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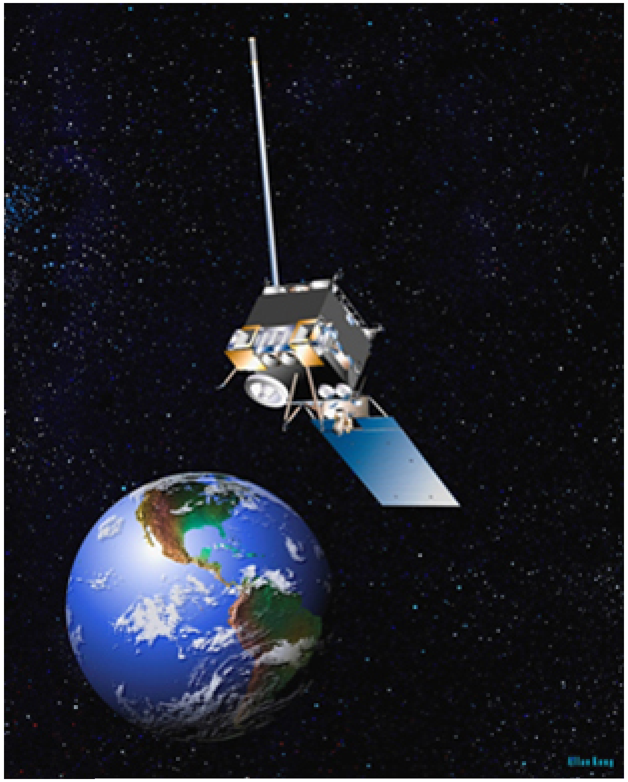
- The objective of this study is to calculate the electron flux for the 1 in 10, 1 in 50, and 1 in 100 year space weather event at geosynchronous orbit

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

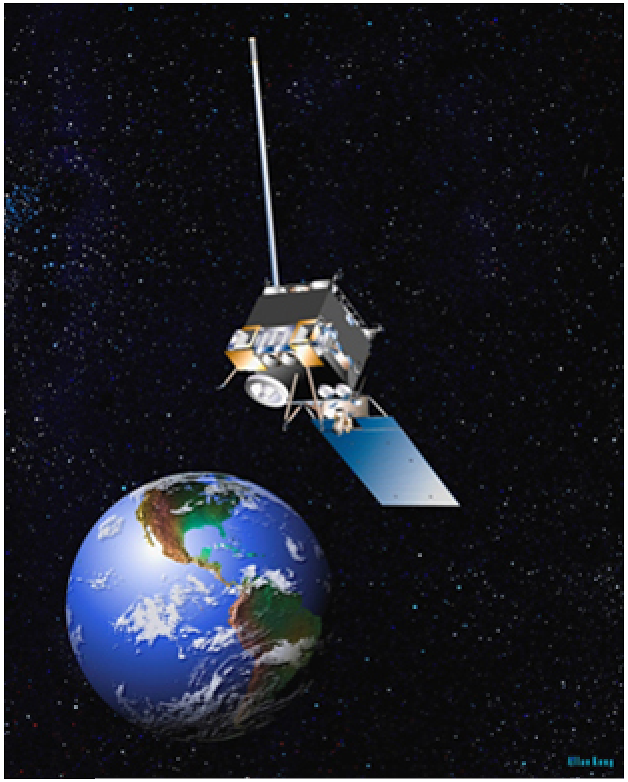


credit: NOAA

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

Data Analysis

- Electron data
  - have been corrected for proton contamination
  - have not been corrected for dead time which could result in an underestimate of the flux by up to a factor of two at the highest count rates



credit: NOAA

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

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 75° and GOES West at 135° W
- The satellites are at different magnetic latitudes with GOES East at 11° N and GOES West at 4° 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

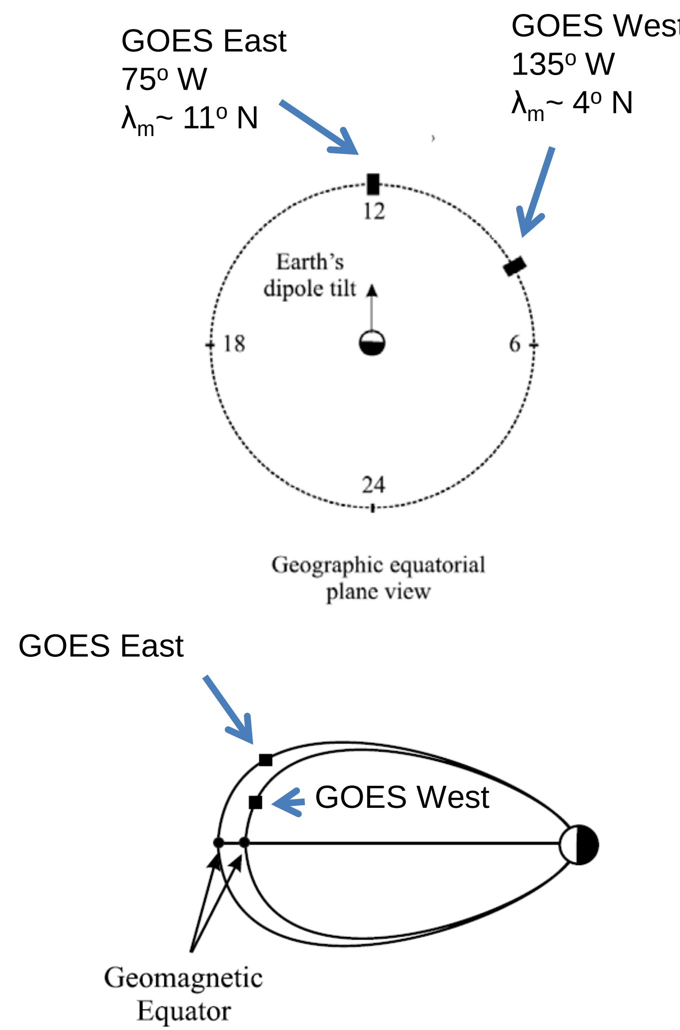
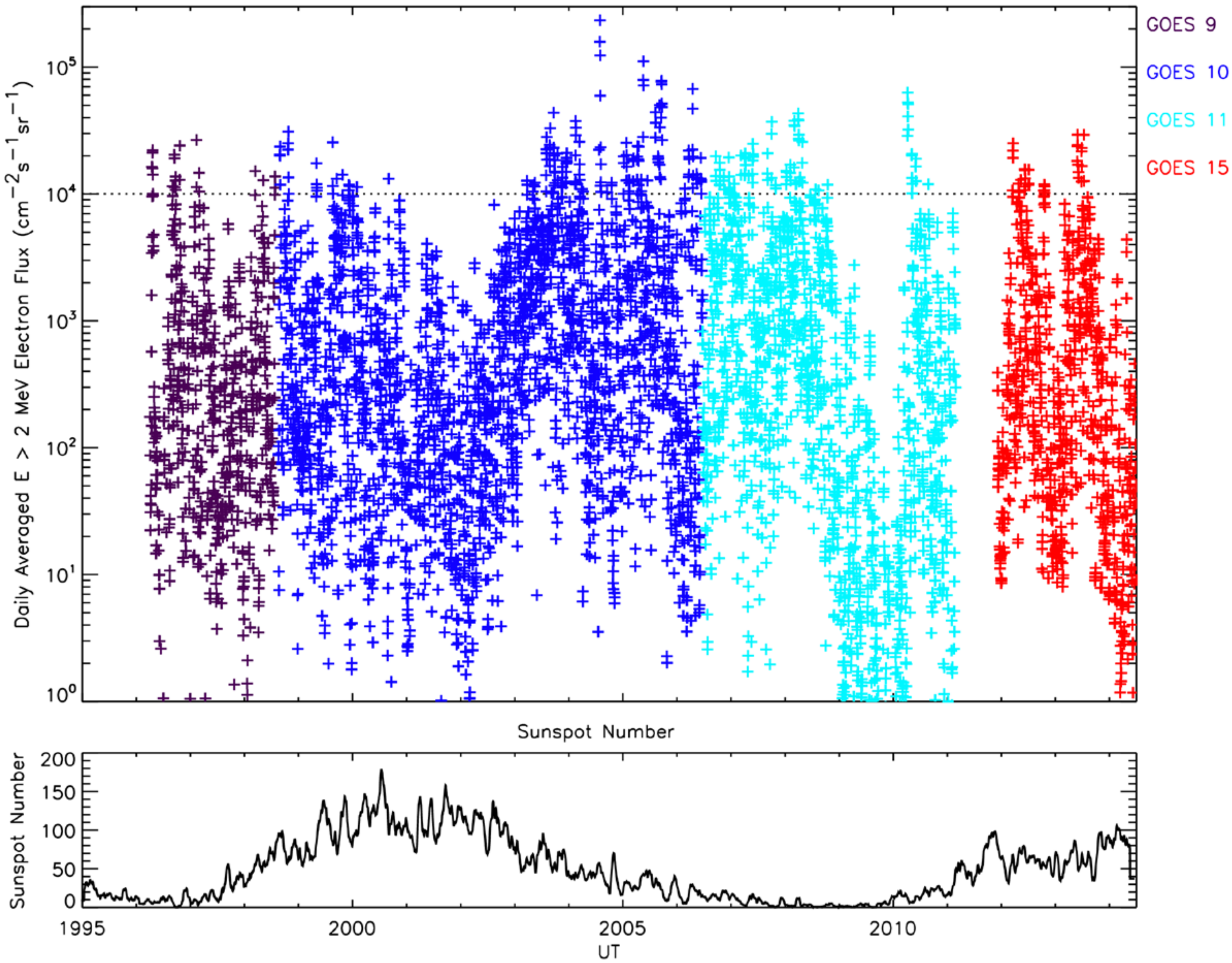


