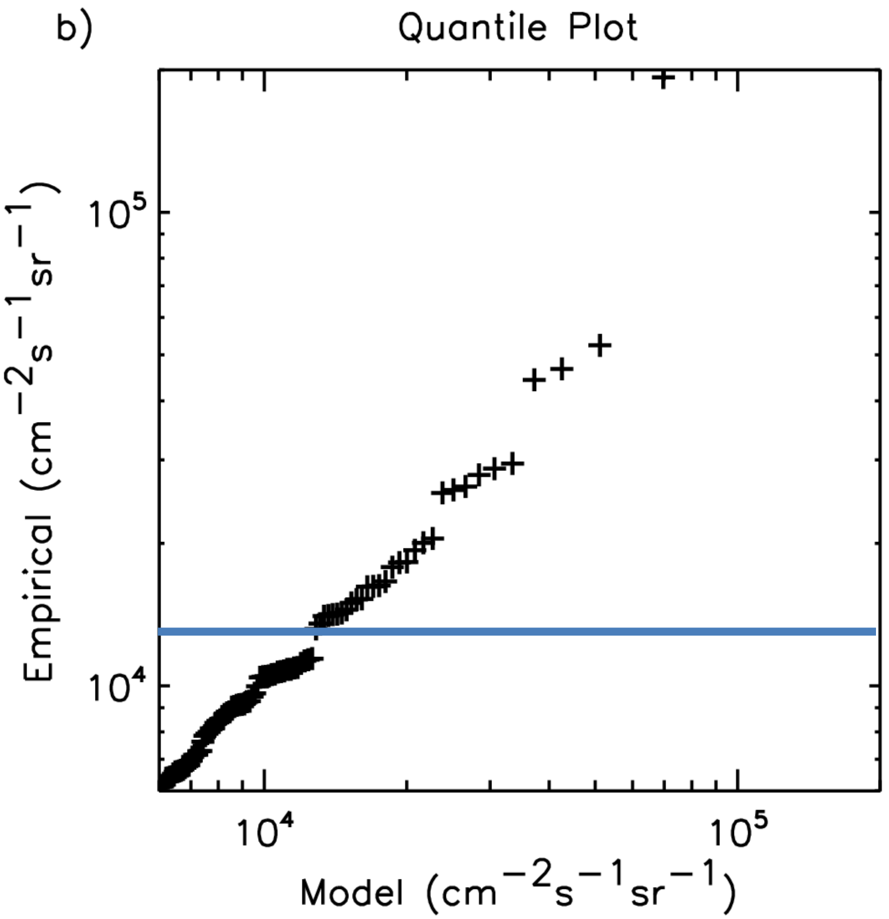
Appendix 6 - Choice of Threshold at GOES West

- We want to fit to the GPD to the extreme values of the distribution
- Need enough points for a meaningful fit
- Quantile plot should be approximately linear
- For GOES West we set the threshold 4.0x10^4 $cm^{-2}s^{-1}sr^{-1}$



Appendix 6 - Choice of Threshold at GOES East

- For GOES East we set the threshold at 1.35×10^4 $cm^{-2}s^{-1}sr^{-1}$



Appendix 7 - Is the Distribution Bounded ?

- The shape parameter controls the behaviour of the tail

  if $\xi < 0$ the distribution has an upper limit

  if $\xi > 0$ the distribution has no upper limit

- The shape parameters for the fits at GOES West and GOES East are 0.61 ± 0.44 and 0.73 ± 0.33

- Our results suggest that there is no upper limit to the flux of $E > 2$ MeV electrons at geosynchronous orbit

Appendix 7 - Is the Distribution Bounded ?

- Early work by Koons [2001] and O'Brien *et al*. [2007] suggests that the flux of E > 2 MeV electrons tends to a limiting value

- We repeated our analysis using log fluxes as done by Koons [2001] and O'Brien *et al.* [2007]

- The new shape parameters became 0.019±0.28 and 0.16±0.23

- The shape parameters for both log fits include negative values within their error bars suggesting that we treat the conclusion that the fluxes have no upper bound with caution

Appendix 7 - Is the Distribution Bounded ?

- The studies demonstrate the difficulty of determining the presence or absence of an upper bound from only 10-20 years data
- A definitive answer probably requires data covering many more decades
- In reality there is likely to be an upper bound set by some physical process but this is not evident from the statistical analysis here