SPACESTORM

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

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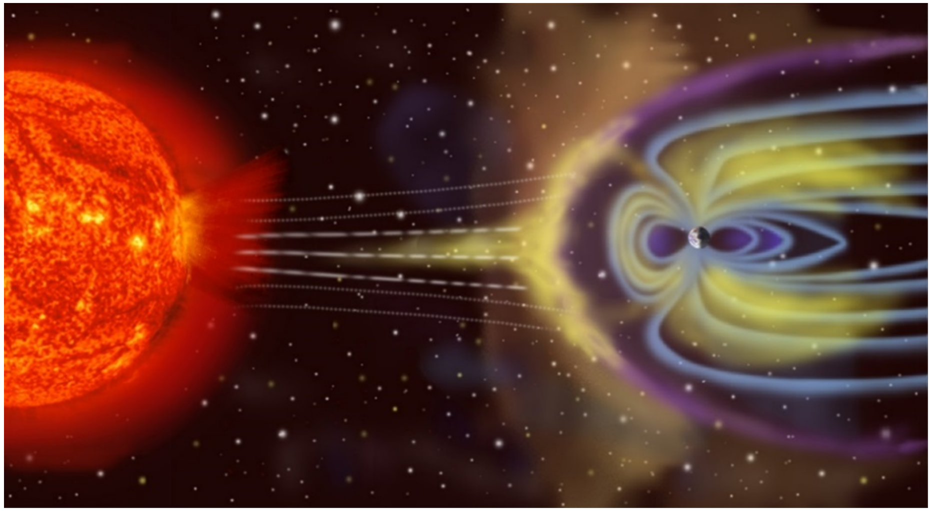
Space Weather

- The Sun is an active star
- It drives changes in the space environment
- These changes can affect technological systems both in space and on the ground



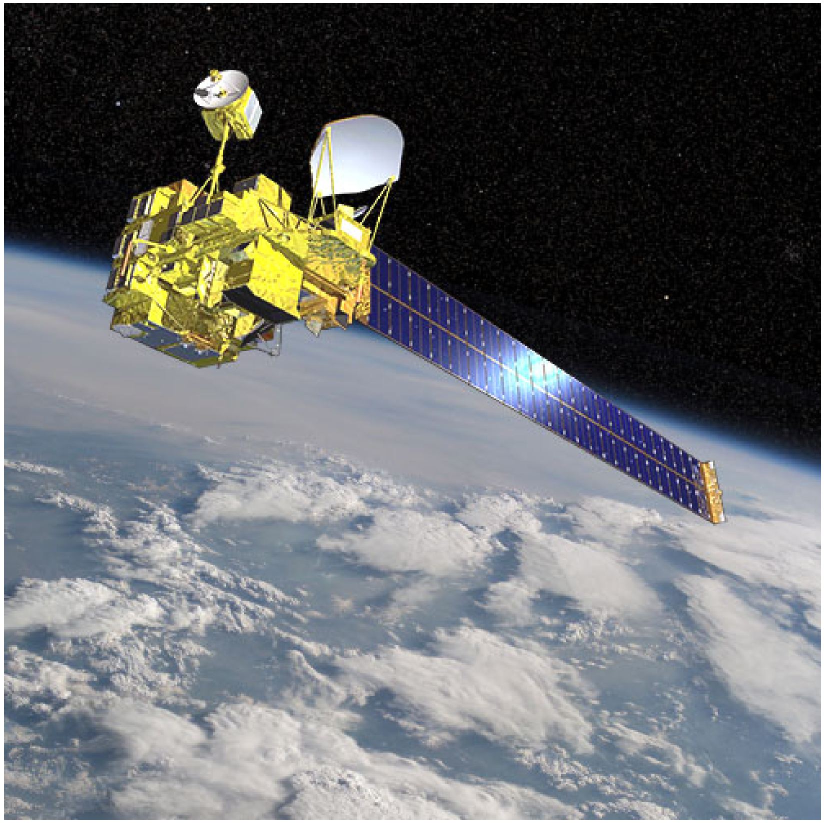
Natural Hazard Risk

- Due to our increasing reliance on modern technological systems space weather is becoming an increasingly important natural hazard risk
  - recognised as a threat to critical infrastructure
  - could significantly affect national security [SNRA, 2011]
  - added to the UK National Risk Register in 2012

Space Weather Effects on Satellites

- The impacts of space weather on satellite operations range from momentary interruptions of service to total loss of capabilities when a satellite fails

- During a major storm in 2003
  - 47 satellites experienced anomalies
  - more than 10 satellites were out of action for more than 1 day
  - the US$ 640 M Midori-2 satellite was a complete loss



Artists impression of Midori-2 satellite

Radiation Damage

- High energy electrons (E > ~100 keV) can penetrate surface materials and embed themselves within insulators and ungrounded conductors

- The subsequent discharge can cause electronic circuit upsets and damage components

- Lower energy electrons (E < ~100 keV) can cause surface charging

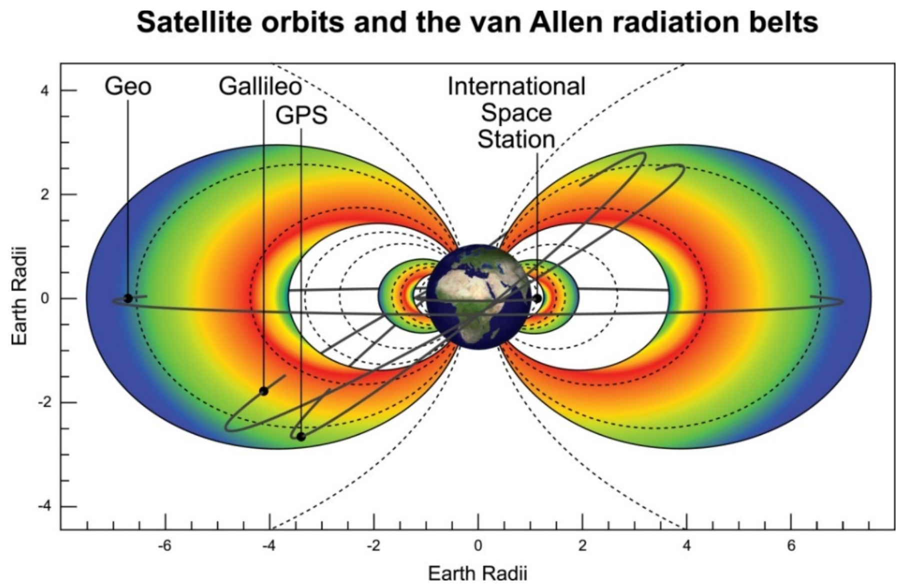
- The subsequent discharge can damage surface materials and underlying components

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 the EU FP7 project SPACESTORM we have conducted extreme value analyses to determine the 1 in 10, 1 in 50, and 1 in 100 space weather event for
  - relativistic electrons at GEO
  - internal charging currents at MEO
  - energetic electrons at LEO



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 days
- 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

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:

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

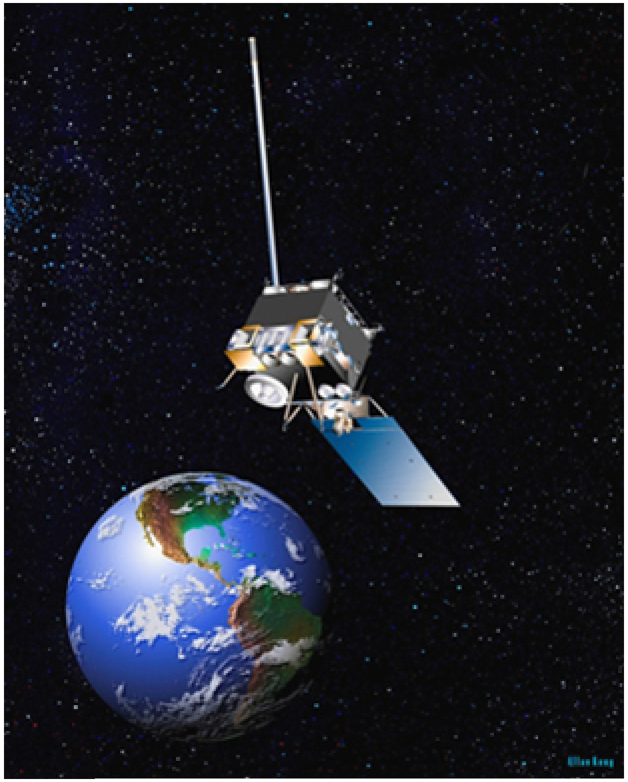
where n_d is the number of data points in a given year, n_c is the number of cluster maxima and n_{tot} is the total number of data points