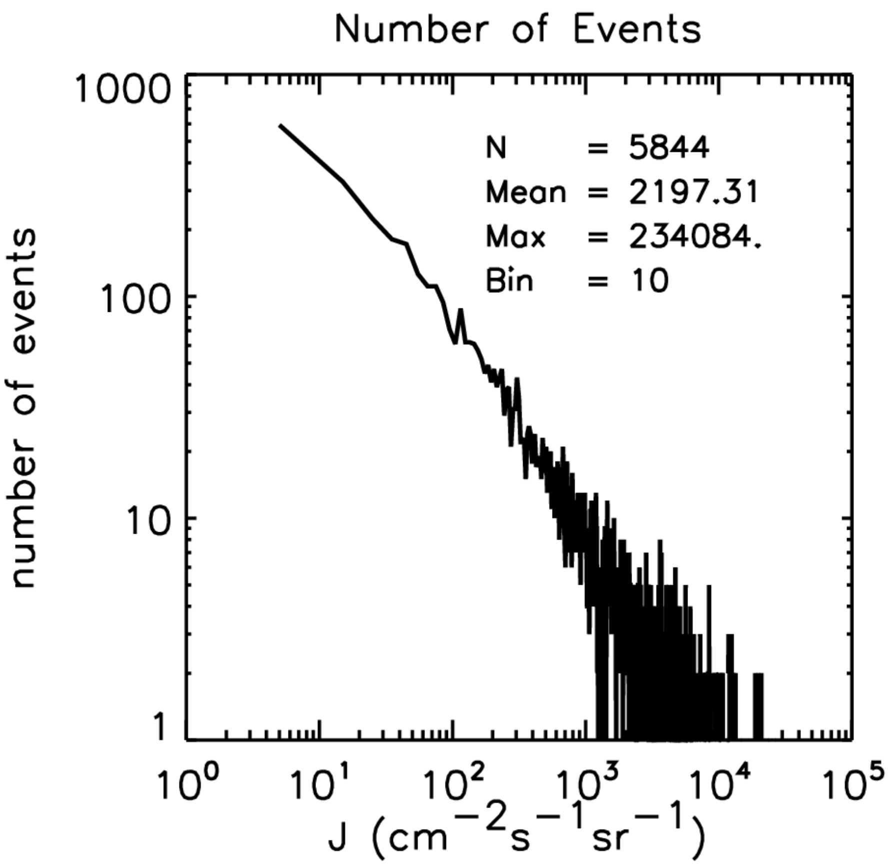
Figure adapted from Onsager *et al*., 2004

GOES West: E > 2 MeV Electrons



GOES West: E > 2 MeV Electrons

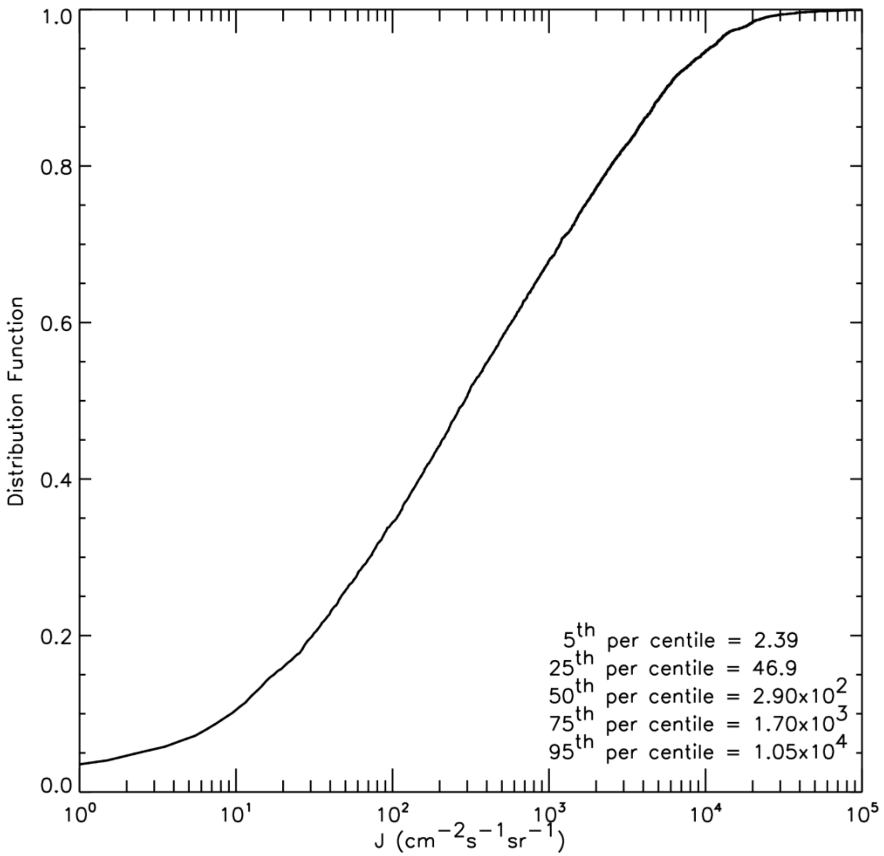
- Total number of days: 5844
- ~16 years of good data
- Mean Flux: 2.20×10^3 $cm^{-2}s^{-1}sr^{-1}$



