Determination of the 1 in 10, 1 in 50 and 1 in 100 Year Space Weather Event

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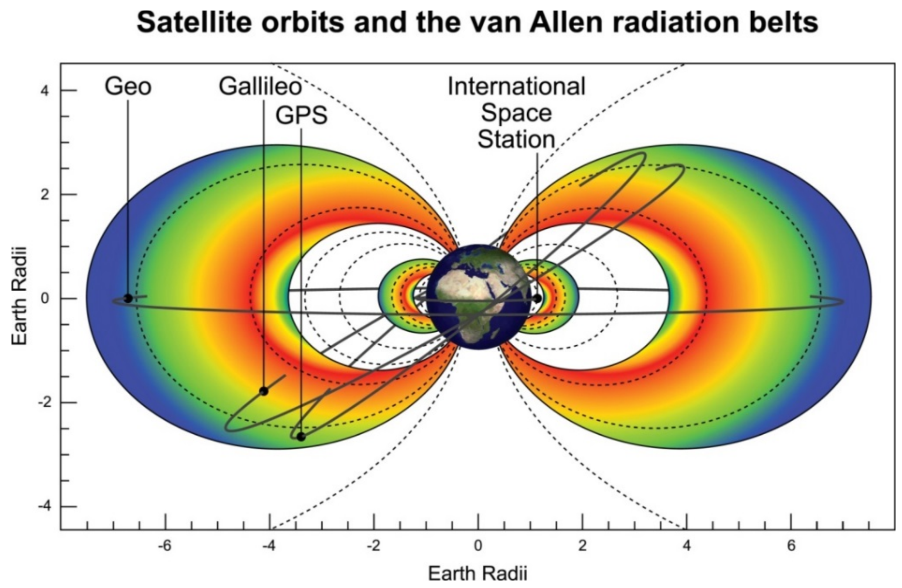
SPACESTORM Close-Out Meeting
Cambridge, UK, 23rd March 2017

Motivation

- Modern satellites have a life expectancy of 10-20 years.
- Satellite operators and engineers therefore require realistic estimates of the worst case environments that may occur on these and longer timescales.
- Satellite insurers also require this information to help them evaluate realistic disaster scenarios.

Extreme Space Weather Events

- As part of SPACESTORM we have conducted extreme value analyses to determine the 1 in 10, 1 in 50, and 1 in 100 year space weather event for
  - relativistic electrons at GEO and HEO
  - internal charging currents at MEO
  - energetic electrons at LEO



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Extreme Value Analysis

- Two main methods for extreme value analysis
  - block maxima
  - exceedances over a high threshold
- The exceedances over the threshold approach makes the best use of the available data and has been successfully applied in many fields
- For this approach the appropriate distribution function is the Generalised Pareto Distribution (GPD)

Declustering

- Values can exceed the threshold on consecutive measurements
- The statistical analysis requires 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 depending on the temporal behaviour of the data
- Identify the maximum excess in each cluster
- Fit the GPD to the cluster maxima

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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 cluster maxima 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

- We fit the GPD to the tail of the distribution using maximum likelihood estimation

Determination of the 1 in N Year Event

- Our major objective is to determine the 1 in N year space weather event

- The value that is exceeded on average once every N years can be expressed in terms of the fitted parameters σ and ξ as:

$$x_N = u + (\sigma/\xi)((N n_d n_c/n_{tot})^{\xi} - 1))$$

where n_d is the number of data points in a given year, n_c is the number of cluster maxima and n_{tot} is the total number of data points

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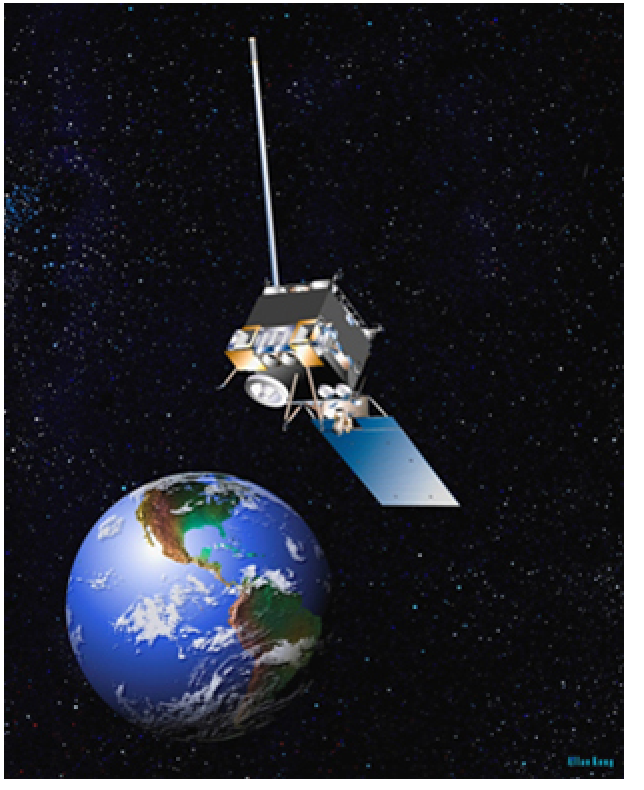
Relativistic Electrons at GEO

- For this study we use data from the EPS sensors on board the NOAA GOES satellites at GEO
- We use 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



credit: NOAA

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

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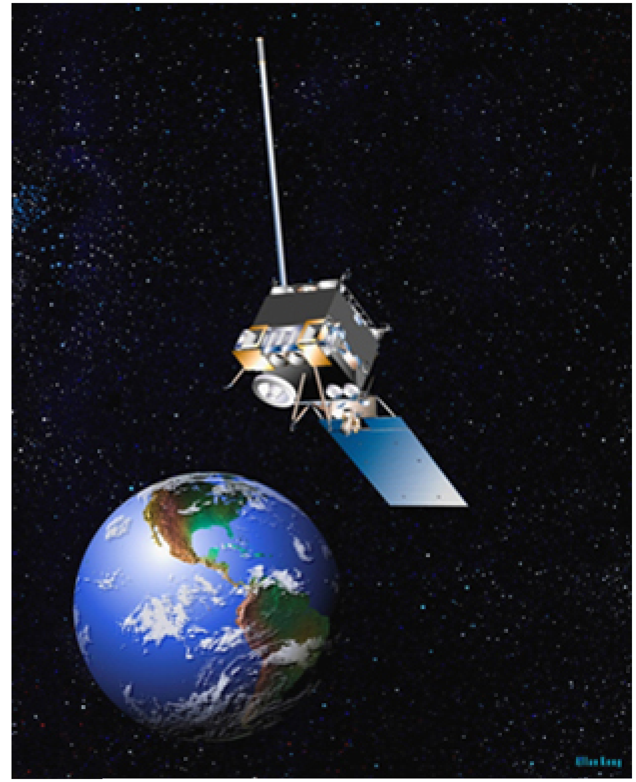
Relativistic Electrons at GEO