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

Relativistic Electrons at GEO

- 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

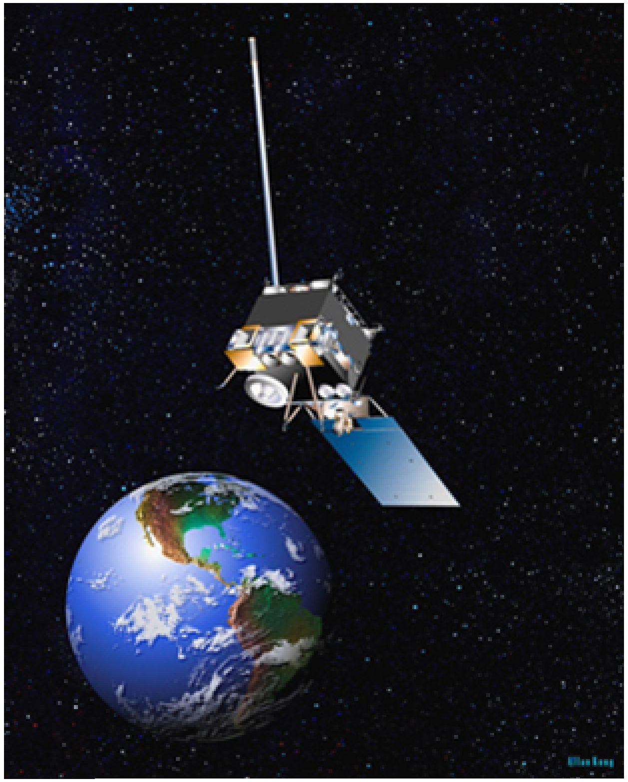


credit: NOAA

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

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

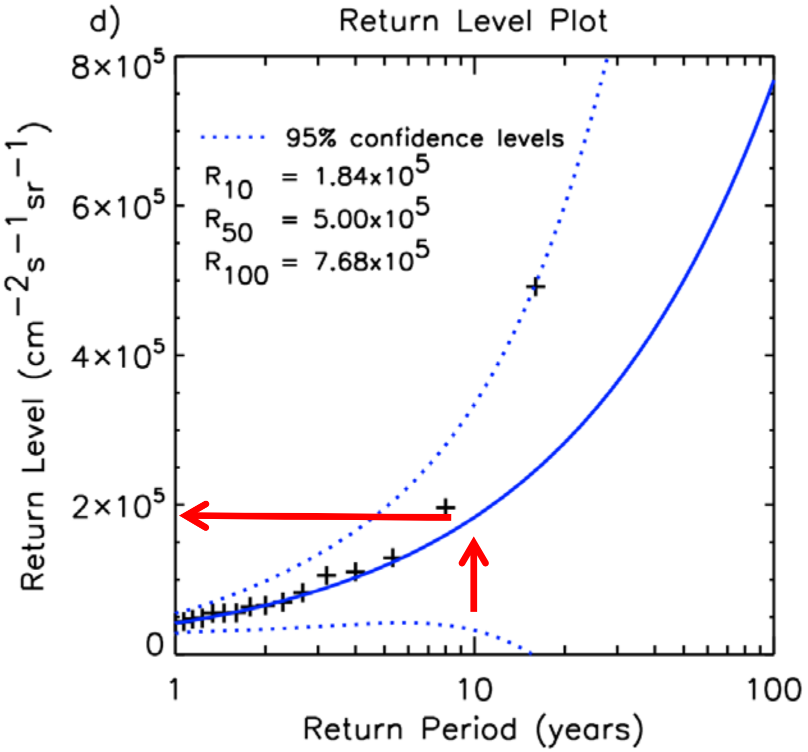


credit: NOAA

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

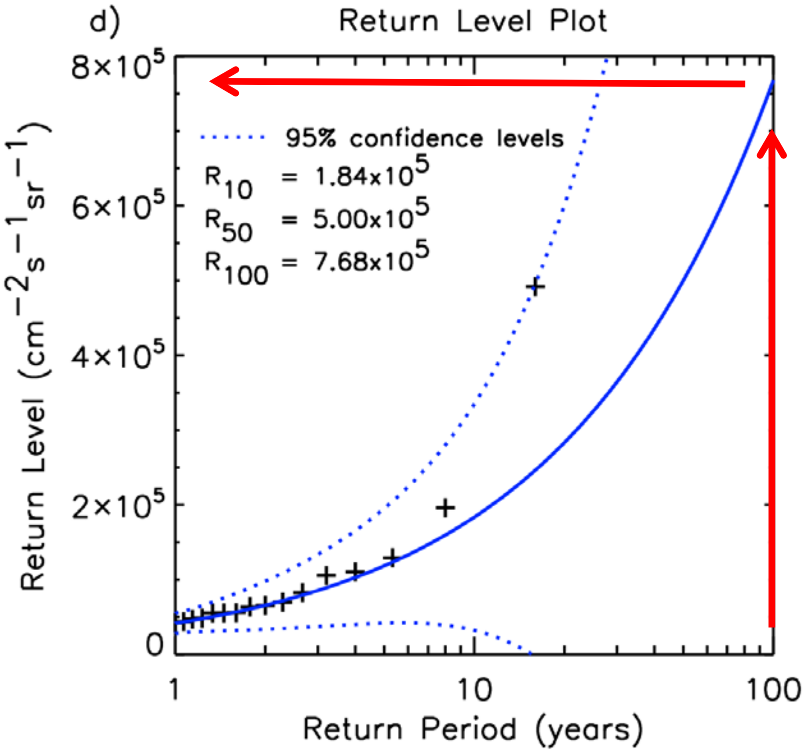
GOES West: Return Level Plot

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



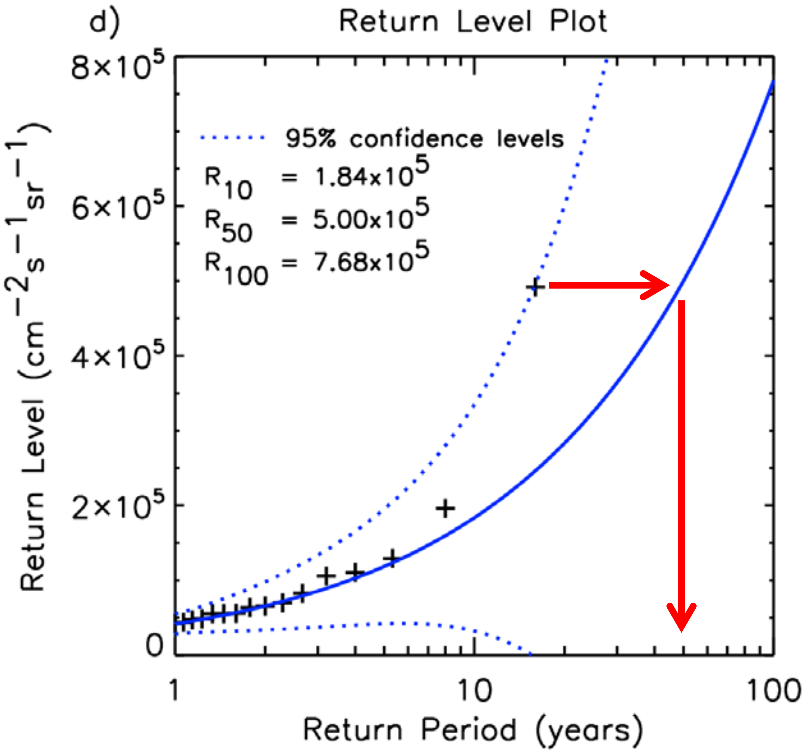
GOES West: Return Level Plot

- One in Ten Year Flux
  - 1.84×10^{5} $cm^{-2}s^{-1}sr^{-1}$
- One in One Hundred Year Flux
  - 7.68×10^{5} $cm^{-2}s^{-1}sr^{-1}$