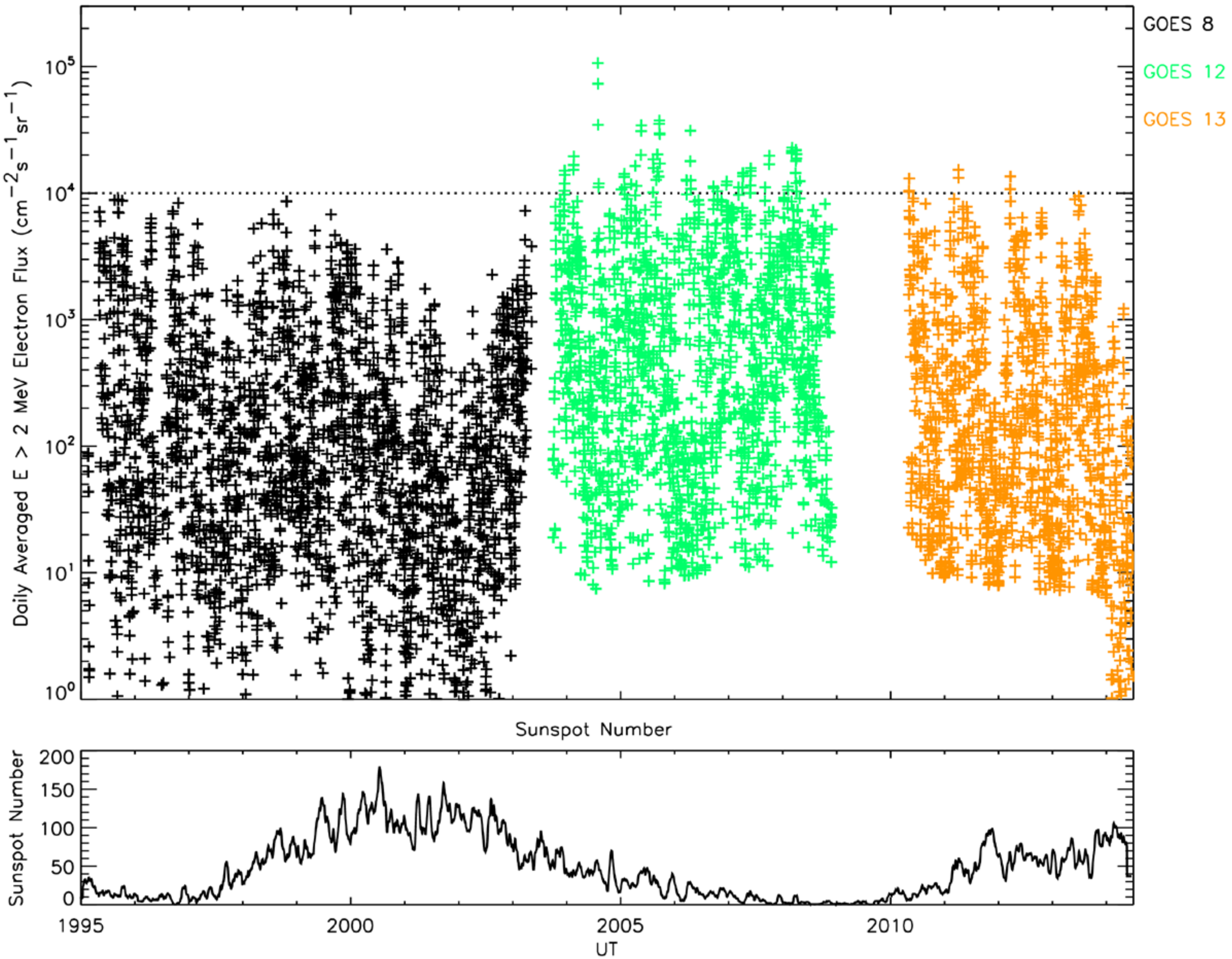
GOES West: Cumulative Distribution Function