- 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



credit: NOAA

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

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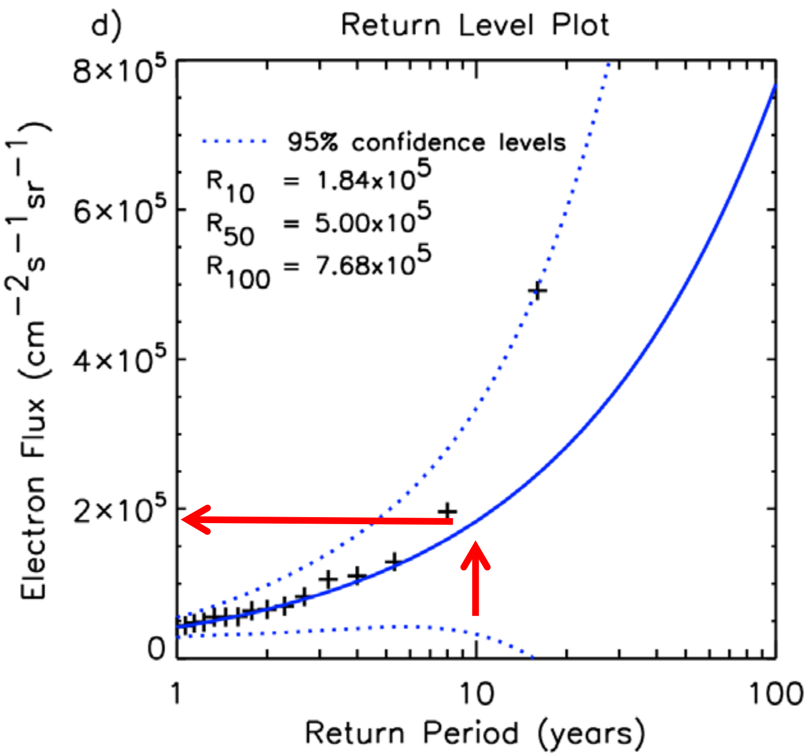
GOES West: Return Level Plot

- 1 in 10 Year Flux
    - 1.84×10^5 $cm^{-2}s^{-1}sr^{-1}$



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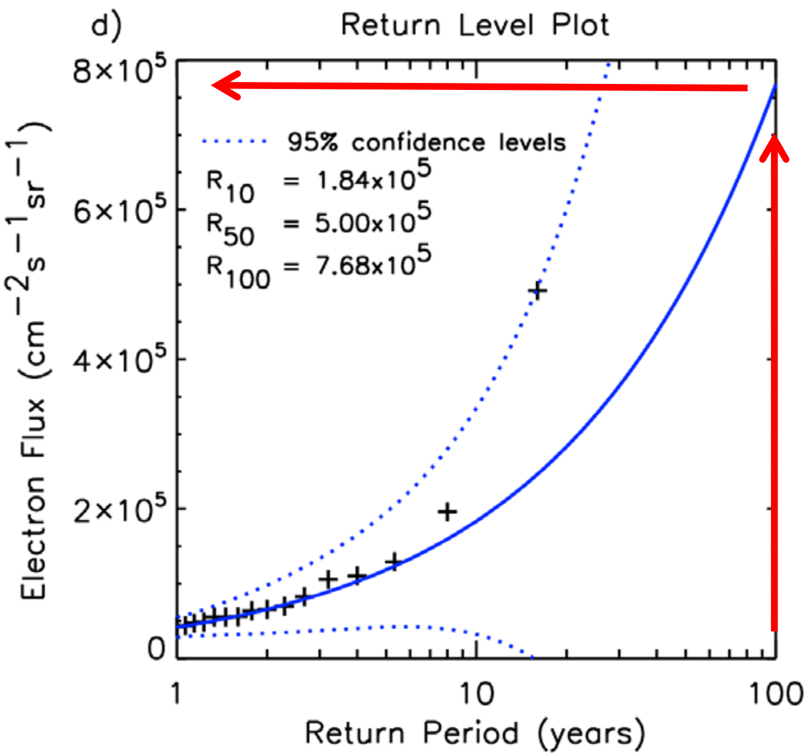
GOES West: Return Level Plot

- 1 in 10 Year Flux
  - 1.84×10^5 $cm^{-2}s^{-1}sr^{-1}$

- 1 in 100 Year Flux
  - 7.68×10^5 $cm^{-2}s^{-1}sr^{-1}$



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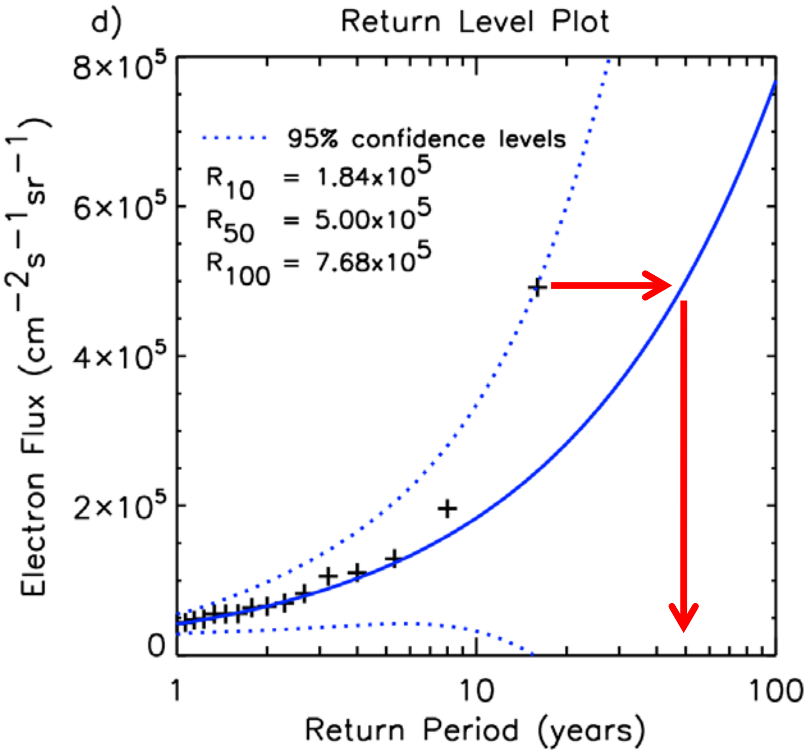
GOES West: Return Level Plot