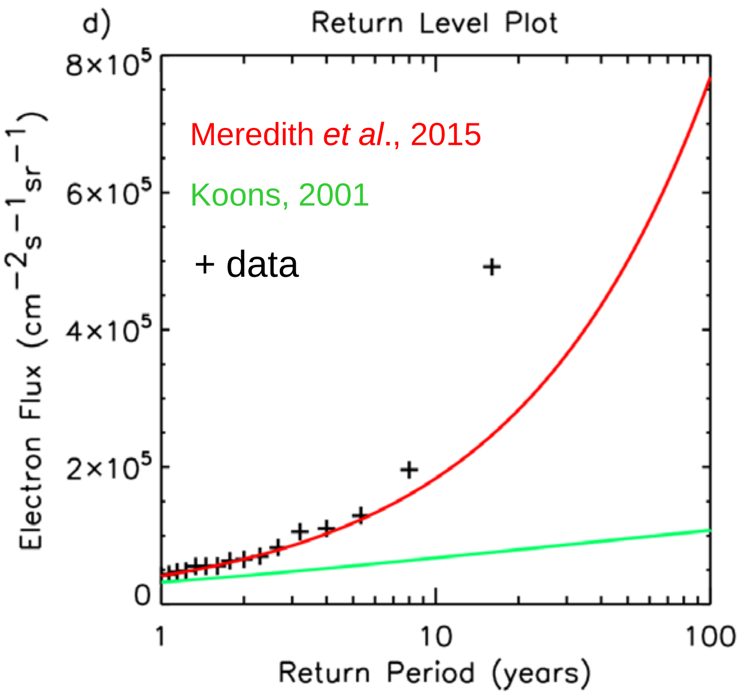
GOES West: Return Level Plot

- Largest observed flux is a one in fifty year event



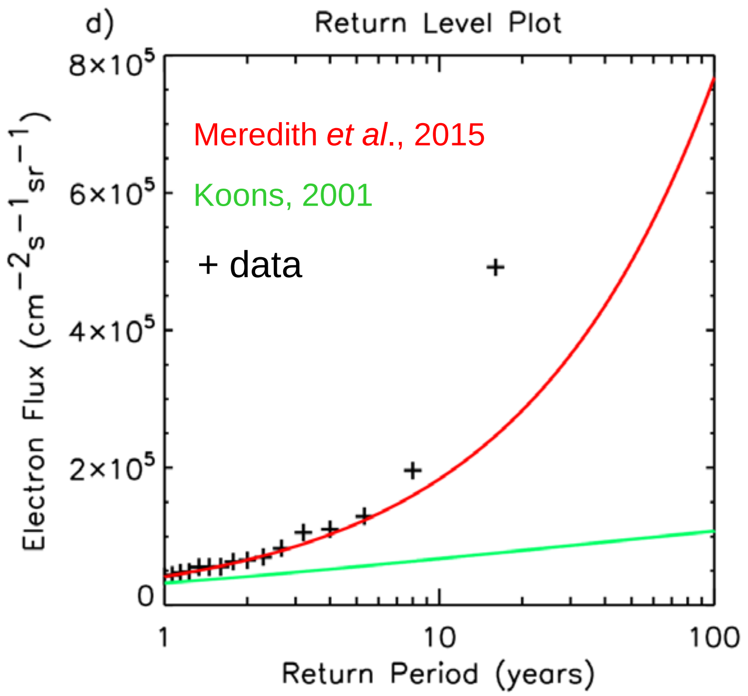
Comparison with Koons [2001] Study

- 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]



Impact

- These new results:
  - have been used to update the figures in the UK National Risk Register
  - have been used in the evaluation of satellite tenders
  - are being used in the EU SPACESTORM project to help assess the impact of an extreme event on satellite materials