- Fluxes cover 5 orders of magnitude

- 95^{th} percentile
  - 1.05×10^4 $cm^{-2}s^{-1}sr^{-1}$

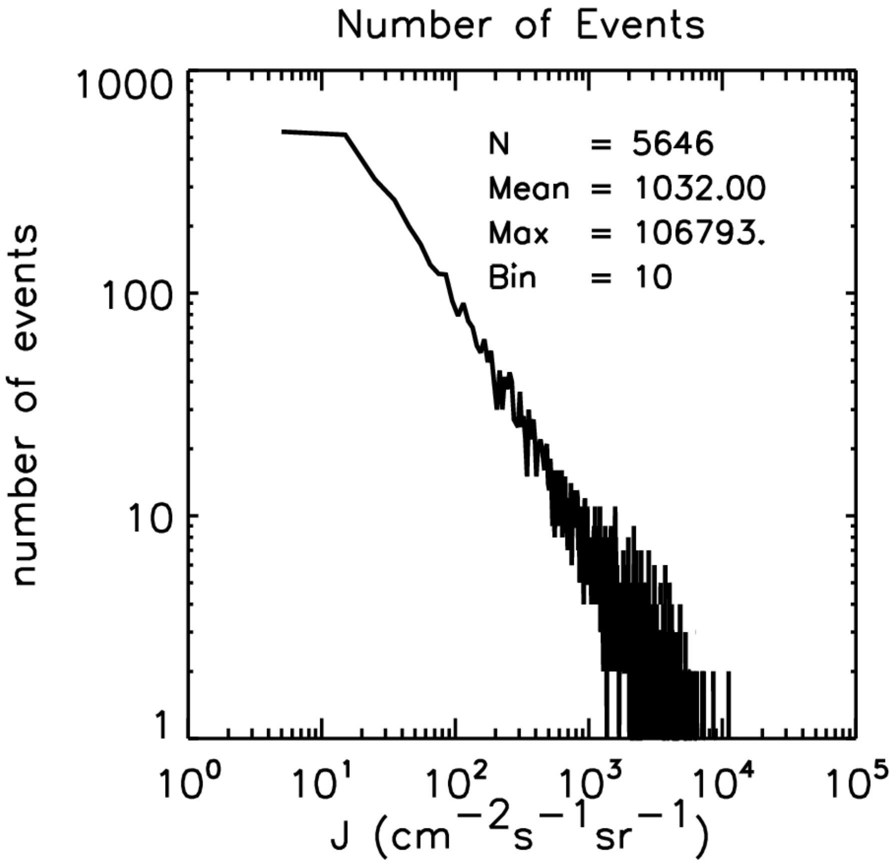


GOES East: E > 2 MeV Electrons



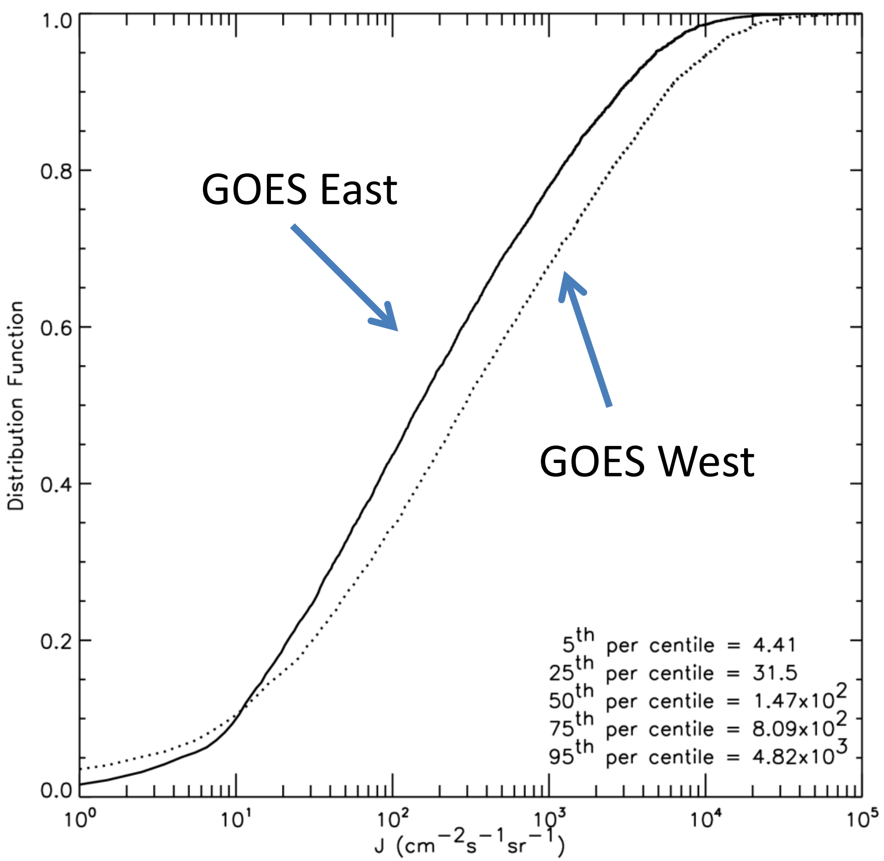
GOES East: E > 2 MeV Electrons

- Total number of days: 5646
- ~15.5 years of good data
- Mean Flux: 1.03x10^3 $cm^{-2}s^{-1}sr^{-1}$



GOES East: Cumulative Distribution Function

- Fluxes at GOES West on average a factor of two higher than those at GOES East



Extreme Value Analysis

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

- For daily data best approach is the exceedances over a threshold approach since this method uses more of the available data

- 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 that represents the probability that a random variable X exceeds some value x given that it already exceeds a threshold u, $Pr(X<x| x>u)$

- Following Koons [2001] we choose a threshold of 10^4 $cm^{-2}s^{-1}$ sr^{-1}

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 Level Plot

- In this study we are interested in the largest flux that is likely to be encountered over a given period of time

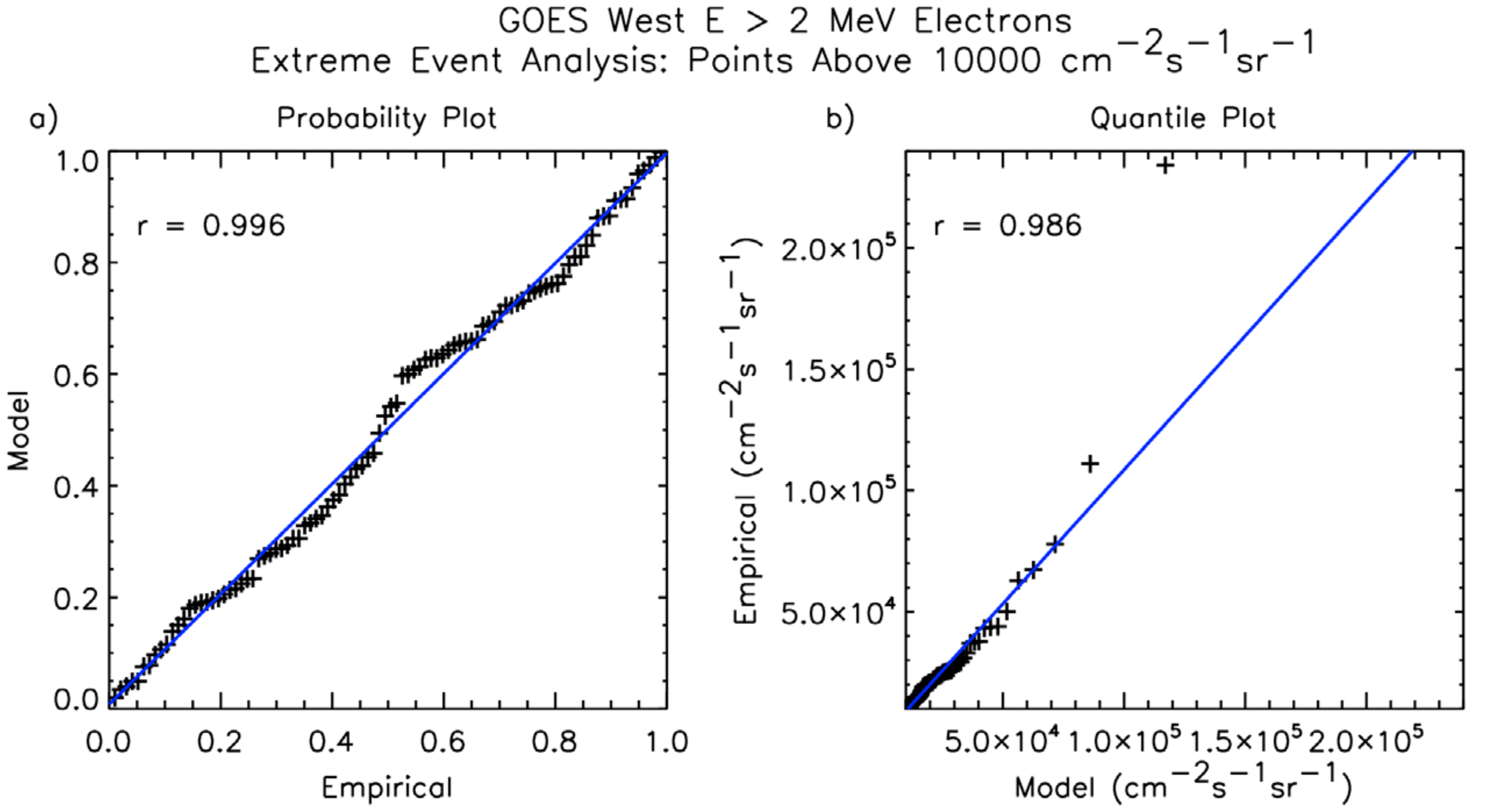
- The level x_N which is exceeded on average once every N years is given by

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

where $\zeta = n_c/n_{tot}$, the number of cluster maxima divided by the total number of daily values and nd = 365.25 is the average number of days in any given year