- Largest observed flux is a 1 in 50 year event



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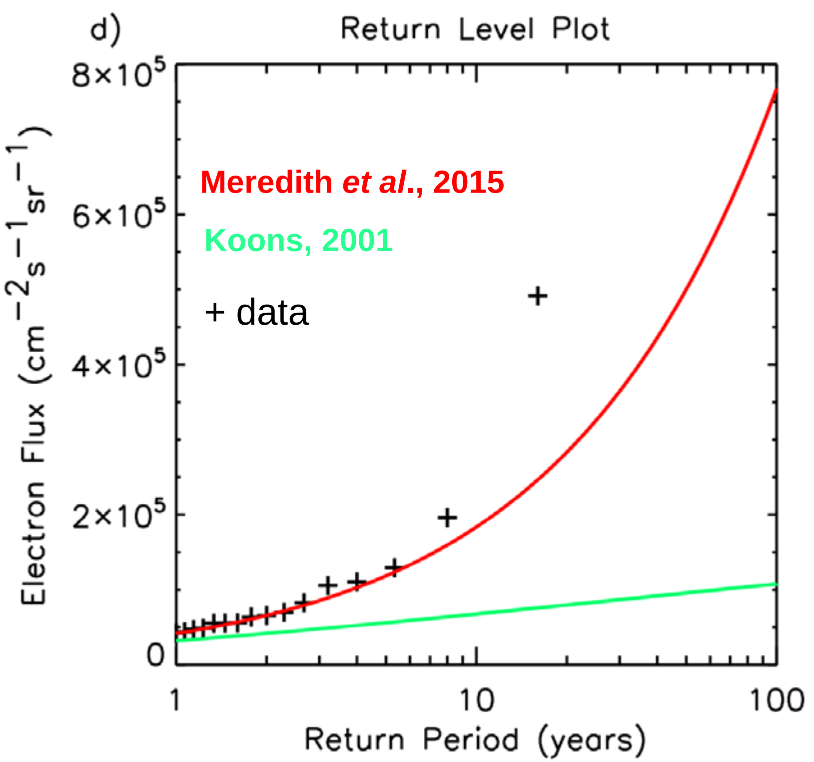
Comparison with Koons [2001] Study

- 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]



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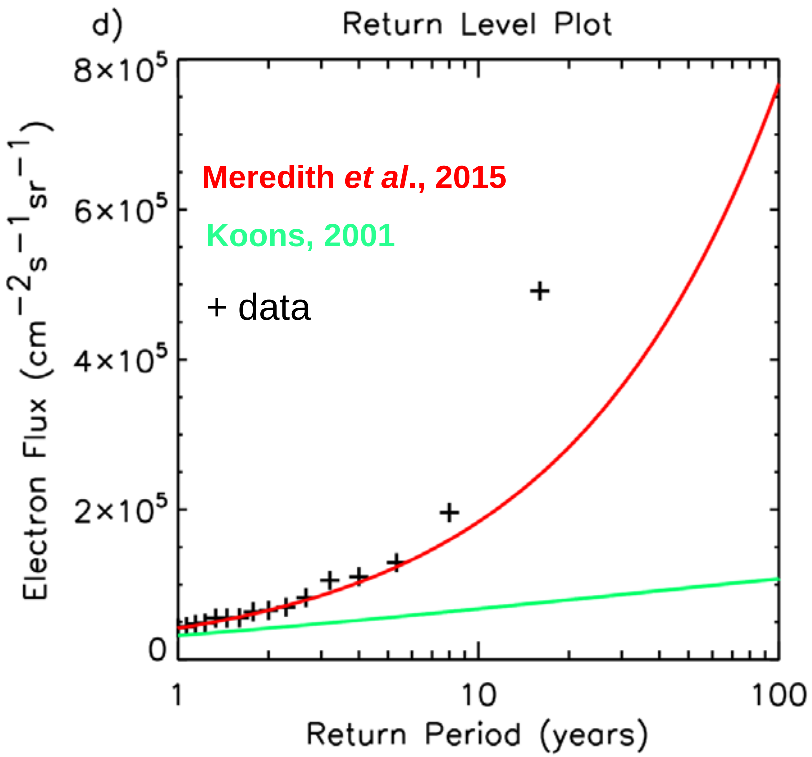
Comparison with Koons [2001] Study

- Reasons for differences between studies include
  - use of modern instrumentation
  - correction of data for dead time
  - declustering of data
  - sorting data according to satellite location



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Impact

- The revised extreme flux levels have been used to update the UK National Risk Assessment

- The results have also been used by a satellite operator in the evaluation of satellite tenders

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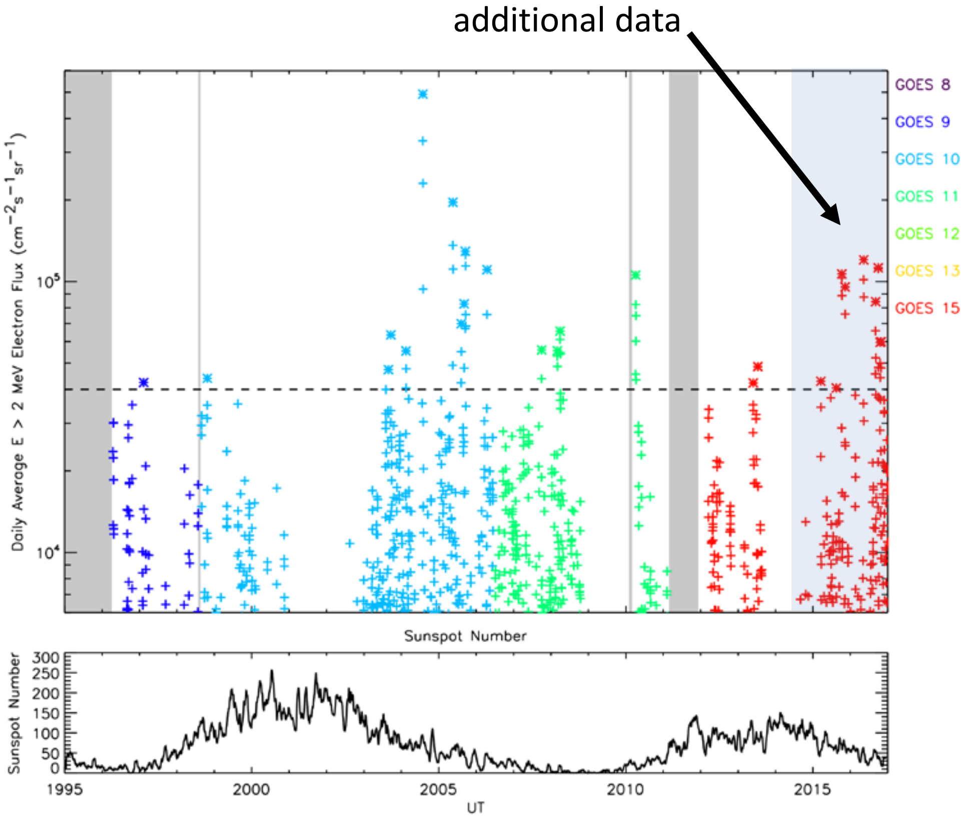
Extended Analysis (1995-2017)

- Analysis recently updated to include an additional 2.5 years of data
- Data now cover 2 solar cycles