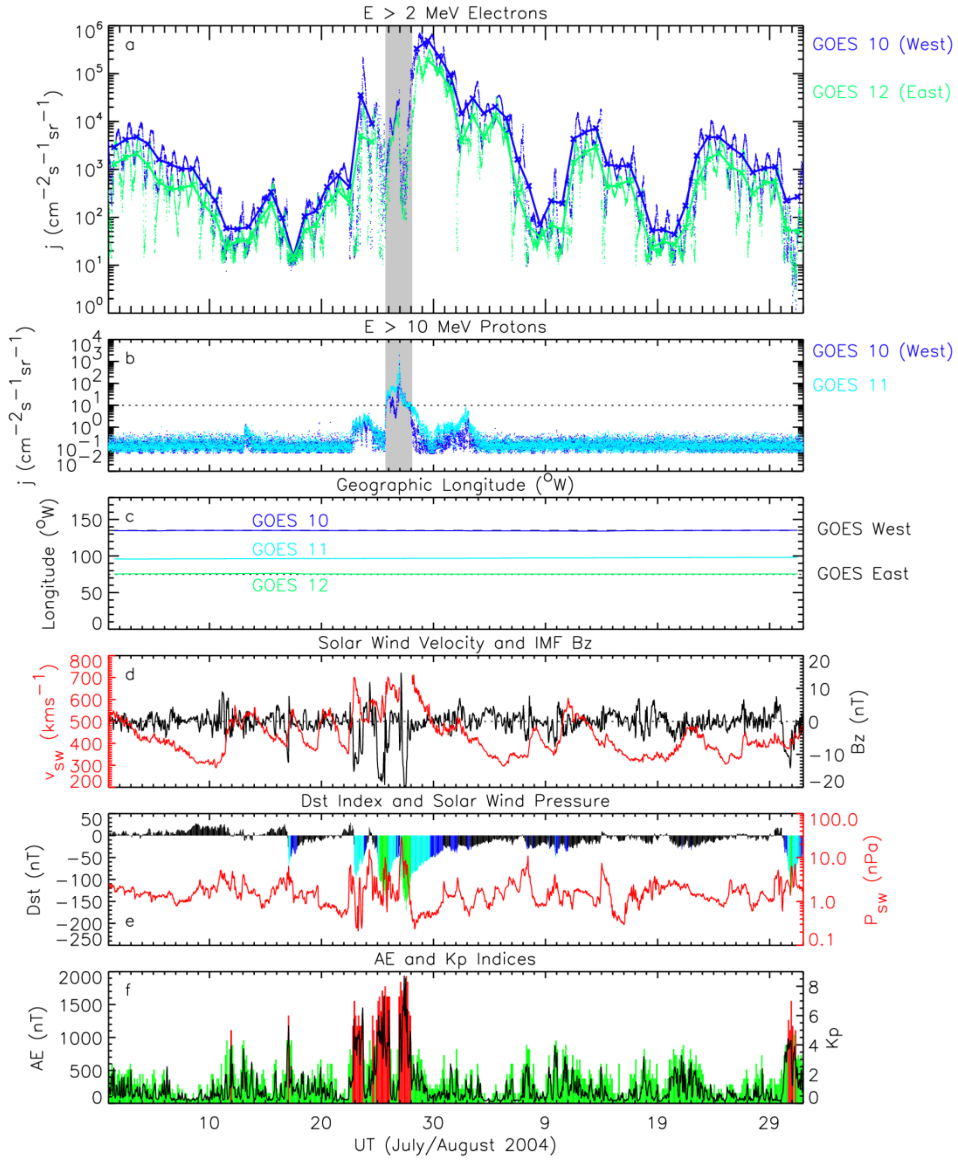
July/August 2004

- 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

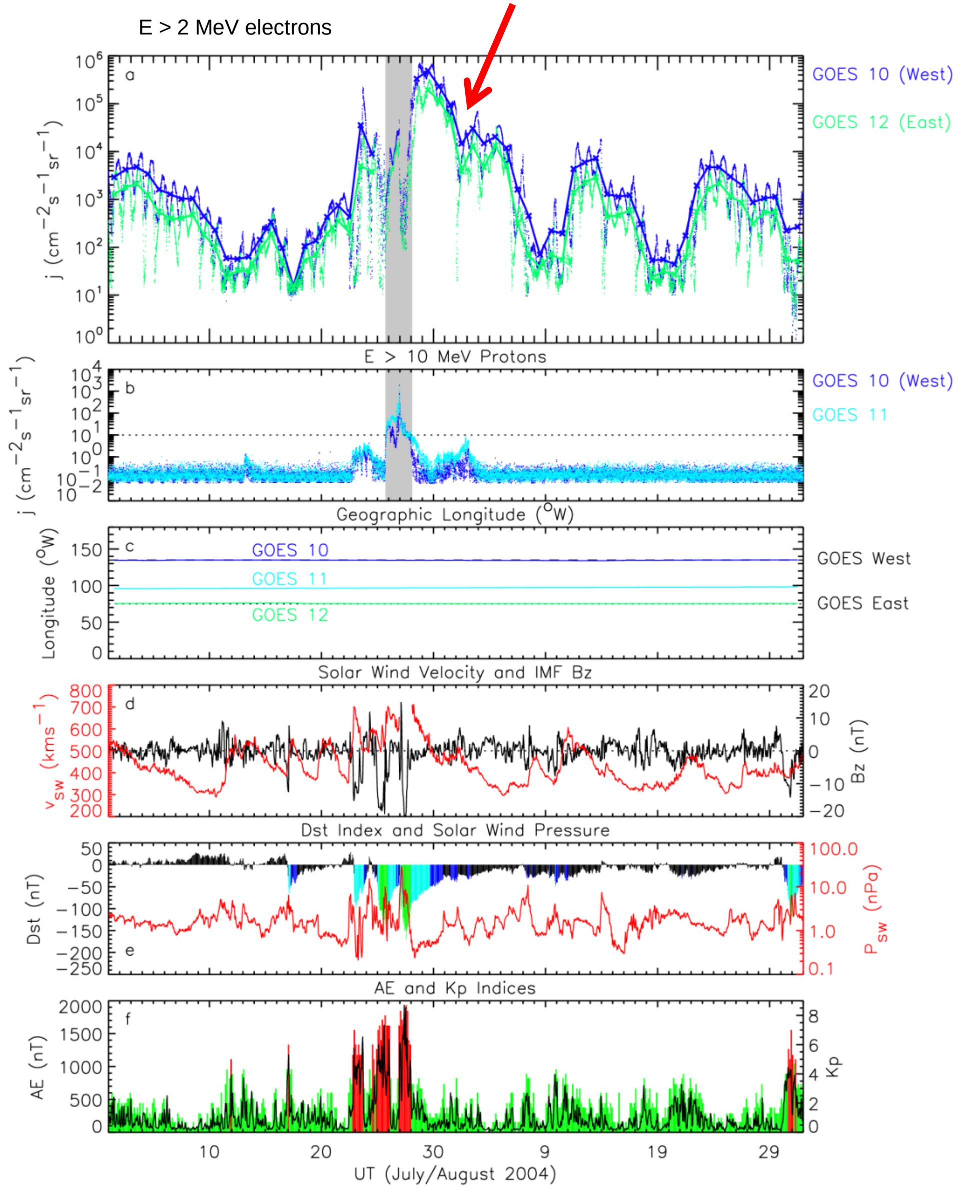
- Independent measurements of this extreme flux event suggests the flux event is real

- 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

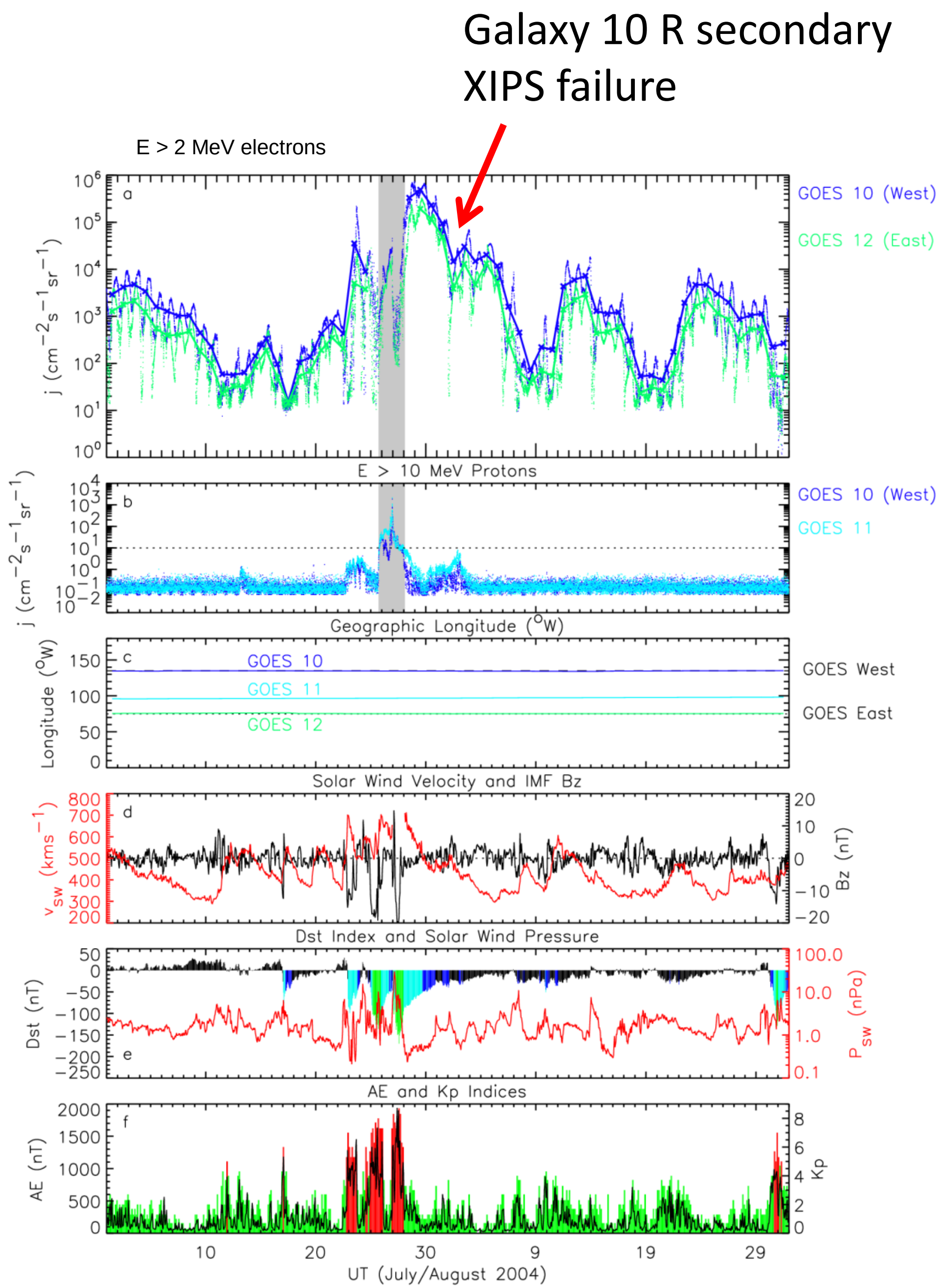
Galaxy 10 R secondary XIPS failure



- 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



Internal Charging Currents at MEO

- Study uses data from ESA's Giove-A satellite
- This satellite was the first test satellite of the Galileo GNSS
- It was launched in December 2005 to
    - test technology in orbit
    - claim frequencies allocated to Galileo

credit: ESA

Orbital Parameters	
Altitude:	23,300 km
Inclination:	56^{o}
Period:	14 hours

Internal Charging Currents at MEO

- Giove-A was initially designed with a lifetime of 27 months
- This lifetime has been greatly exceeded and the satellite continues to acquire good data
- For this study we use data from the SURF internal charging monitor
- Use data from 29th December 2005 to 5th January 2016

credit: ESA

Orbital Parameters	
Altitude:	23,300 km
Inclination:	56^{o}
Period:	14 hours

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
  - each plate is connected to an electrometer to measure the deposited current
  - measured currents lie in the range of $fAcm^{-2}$ to $pAcm^{-2}$