- A plot of x_N against N is known as a return level plot

GOES West: Extreme Value Analysis

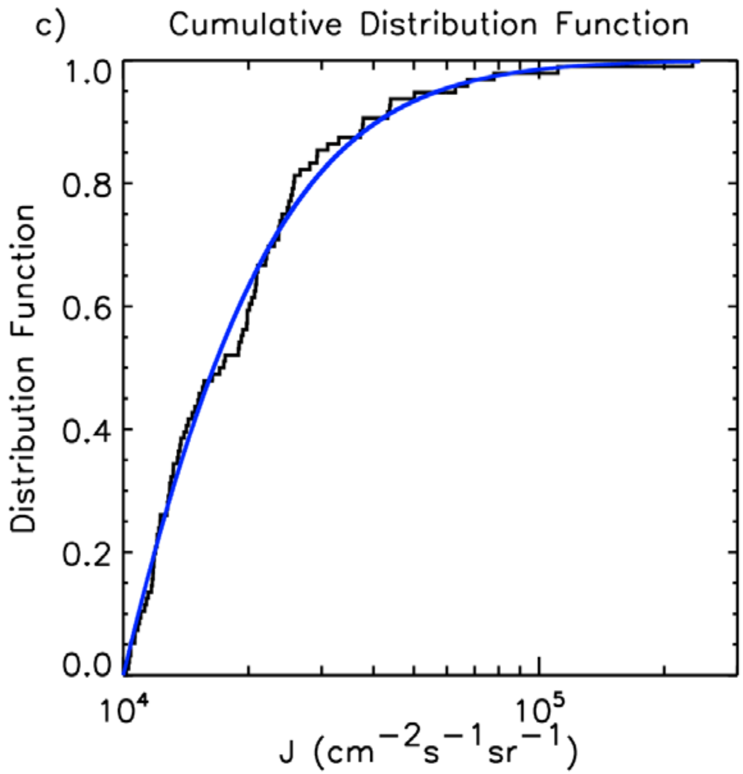


- The probability and quantile plots are both approximately linear showing that the GPD is a good method for modelling the exceedances

GOES West: CDF of Exceedances

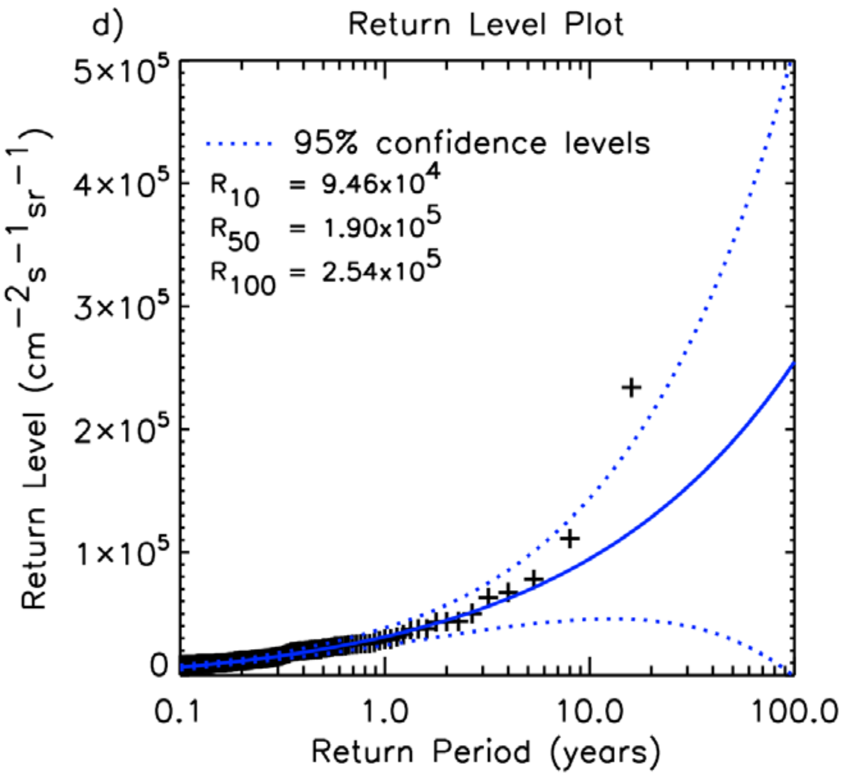
- Maximum likelihood estimates of the scale and shape parameter are 8.12×10^3 and 0.403

- The shape parameter is positive which implies that there is no upper limit to the maximum flux



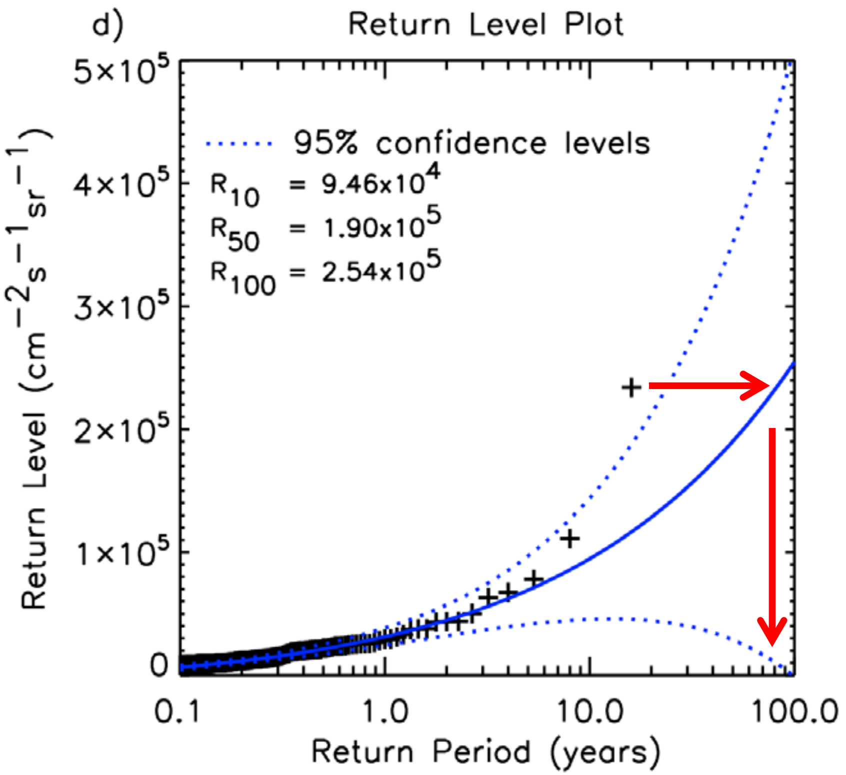
GOES West: Return Level Plot

- One in Ten Year Flux
  - 9.46×10^4 $cm^{-2}s^{-1}sr^{-1}$
- One in Fifty Year Flux
  - 1.90×10^5 $cm^{-2}s^{-1}sr^{-1}$
- One in One Hundred Year Flux
  - 2.54×10^5 $cm^{-2}s^{-1}sr^{-1}$