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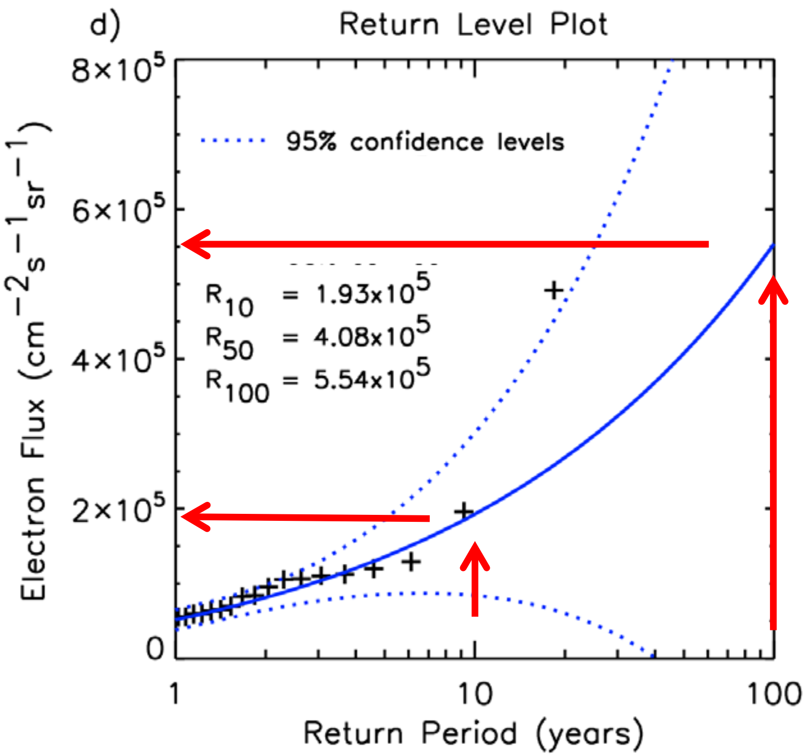
Extended Analysis (1995-2017)

- 1 in 10 Year Flux
  - 1.93×10^5 $cm^{-2}s^{-1}sr^{-1}$
  - 5% increase
- 1 in 100 Year Flux
  - 5.54×10^5 $cm^{-2}s^{-1}sr^{-1}$
  - 30% decrease
  - 5 times the Koons [2001] estimate
- Largest event seems more extreme – 1 in 80 year event



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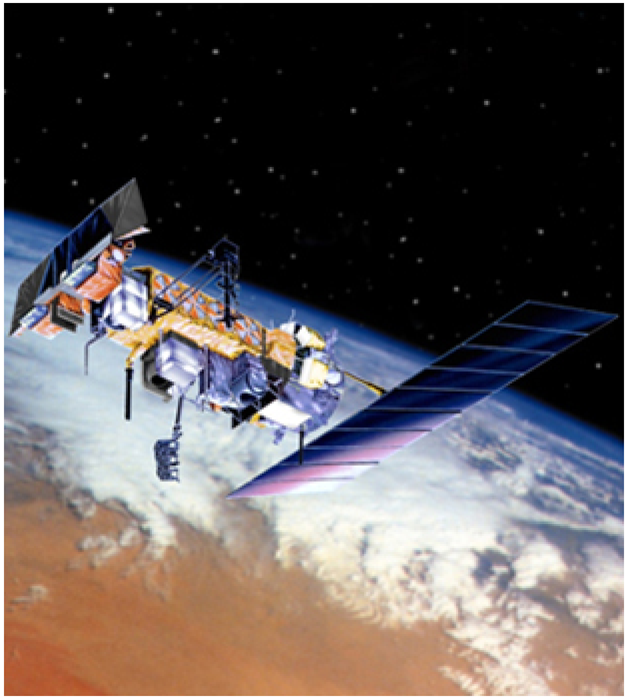
Energetic Electrons at LEO

- We use the 2 s resolution $E > 30$ keV, $E > 100$ keV, and $E > 300$ keV MEPED electron data from NOAA15 to NOAA19 from 1 July 1998 to 30 June 2014

- We calculated the maximum flux in each 3 h window as a function of energy and L^*

NOAA-19



credit: NOAA

Typical Orbital Parameters
Altitude: 854 km
Inclination: 98.7°
Period: 102.1 min

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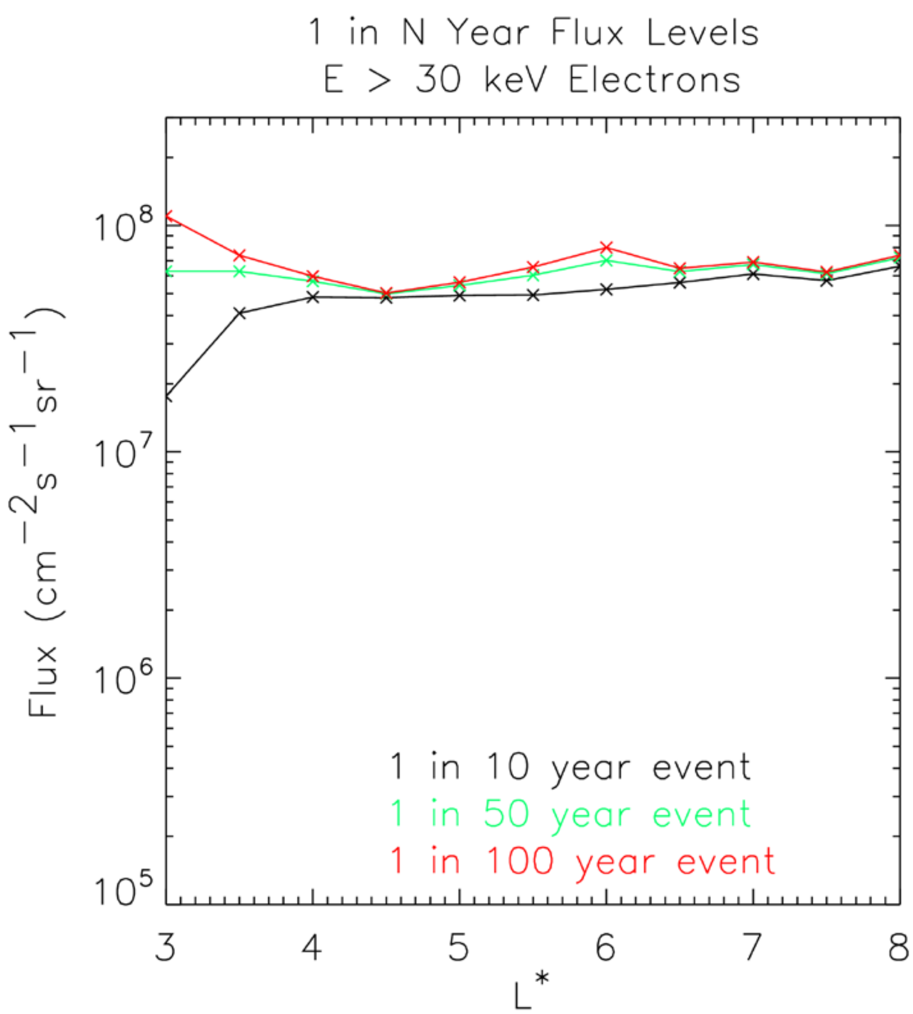
E > 30 keV Electrons: 1 in N Year Event Levels