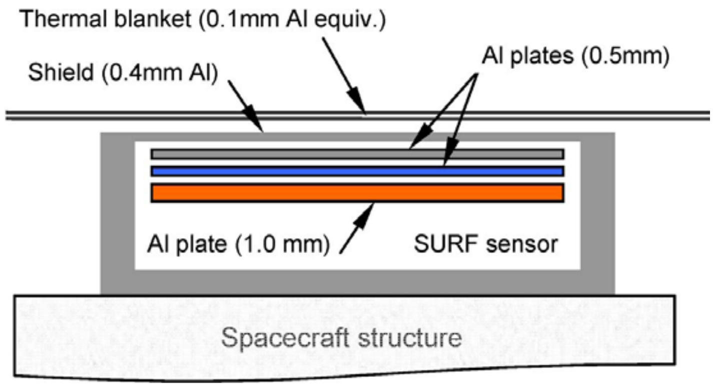


Plate	Threshold	Peak Response
Top	500 keV	700-900 keV
Middle	700 keV	1.1-1.4 MeV
Bottom	900 keV	1.6-2.0 MeV

Data Analysis

- We determined the daily-averaged plate currents as a function of L* for 10 evenly spaced values of L* from L*=4.75 to L* = 7.00

    - ~3025 good quality data points at each L* corresponding to 8.3 years of operational data

Data Analysis

- We determined the daily-averaged plate currents as a function of L* for 10 evenly spaced values of L* from L*=4.75 to L* = 7.00

  - ~3025 good quality data points at each L* corresponding to 8.3 years of operational data

- To compare with engineering standards we also calculated the daily averaged plate currents averaged along the orbit path

  - to ensure good coverage used days with > 50% coverage

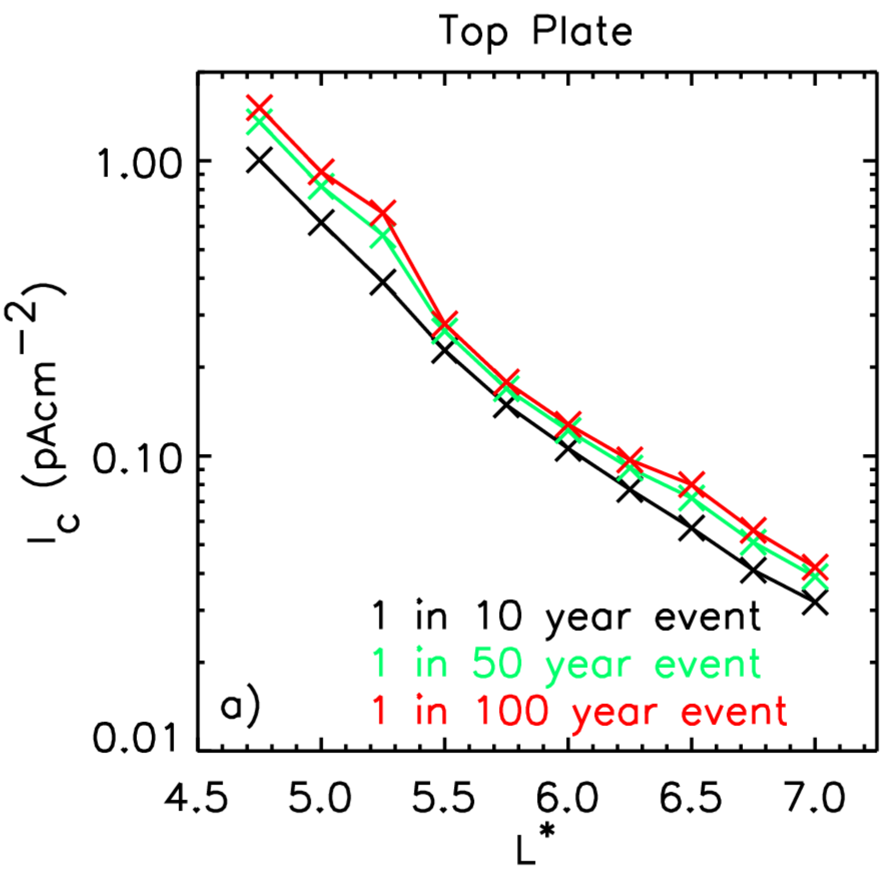
  - 2758 good quality data points corresponding to 7.6 years of operational data

Top Plate: 1 in N Year Event Levels

- 1 in 10 year top plate current
  - decreases with increasing L*
  - ranges from 1.0 pAcm^{-2} at L*= 4.75 to 0.03 pAcm^{-2} at L* = 7.0