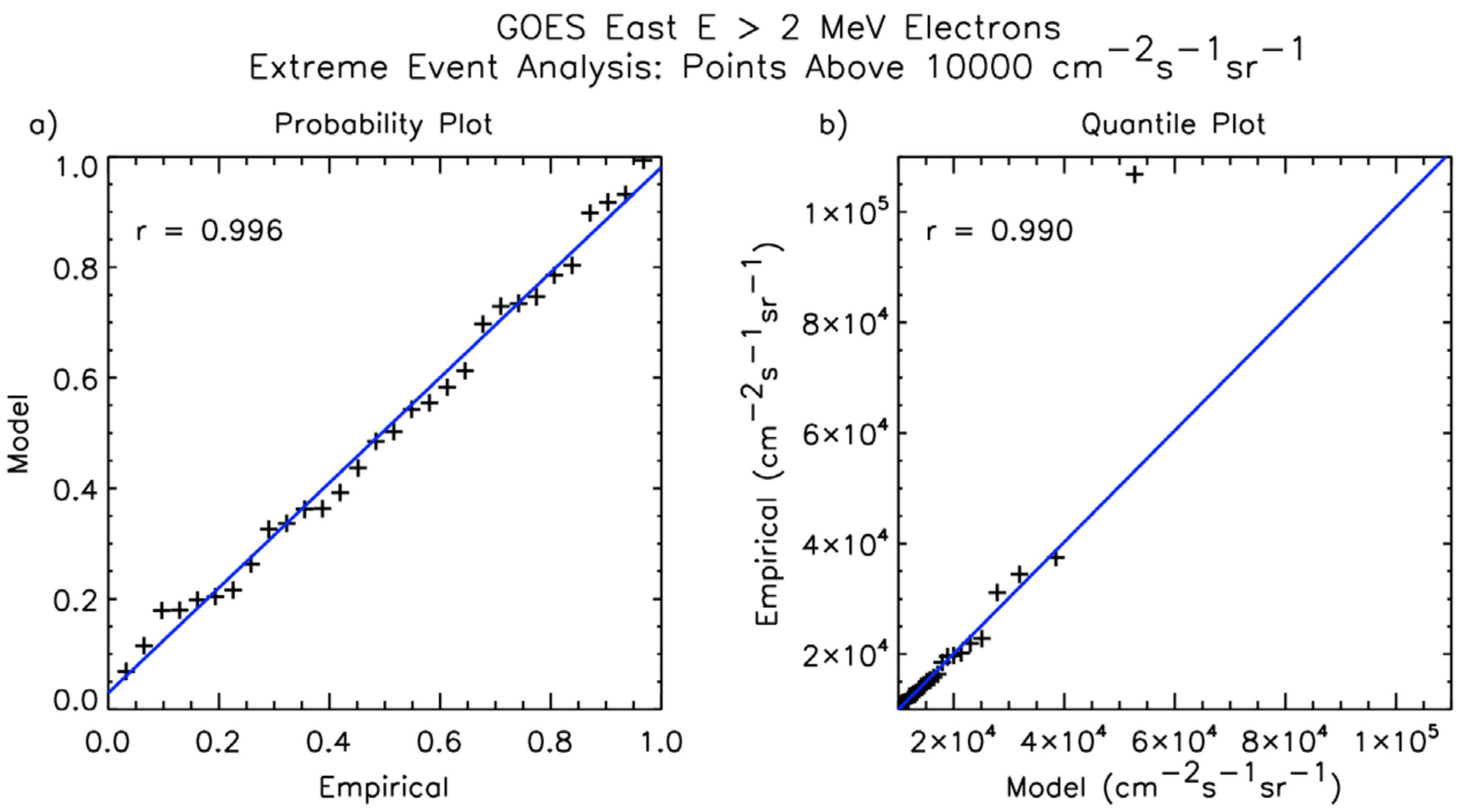


GOES West: Return Level Plot

- Largest observed flux is a one in eighty year event



GOES East: Extreme Value Analysis

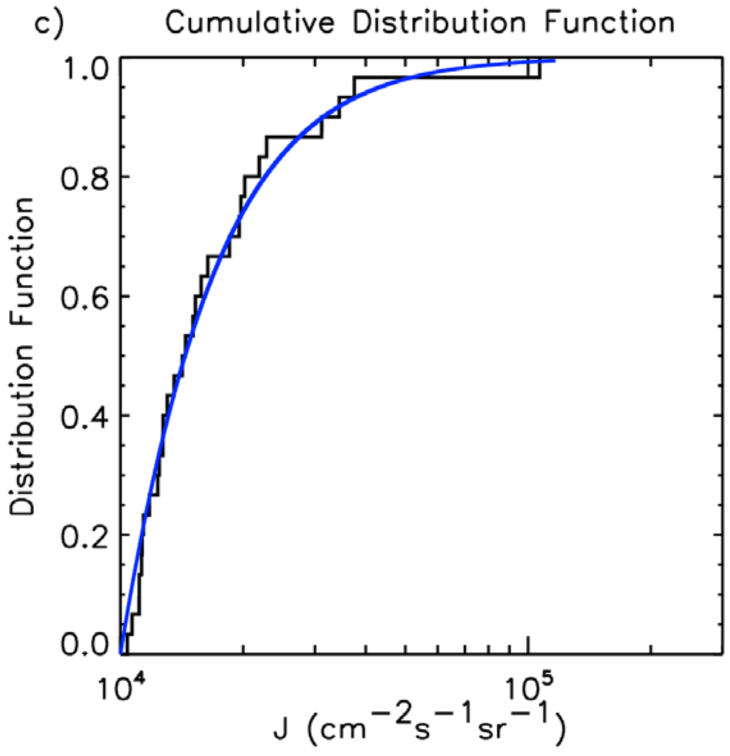


- The probability and quantile plots are both approximately linear showing that the GPD is a good method for modelling the exceedances

GOES East: CDF of Exceedances

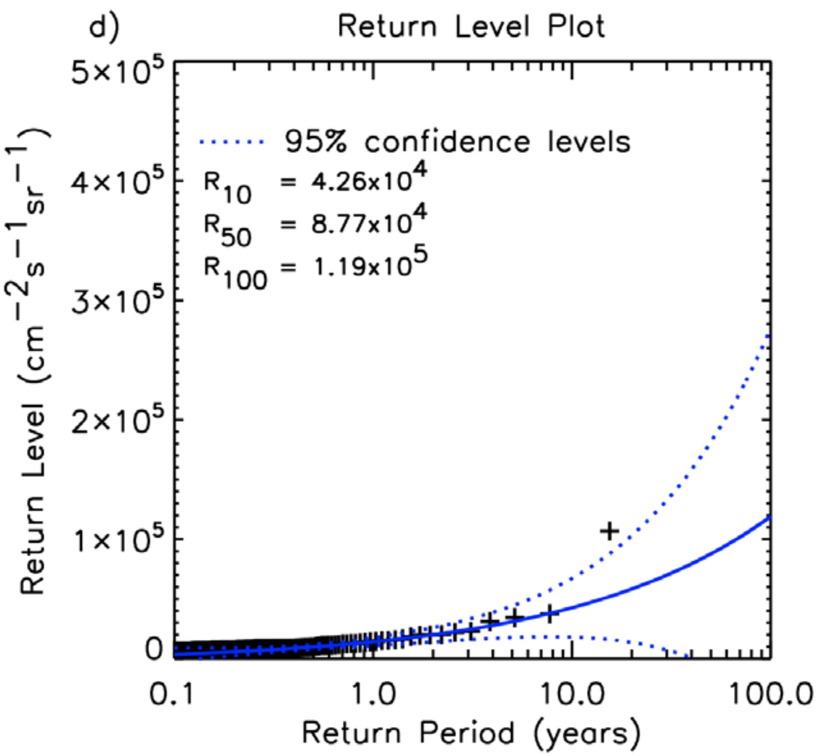
- Maximum likelihood estimates of the scale and shape parameter are 5.45×10^3 and 0.429