- The 1 in 10 year flux of E > 30 keV electrons (black line) shows a gradual increasing trend with L* ranging from 1.8×10^7 $cm^{-2}s^{-1}sr^{-1}$ at L* = 3.0 to 6.6×10^7 $cm^{-2}s^{-1}sr^{-1}$ at L* = 8.0

- The 1 in 100 year flux (red line) is generally a factor of 1.1 to 1.5 larger than the corresponding 1 in 10 year event



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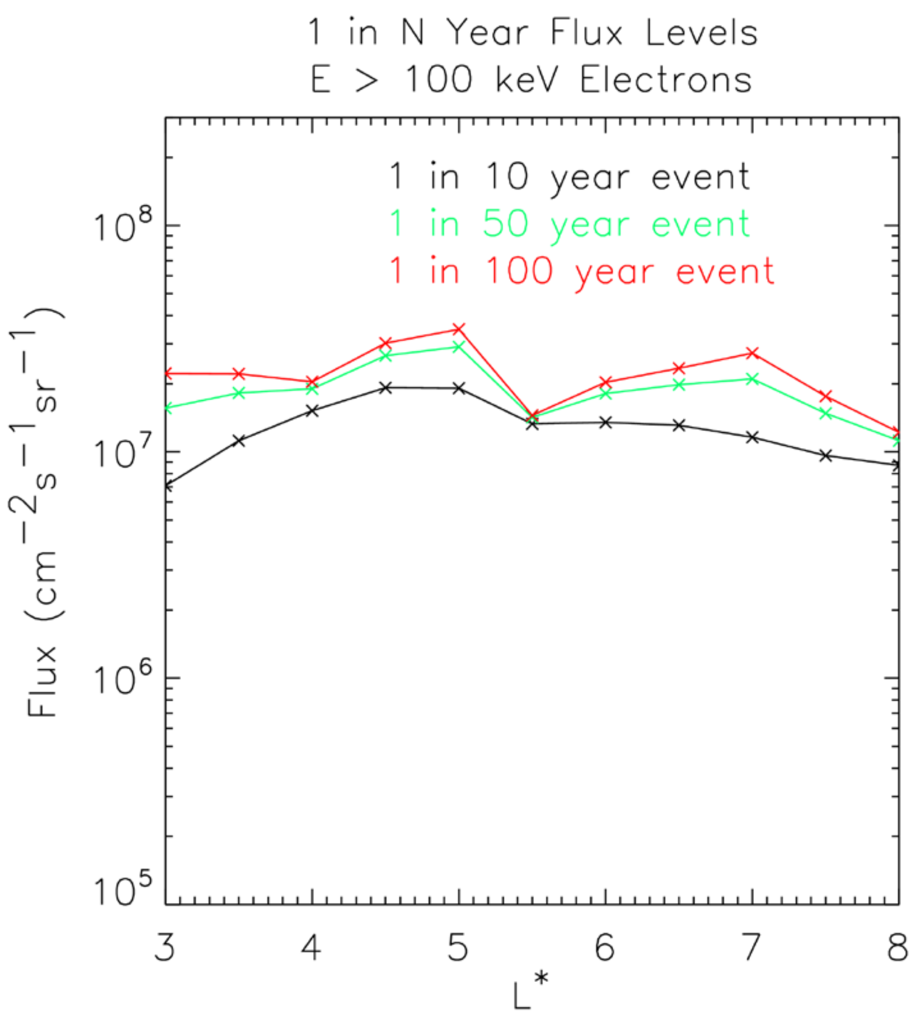
E > 100 keV Electrons: 1 in N Year Event Levels

- The 1 in 10 year flux of E > 100 keV electrons (black line) peaks at 1.9×10^7 $cm^{-2}s^{-1}sr^{-1}$ at L* = 4.5–5.0 decreasing to minima of 7.1×10^6 and 8.7×10^6 $cm^{-2}s^{-1}sr^{-1}$ at L*= 3.0 and L* = 8.0 respectively

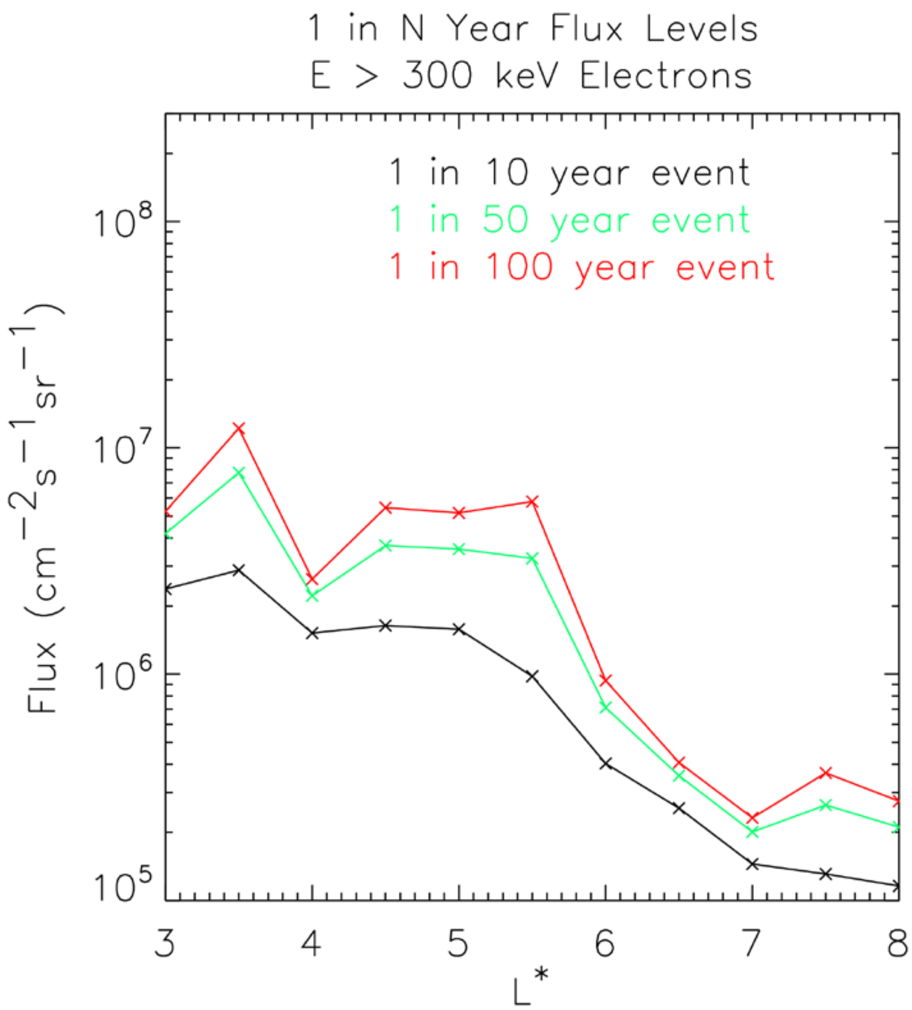
- The 1 in 100 year event is a factor of 1.1 to 3.1 larger than the corresponding 1 in 10 year event