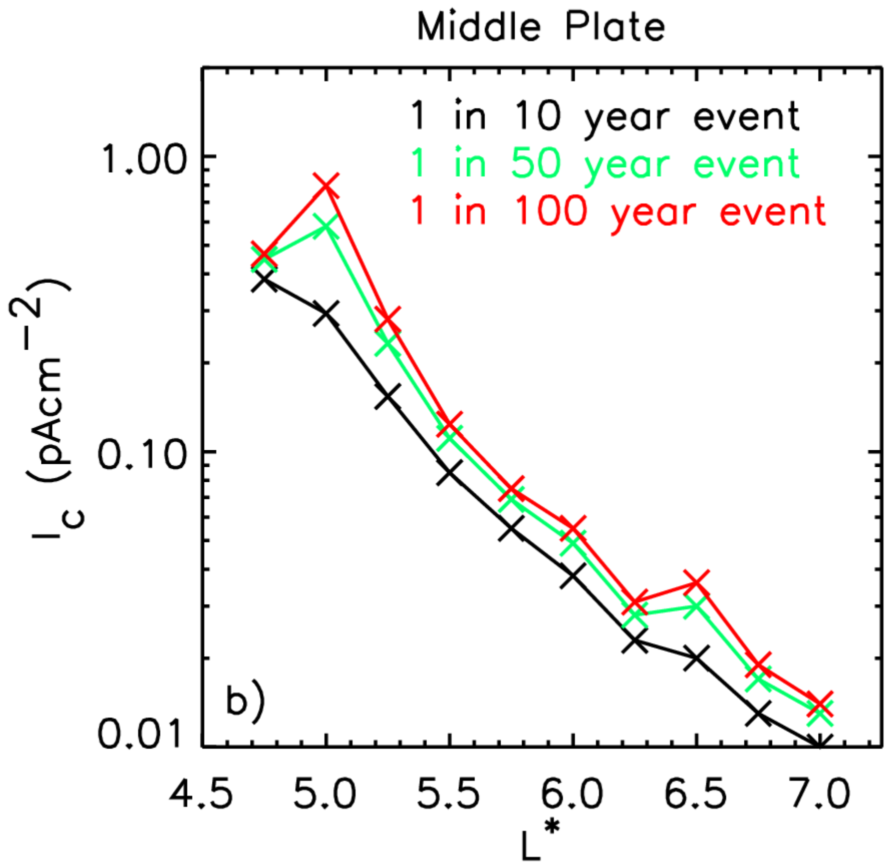
- 1 in 100 year top plate current

  is generally a factor of 1.2 – 1.8 times larger than the 1 in 10 year event



Middle Plate: 1 in N Year Event Levels

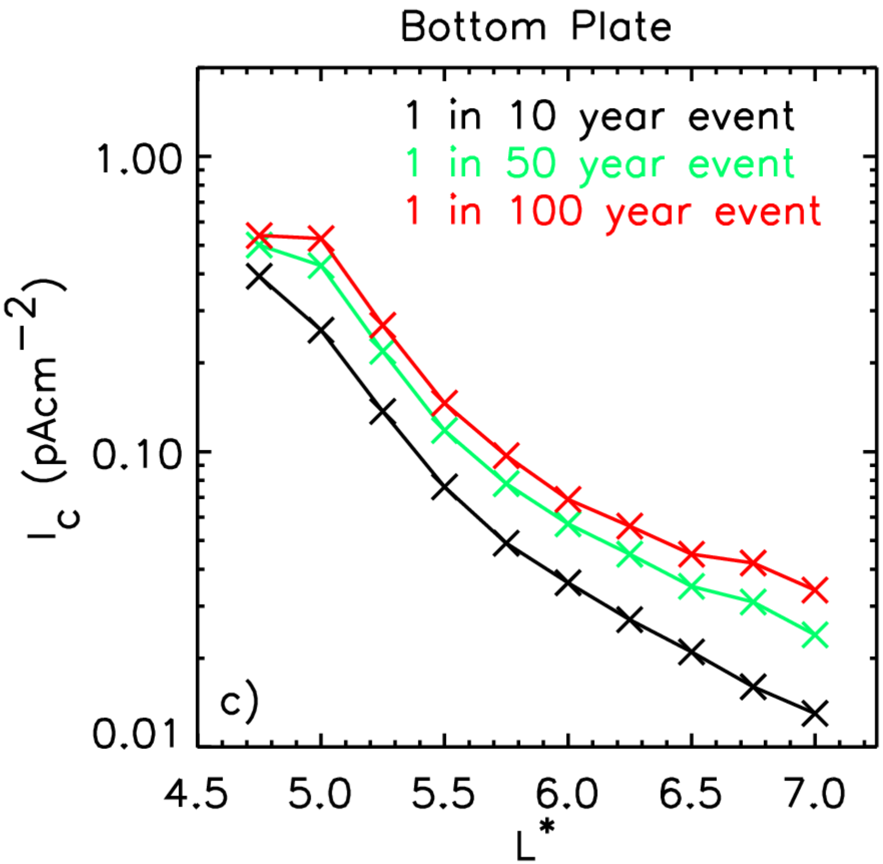
- 1 in 10 year middle plate current
  - decreases with increasing L*
  - ranges from 0.4pAcm^{-2} at L*= 4.75 to 0.01 pAcm^{-2} at L* = 7.0
- 1 in 100 year middle plate current is generally a factor of 1.2 – 2.7 times larger than the 1 in 10 year event



Bottom Plate: 1 in N Year Event Levels

- 1 in 10 year bottom plate current
  - decreases with increasing 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



Comparison with Engineering Design Standards

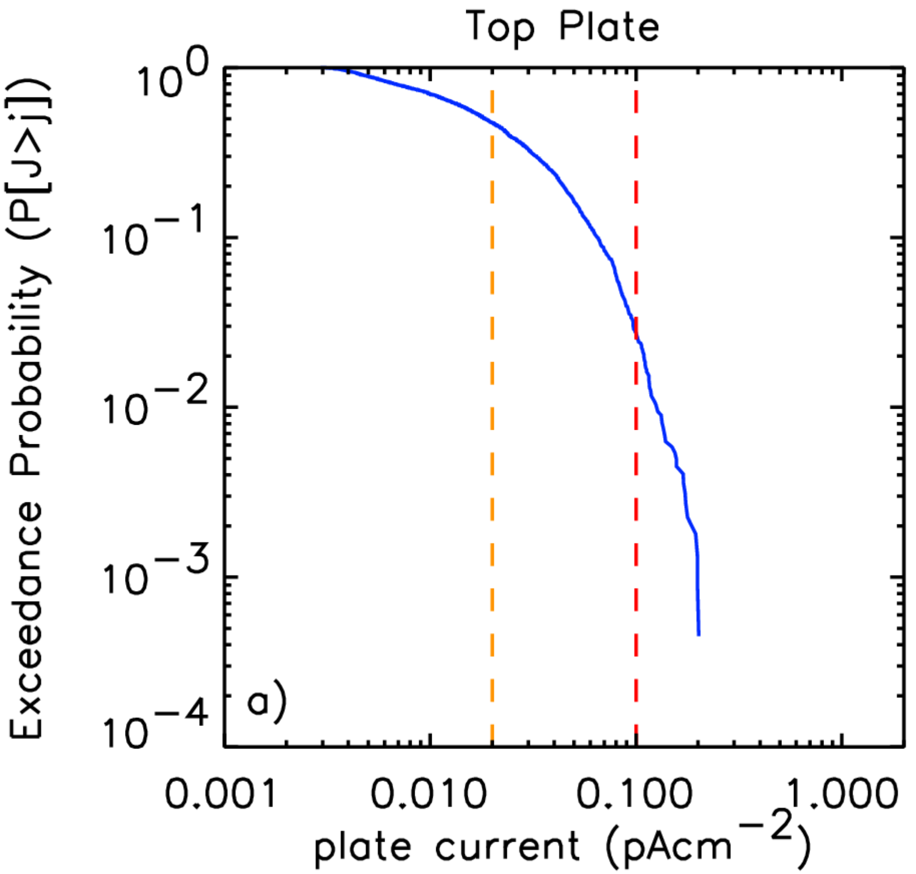
- Both NASA and the European Cooperation for Space Standardization (ECSS) have guidelines on charging current
  - a maximum average current of 0.1 $pAcm^{-2}$ over a 24 hour period is commonly adopted

- 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

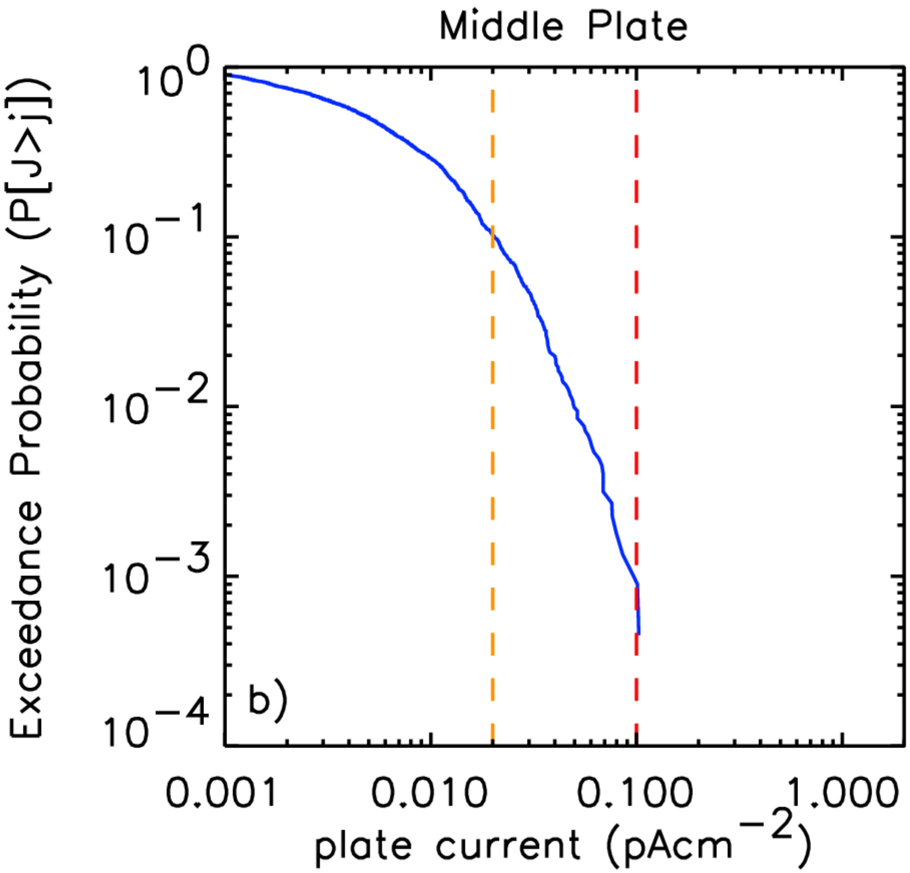
Daily-Averaged Top Plate Currents Averaged Along Orbit Path

- Top plate currents cover just under two orders of magnitude ranging from 0.003 to 0.2 $pAcm^{-2}$
- Lower design threshold is exceeded on 1045 days (47% of days)
- Upper design threshold is exceeded on 60 days (2.7% of days)