- The shape parameter is positive which implies that there is no upper limit to the maximum flux



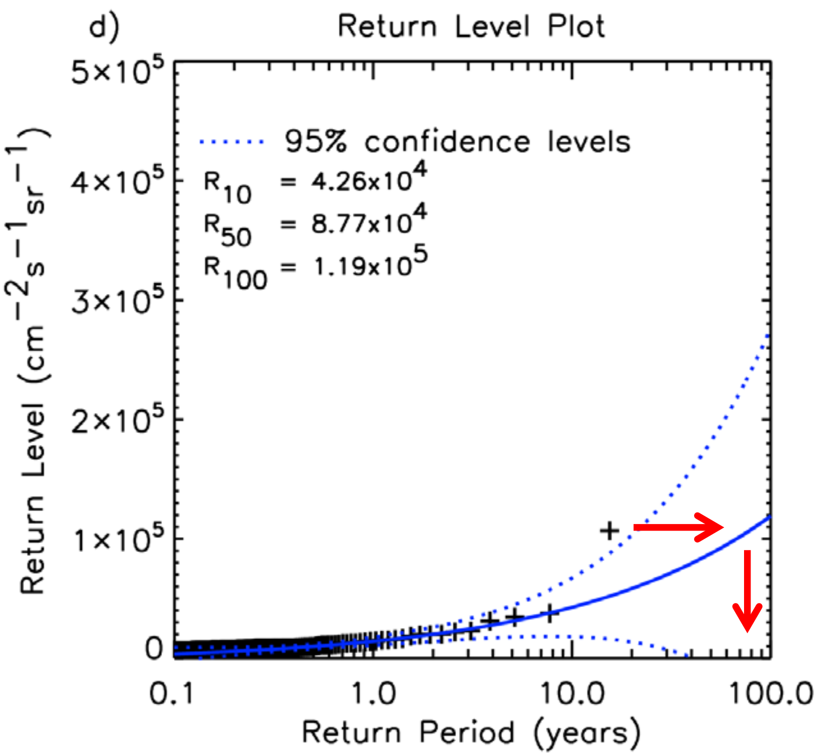
GOES East: Return Level Plot

- One in Ten Year Flux
  - $4.26x10^4$ $cm^{-2}s^{-1}sr^{-1}$
- One in Fifty Year Flux
  - $8.77x10^4$ $cm^{-2}s^{-1}sr^{-1}$
- One in One Hundred Year Flux
  - $1.19x10^5$ $cm^{-2}s^{-1}sr^{-1}$