E > 300 keV Electrons: 1 in N Year Event Levels

- In contrast to the E > 30 keV electrons, the 1 in 10 year flux of E > 300 keV electrons shows a general decreasing trend with L^* ranging from 2.4×10^6 $cm^{-2}s^{-1}sr^{-1}$ at L*= 3.0 to 1.2×10^5 $cm^{-2}s^{-1}sr^{-1}$ at L*= 8.0

- The 1 in 100 year event (red line) is a factor of 1.7 to 5.9 larger than the corresponding 1 in 10 year event



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Internal Charging Currents at MEO

- For this study we use data from the SURF internal charging monitor on board ESA's Giove-A spacecraft in MEO

- Use data from 29th December 2005 to 5th January 2016

credit: ESA

Orbital Parameters
Altitude: 23,300 km
Inclination: 56°
Period: 14 hours

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SURF Internal Charging Monitor

- SURF is designed to measure the small currents which penetrate spacecraft surfaces and cause internal charging
  - consists of three aluminium collector plates mounted in a stack
  - top, middle and bottom plate respond to electrons with energies greater than 500, 700 and 900 keV respectively

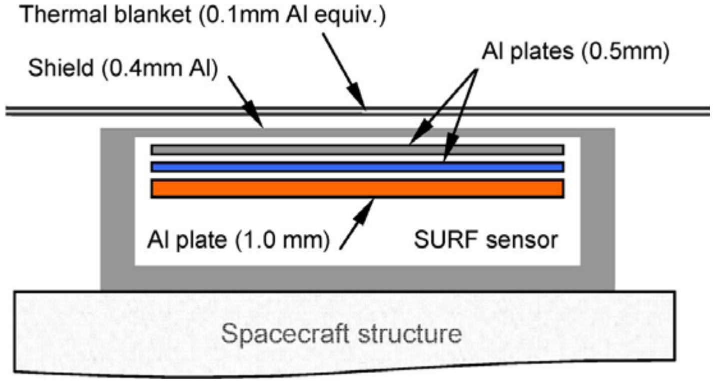

Plate	Threshold	Peak Response
Top	500 keV	700-900 keV
Middle	700 keV	1.1-1.4 MeV
Bottom	900 keV	1.6-2.0 MeV

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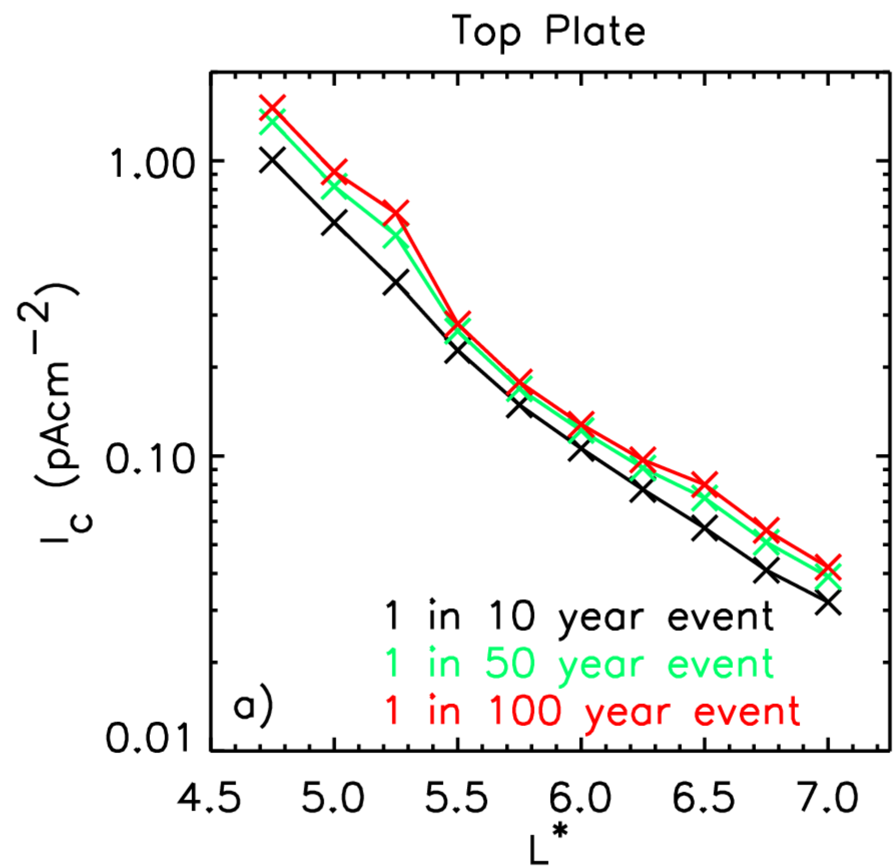
Top Plate: 1 in N Year Event Levels

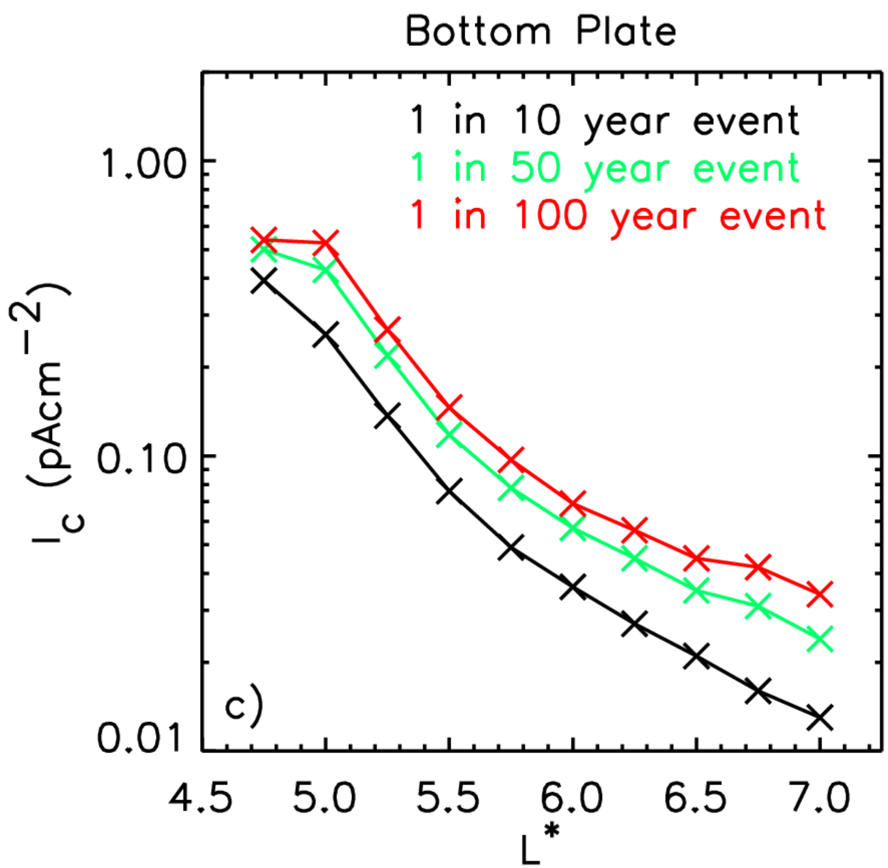
- 1 in 10 year top plate current
  - decrease with L*
  - ranges from 1.0 pAcm^{-2} at L*= 4.75 to 0.03 pAcm^{-2} at L* = 7.0
- 1 in 100 year top plate current is generally a factor of 1.2 – 1.8 times larger than the 1 in 10 year event