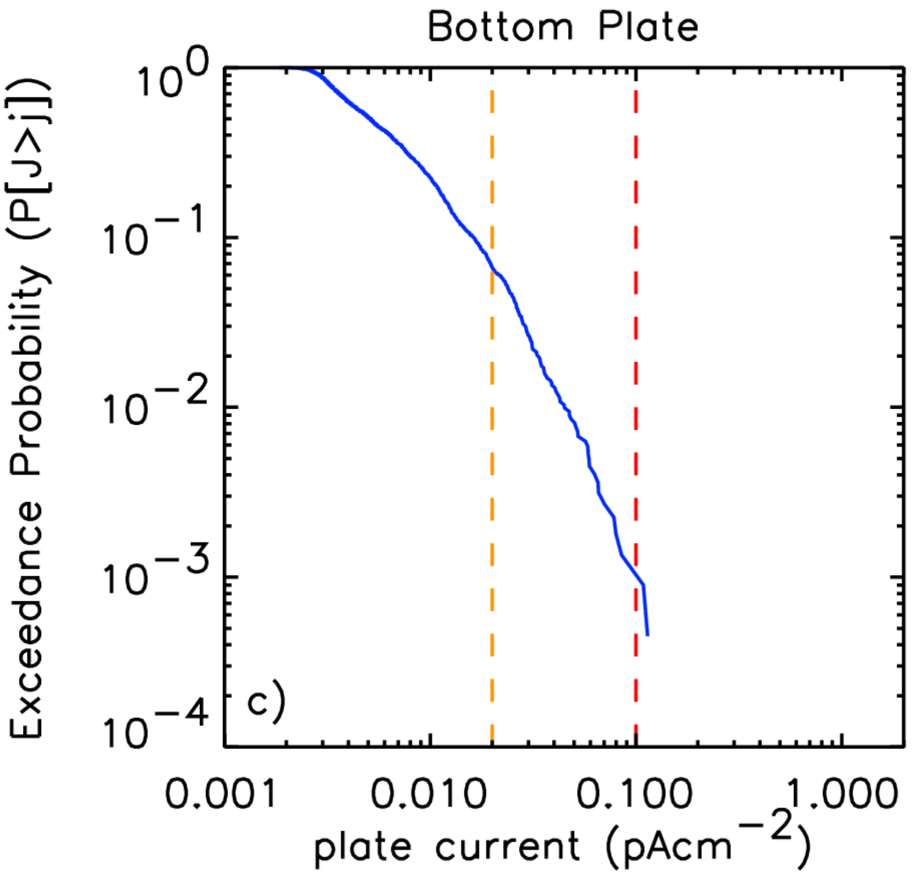
Daily-Averaged Middle Plate Currents Averaged Along Orbit Path

- Middle plate currents cover two orders of magnitude ranging from 0.001 to 0.1 $pAcm^{-2}$
- Lower design threshold is exceeded on 222 days (10% of days)
- Upper design threshold is exceeded on 3 days (0.1% of days)



Daily-Averaged Bottom Plate Currents Averaged Along Orbit Path

- Bottom plate currents cover just under two orders of magnitude ranging from 0.002 to 0.1 $pAcm^{-2}$
- Lower design threshold is exceeded on 149 days (6.7% of days)
- Upper design threshold is exceeded on 3 days (0.1% of days)



1 in N Year Events Averaged Along Orbit Path

- We also conducted an extreme value analysis of the daily-averaged plate currents averaged along the orbit path

- The 1 in 10 year top, middle and bottom plate currents are 0.22, 0.094 and 0.094 $pAcm^{-2}$ respectively

- The 1 in 100 year top, middle and bottom plate currents are factors of 1.1, 1.3 and1.4 times larger than the corresponding 1 in 10 year event

- The return periods of the 0.1 $pAcm^{-2}$ upper design threshold are 113 days, 16.1 years and 13.3 years for the top, middle and bottom plates respectively

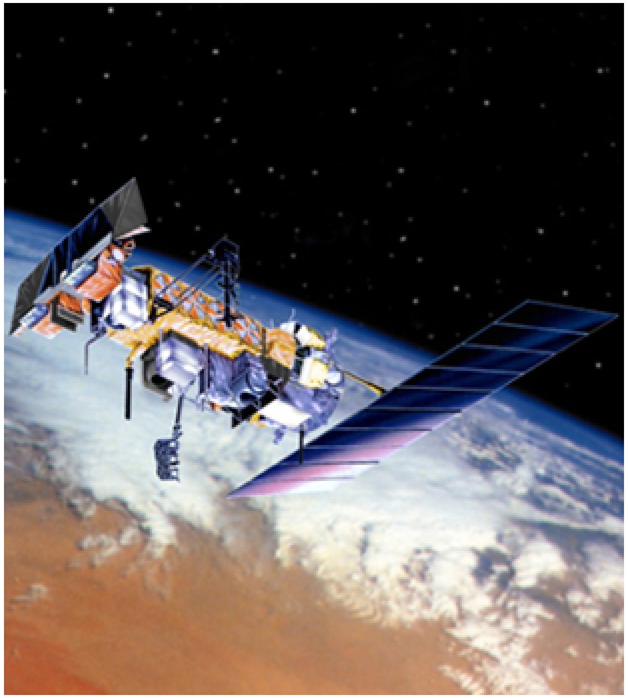
Energetic Electrons at LEO

- We used 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 sorted it according to satellite location, corrected for ring current protons, and excluded solar proton events and periods of poor quality data