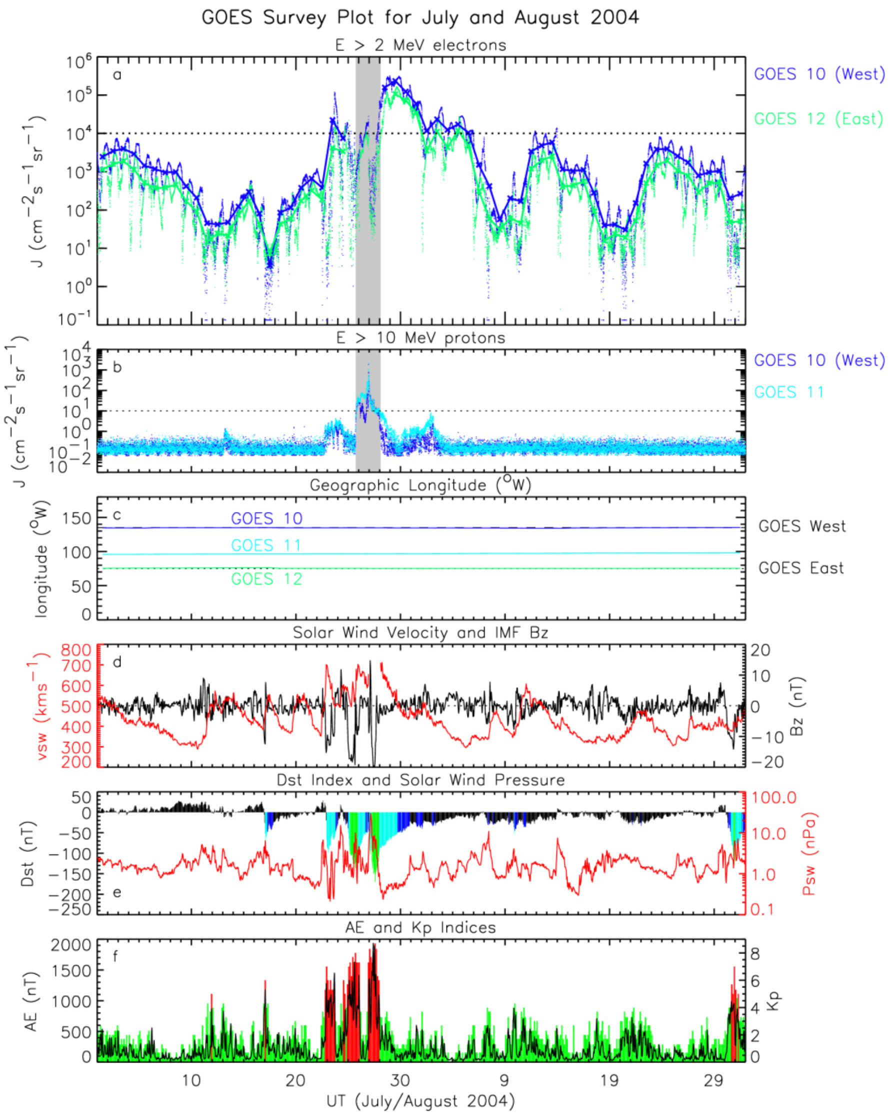
GOES East: Return Level Plot

- Largest observed flux is a one in eighty year event



July/August 2004

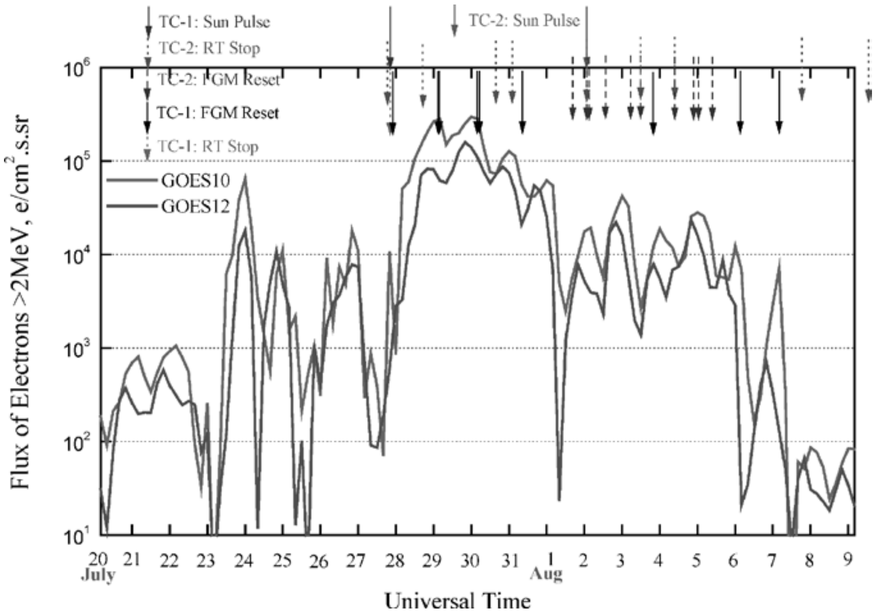
- Largest E > 2 MeV flux of 2.34x10^5 cm^{-2}s^{-1}sr^{-1} observed at GOES-West on 29th July 2004
- Coincided with the largest E > 2 MeV flux of 1.07x10^5 cm^{-2}s^{-1}sr^{-1} at GOES-East
- Independent measurements of this extreme flux event suggests the flux event is real
- GOES-West flux exceeded 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]

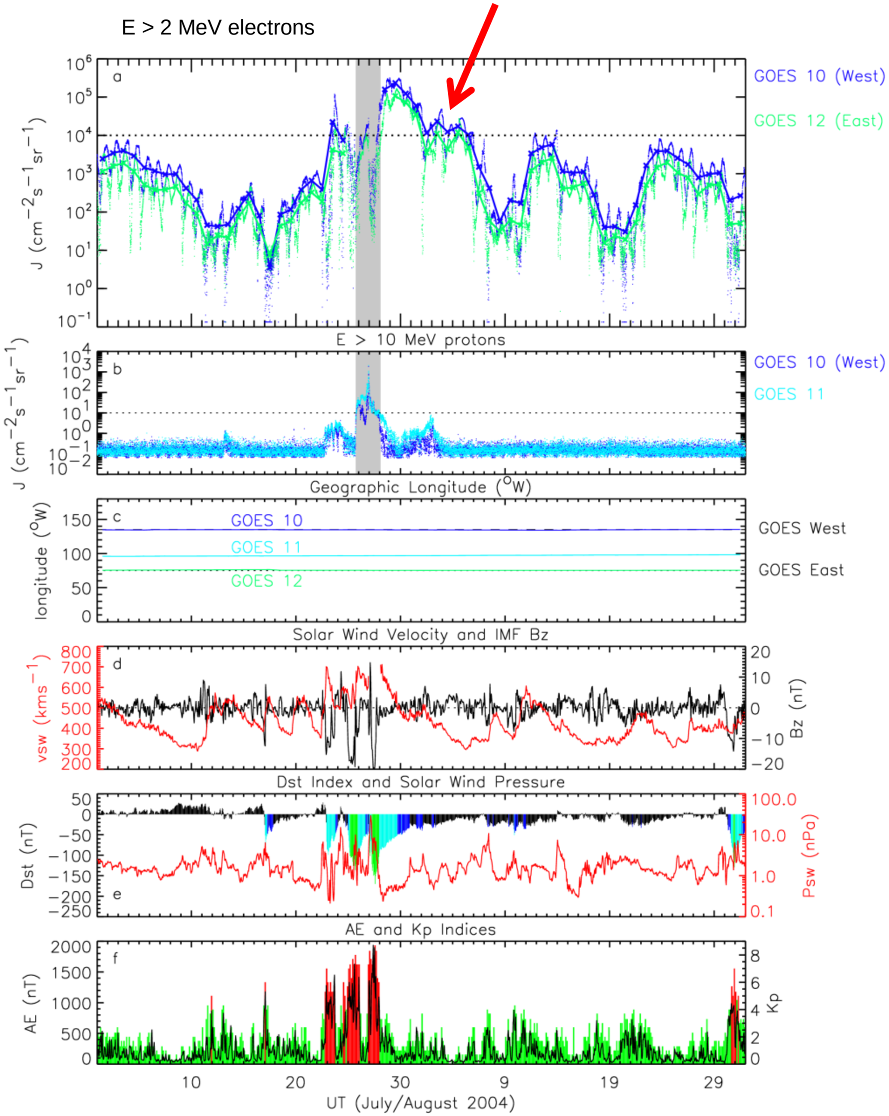
- These anomalies largely occurred in the Earth's radiation belt and were attributed to internal charging [Han *et al*., 2005]



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

Conclusions

- The daily average flux of E > 2 MeV electrons measured at GOES West is typically a factor of two higher than that measured at GOES East
- The flux of E > 2 MeV electrons is larger at GOES West than at GOES East because GOES West is at a lower magnetic latitude and hence L shell. Thus geosynchronous satellites located near the magnetic equator at 20^{o}E and 160^{o}W will experience the largest fluxes.
- The 1 in 10, 1in 50 and 1 in 100 year event at GOES West are 9.46×10^4 1.90×10^5 and 2.54×10^5 $cm^{-2}s^{-1}sr^{-1}$ respectively
- The largest event seen during the study period was particularly extreme. Our study suggests that this was a one in eighty 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

Top Ten Flux Events at GOES West

	Flux ($cm^{-2}s^{-1}sr^{-1}$)	Date
1	2.34×10^{5}	29th July 2004
2	1.58×10^{5}	28th July 2004
3	1.24×10^{5}	30th July 2004
4	1.11×10^{5}	18th May 2005
5	7.93×10^{4}	17th May 2005
6	7.79×10^{4}	18th September 2005
7	7.67×10^{4}	17th September 2005
8	7.31×10^{4}	19th September 2005
9	7.16×10^{4}	19th May 2005
10	6.73×10^{4}	17th April 2006

Top Ten Flux Events at GOES East

	Flux ($cm^{-2}s^{-1}sr^{-1}$)	Date
1	$1.07x10^5$	29th July 2004
2	$7.32x10^4$	30th July 2004
3	$3.75x10^4$	19th September 2005
4	$3.53x10^4$	18th September 2005
5	$3.47x10^4$	31st July 2004
6	$3.44x10^4$	19th May 2005
7	$3.12x10^4$	17th April 2006
8	$3.10x10^4$	18th May 2005
9	$2.97x10^4$	20th September 2005
10	$2.92x10^4$	21st September 2005

Appendix 1 - Exclusions

- 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

	5000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	10000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	15000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	20000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)
1 in 10 year	9.94×10^4	9.46×10^4	9.39×10^4	8.58×10^4
1 in 50 year	1.92×10^5	1.90×10^5	1.84×10^5	1.64×10^5
1 in 100 year	2.54×10^5	2.54×10^5	2.43×10^5	2.17×10^5

GOES East

	5000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	10000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	15000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)	20000 $cm^{-2}s^{-1}sr^{-1}$ ($cm^{-2}s^{-1}sr^{-1}$)
1 in 10 year	4.17×10^4	3.92×10^4	4.26×10^4	4.26×10^4
1 in 50 year	7.28×10^5	7.06×10^4	9.10×10^5	8.77×10^4
1 in 100 year	9.13×10^4	8.99×10^4	1.26×10^5	1.19×10^5