Bottom Plate: 1 in N Year Event Levels

- 1 in 10 year bottom plate current
  - decrease with L*
  - ranges from 0.4 $pAcm^{-2}$ at L*= 4.75 to 0.01 $pAcm^{-2}$ at L* = 7.0

- 1 in 100 year bottom plate current is generally a factor of 1.4 – 2.6 times larger than the 1 in 10 year event



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Comparison with Engineering Design Standards

- Both NASA and the European Cooperation for Space Standardization (ECSS) have guidelines on charging current
  - a maximum average current of 0.1 $pAcm^{-2}$ over a 24 hour period is commonly adopted

- For dielectrics operating at temperatures less than $25^{o}C$ the ECSS have adopted a threshold of 0.02 $pAcm^{-2}$

- For comparison with engineering design standards we repeated the analysis using daily-averaged plate currents over the entire orbit path

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1 in N Year Events Averaged Along Orbit Path

- The 1 in 10 year top plate current is a factor of 2.1 times the upper design threshold

- The 1 in 10 year middle and bottom plate currents are equal to the upper design threshold

Plate	1 in 10 year current ($pAcm^{-2}$)	1 in 100 year current ($pAcm^{-2}$)
Top	0.21	0.24
Middle	0.1	0.14
Bottom	0.1	0.16

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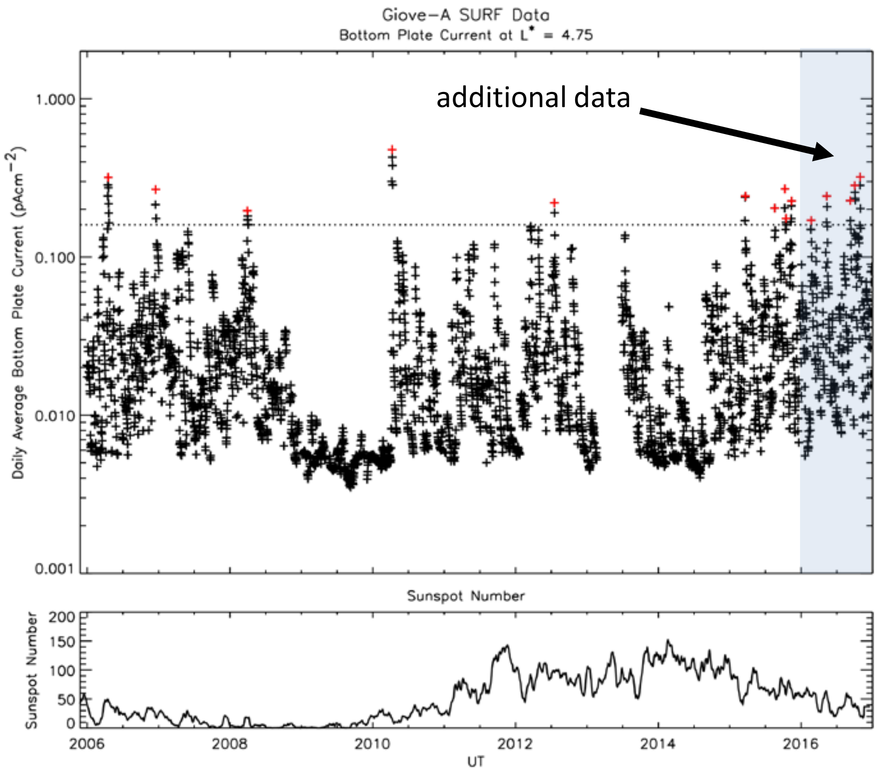
Updated Analysis

- We recently updated the analysis to include an extra year of data
- We found only small differences in return levels when the extra year was included – of the order 2 – 5 %



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Relativistic Electrons from HEO

- We use data from SREM on board ESA's INTEGRAL spacecraft in HEO

- Use data from October 2002 to 31st December 2016

Integral

credit: ESA

Orbital Parameters	
Apogee:	153,000 km
Perigee:	10,000 km
Inclination:	51.6°
Period:	72 h

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Relativistic Electrons from HEO

- Flux intensities derived using SREM dedicated inverse scheme developed by Sandberg *et al*. [2012]

- Use data within 15^o of magnetic equator

- Determine the 1 in N year space weather events as a function of energy and L*

Integral

credit: ESA

Orbital Parameters	
Apogee:	153,000 km
Perigee:	10,000 km
Inclination:	51.6^o
Period:	72 h

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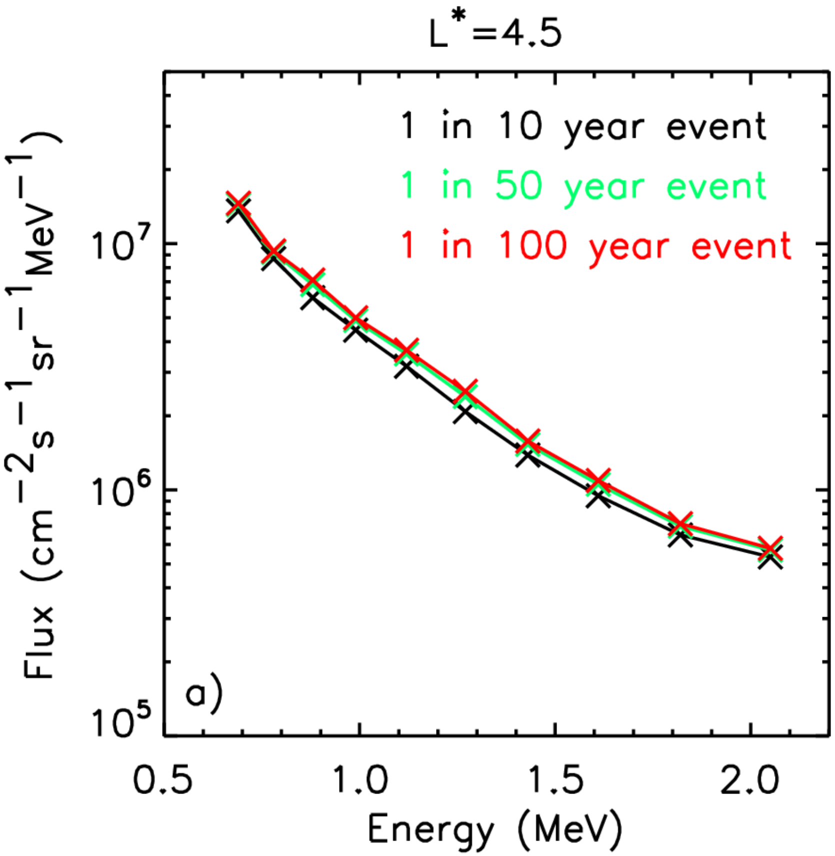
L* = 4.5