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

NOAA-19



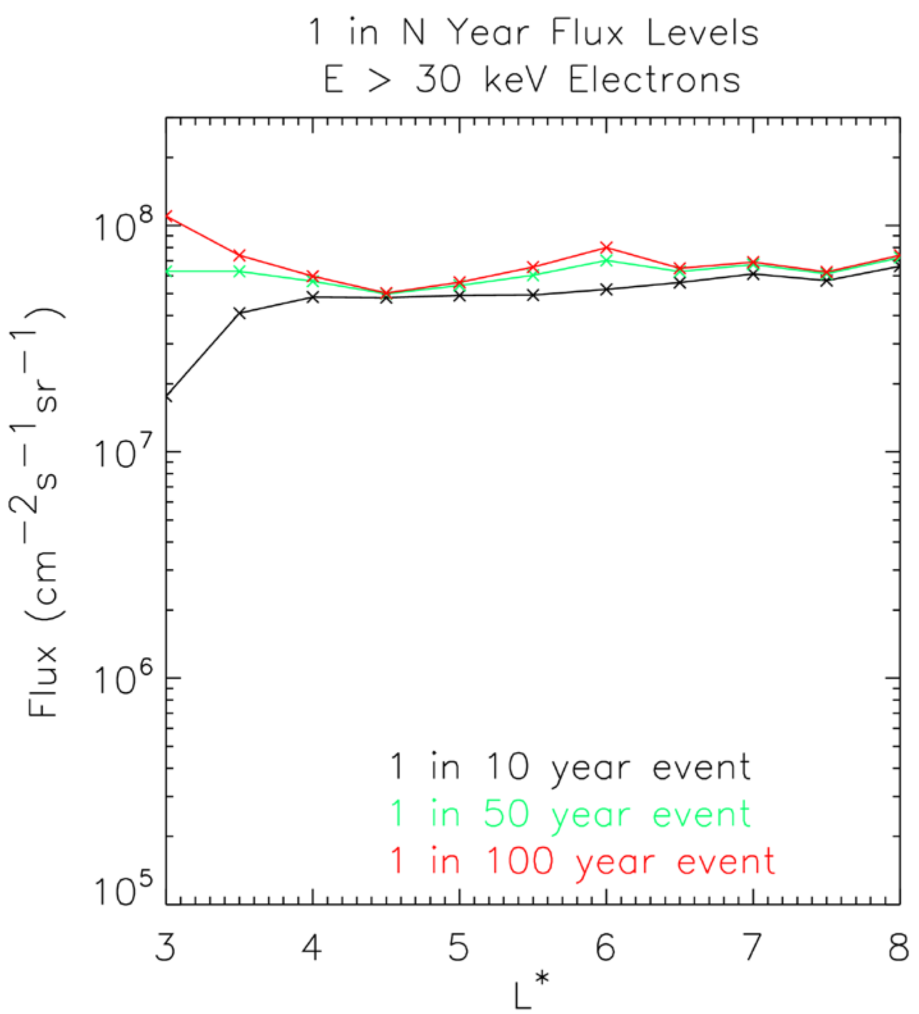
credit: NOAA

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

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

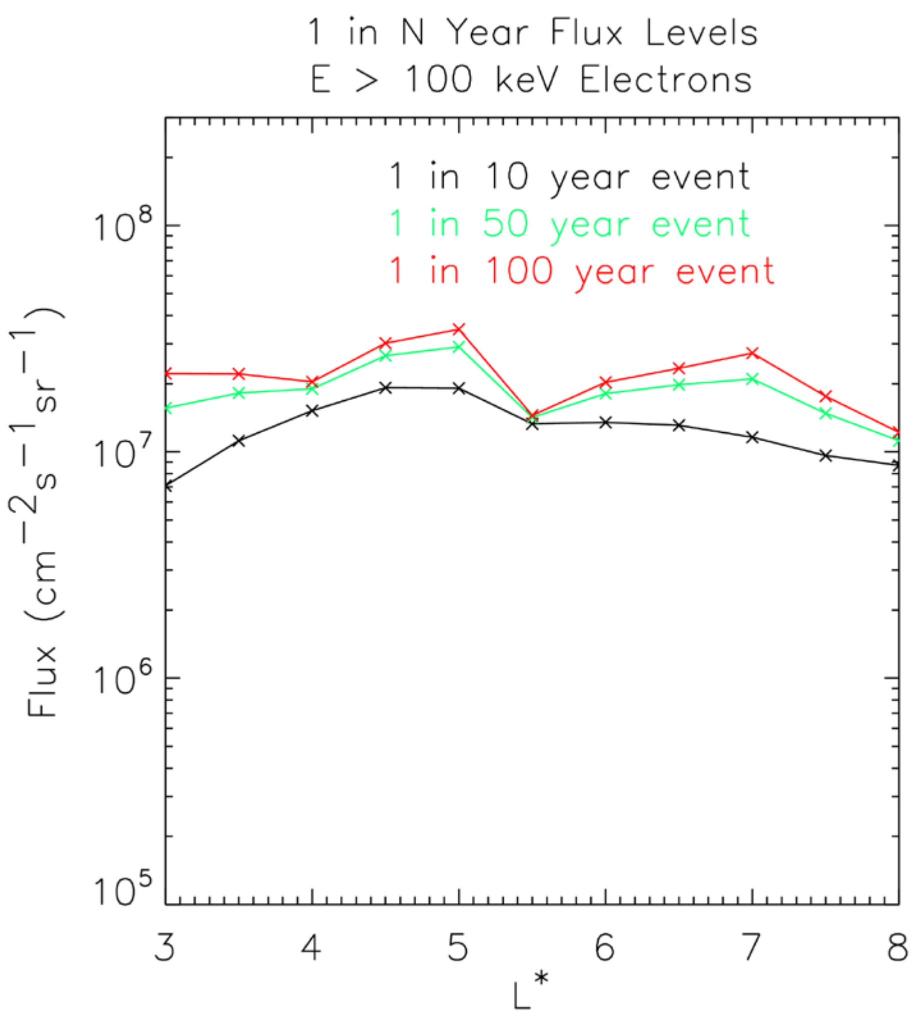
- The 1 in 100 year flux (red line) is generally a factor of 1.1 to 1.5 larger than the corresponding 1 in 10 year event



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

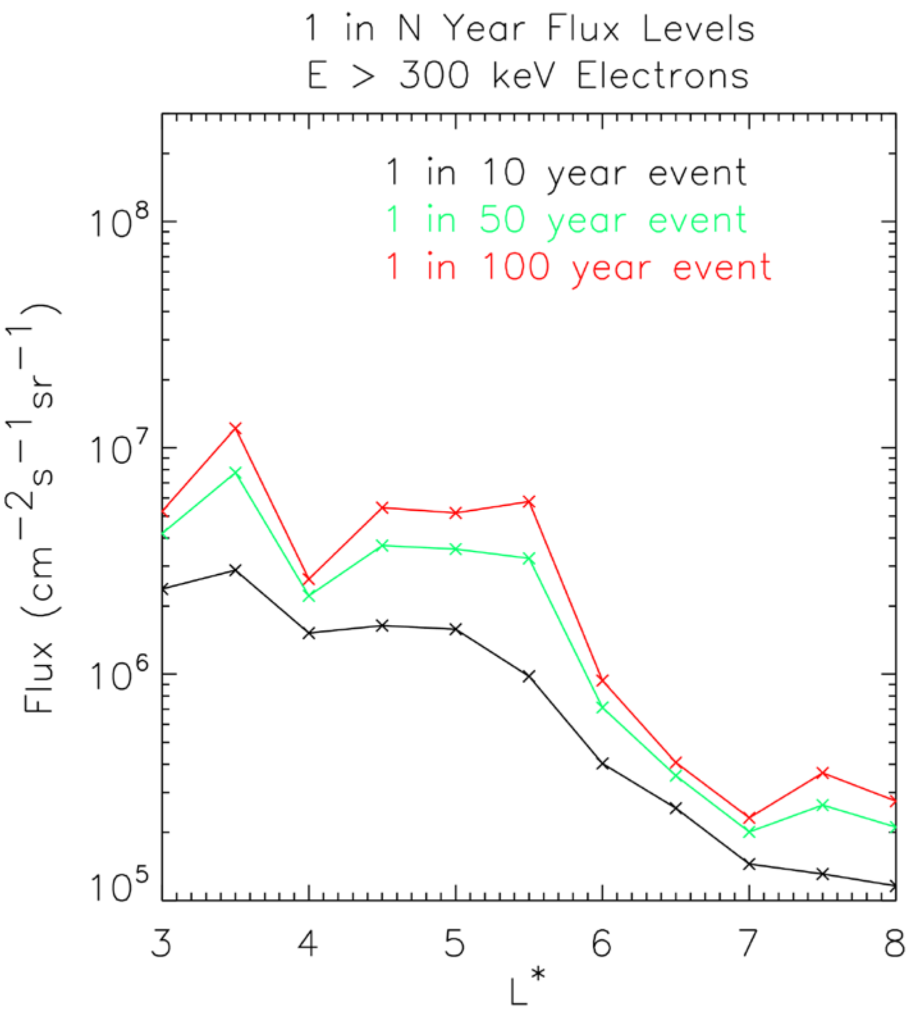
- The 1 in 10 year flux of E > 100 keV electrons (black line) peaks at 1.9×10^{7} $cm^{-2}s^{-1}sr^{-1}$ at L^{*} = 4.5–5.0 decreasing to minima of 7.1×10^{6} and 8.7×10^{6} $cm^{-2}s^{-1}sr^{-1}$ at L^{*}= 3.0 and 8.0 respectively

- 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



Implications for Electric Orbit Raising

- The fact that potentially large fluxes of energetic electrons can penetrate as low as L* = 3.0 is a concern for electric orbit raising [e.g., Horne and Pitchford, 2015]

- The situation is most severe at higher energies

- For example, at the 0.1% exceedance level, the flux of E > 300 keV electrons is almost an order of magnitude higher at L* = 3.0 than that at geosynchronous orbit

- This suggests that satellites undergoing electric orbit raising could experience considerably more damaging radiation than normally encountered at geosynchronous orbit

Conclusions

- The 1 in 10 and 1 in 100 year fluxes of E > 2 MeV electrons at GEO are 3 and 7 times larger than previous estimates

- The largest flux of E > 2 MeV electrons observed at GEO was a 1 in 50 year event

- The 1 in 10 year plate middle plate currents in MEO range from 0.4 pAcm^{-2} at L* = 4.75 to 0.01 pA cm^{-2} at L* = 7.0

- The 1 in 10 year E > 30 keV electron flux in LEO increases 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 10 year E > 300 keV electron flux in LEO decreases 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

Conclusions

- The 1 in N year event values provide “benchmarks” to compare against current or previous space weather conditions

- 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

Acknowledgements

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