- 1 in 10 year flux decreases from $1.4 \times 10^7\ cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ at E = 0.69 MeV to $5.3 \times 10^5\ cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ at E = 2.05 MeV
- 1 in 100 year flux is a factor of 1.1 to 1.2 times larger than the 1 in 10 year flux



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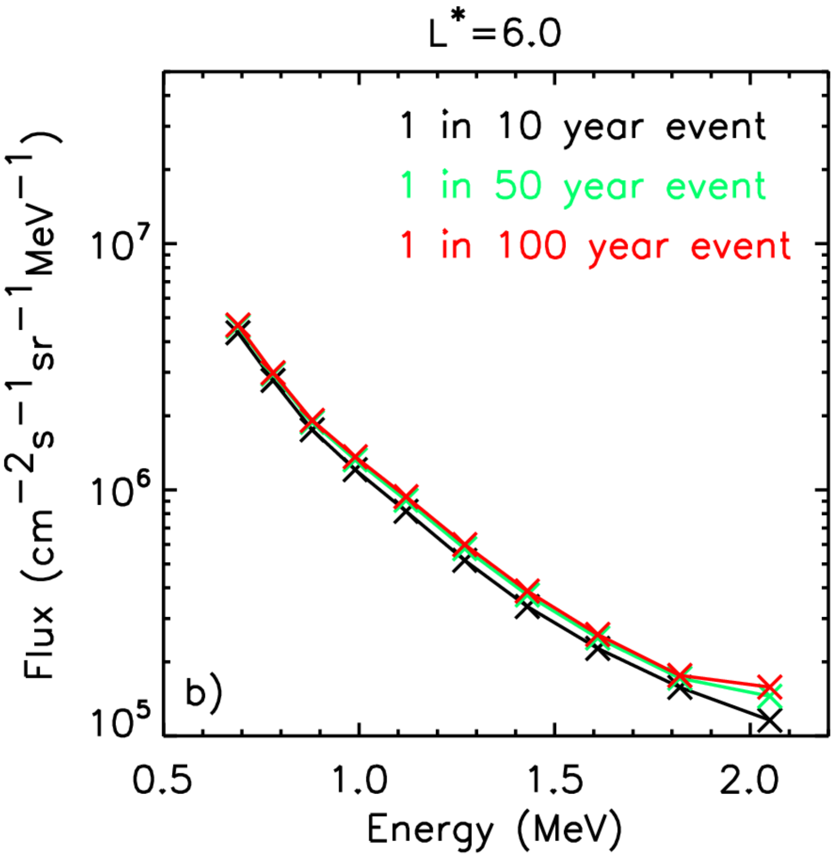
L* = 6.0

- 1 in 10 year flux decreases from 4.4×10^6 $cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ at E = 0.69 MeV to 1.2×10^5 $cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ at E = 2.05 MeV
- 1 in 100 year flux is a factor of 1.1 to 1.4 times larger than the 1 in 10 year flux
- 1 in N year fluxes at GEO a factor of 3-4 less than at equatorial MEO



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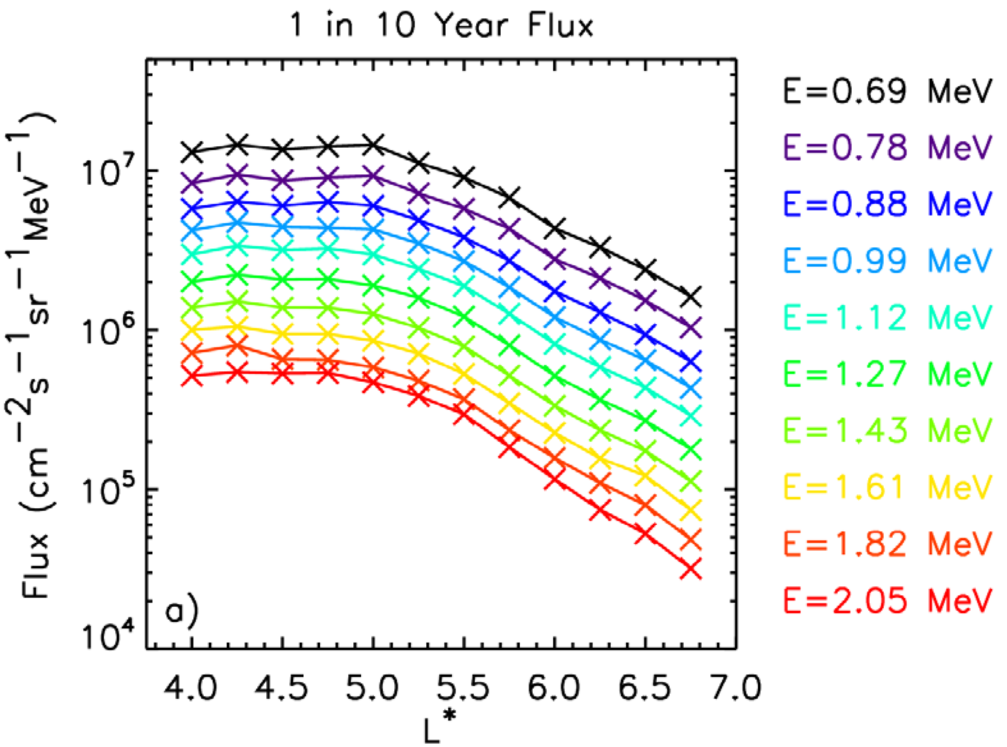
1 in 10 Year Fluxes as a function of L* and Energy

- Results can be used to determine the 1 in 10 year electron flux as a function of energy and L*

- Results cover the range
  - 0.69 – 2.05 MeV
  - 4.0 < L* < 6.75



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Summary

- The 1 in N year fluxes and plate currents computed as part of this work package serve as benchmarks against which to compare other space weather events in GEO, MEO and LEO
- They can be used to assess how hostile the space weather environment might become in a worst-case scenario.
- The results may also be used to compute the return period of any given space weather event to determine if the event was particularly extreme for any given location.

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Acknowledgements

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