Extreme relativistic electron fluxes in the Earth’s outer radiation belt

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Space Weather Hazard

- Relativistic electrons are an important space weather hazard.

- They can penetrate satellite surfaces and embed themselves in insulating materials.

- The charge can build up and eventually exceed breakdown levels.

- The subsequent discharge can damage components and even destroy a satellite.
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

• From a scientific point of view it is interesting to know
  • How large the fluxes might become during an extreme event
  • Is there a limit to the fluxes?
The objective of this study is to calculate the 1 in 10 and 1 in 100 year relativistic electron fluxes throughout the Earth’s outer radiation belt.
The data used in this study were collected by the Radiation Environment Monitor (IREM) on board ESA’s INTEGRAL satellite.

INTEGRAL was launched into HEO on 17th October 2002.

Use data from October 2002 to 31st December 2016.

**Orbital Parameters**
- Apogee: 153,000 km
- Perigee: 9,000 km
- Inclination: 52.25°
- Period: 71.8 h

Credit: ESA
IREM is a modified version of ESA SREM - a space-dedicated detector assembly designed to measure high energy electrons and protons.

IREM count-rates $C_i$ are given by the convolution of the incident proton and electron differential fluxes and the corresponding response functions

$$C_i = \sum_{q=p,e} \int_0^\infty f_q(E)RF_{i,q}(E)dE$$

For the calculation of IREM electron fluxes we applied the SVD-based scheme developed by Sandberg et al. [2012]

We developed scaling factors for the electron fluxes using a large number (400) of magnetic conjunctions between INTEGRAL/IREM and Van Allen probe B/MagEIS
INTEGRAL has a highly evolving orbit with variable inclination and eccentricity.

- Use data within 15° of magnetic equator.

- Analyse data as a function of energy and $L^*$ in the range
  - $0.69 \leq E \leq 2.05$ MeV
  - $4.0 \leq L^* \leq 6.75$
Coverage

- The coverage is good, but not identical, at all $L^*$ values

- The coverage ranges from a minimum of 1042 data points at $L^* = 4.0$ to a maximum of 1245 data points at $L^* = 6.5$

- This corresponds to a minimum and maximum data coverage of 8.5 and 10.2 years respectively
Summary Plots

- To inspect the data we produced annual summary plots.
- We plotted the IREM data at 2 representative $L^*$ values together with the GOES $E > 2$ MeV fluxes.
- Data confirmed to be very clean and no outliers were found.
Exceedance Probability at L* = 6.0

- At L* = 6.0, representative of geosynchronous orbit
  - fluxes cover three orders of magnitude
  - largest observed fluxes range from \(1.4 \times 10^5\) cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\)MeV\(^{-1}\) at \(E = 2.05\) MeV to \(4.6 \times 10^6\) cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\)MeV\(^{-1}\) at \(E = 0.69\) MeV
Exceedance Probability at $L^* = 4.5$

- At $L^* = 4.5$, representative of the location of the peak in the fluxes in GNSS type orbits
  - fluxes cover three orders of magnitude
  - largest observed fluxes range from $5.6 \times 10^5$ cm$^{-2}$s$^{-1}$sr$^{-1}$MeV$^{-1}$ at $E = 2.05$ MeV to $1.4 \times 10^7$ cm$^{-2}$s$^{-1}$sr$^{-1}$MeV$^{-1}$ at $E = 0.69$ MeV
• We perform extreme value analysis using the exceedances over a high threshold method.

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

• We decluster the data to avoid counting individual events more than once and fit the GPD to the cluster maxima.
The GPD may be written in the form

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

where: \( x \) are the cluster maxima above the chosen threshold \( u \)

\( \xi \) is the shape parameter which controls the behaviour of the tail

\( \sigma \) 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 flux that is exceeded on average once every N years can be expressed in terms of the fitted parameters $\sigma$ and $\xi$ as:

  $$x_N = u + \left( \frac{\sigma}{\xi} \right) \left( \frac{Nn_d n_c}{n_{tot}} \right)^\xi - 1$$

  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.
Return Level Plot for 0.99 MeV Electrons at $L^* = 6.0$

- 1 in 10 year flux
  - $1.21 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{MeV}^{-1}$
• 1 in 10 year flux
  • $1.21 \times 10^6$ cm$^{-2}$s$^{-1}$sr$^{-1}$MeV$^{-1}$
• 1 in 100 year flux
  • $1.36 \times 10^6$ cm$^{-2}$s$^{-1}$sr$^{-1}$MeV$^{-1}$
At $L^* = 6.0$, representative of geosynchronous orbit, we find:

- 1 in 10 year flux ranges from $4.4 \times 10^6 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}^{-1}$ at $E = 0.69 \text{ MeV}$ to $1.2 \times 10^5 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}^{-1}$ at $E = 2.05 \text{ MeV}$

- 1 in 100 year flux is a factor of 1.1 to 1.4 times larger than the 1 in 10 year flux
The analysis shows that the electron fluxes generally tend to limiting values.

The limiting fluxes at $L^* = 6.0$ are up to a factor of 1.5 times larger than the 1 in 10 year fluxes.
Comparison with O’Brien et al. [2007]

- The limiting fluxes at $L^* = 6.0$ are in good agreement with those from the LANL study O’Brien et al. [2007]
The largest daily average flux of $E > 2$ MeV electrons observed by GOES between 1986 and 1999 occurred on 28\textsuperscript{th} March 1991 [Fennell \textit{et al.}, 2000].

Return period is 13.7 years – results should be similar in magnitude to a 1 in 10 year event.

CRRES spectrum of worst cases at $L^* = 6.0$ also occurred at this time and is similar in magnitude to the IREM 1 in 10 year fluxes.
At $L^* = 4.5$, representative of the location of the peak fluxes encountered in GNSS type environments, we find

- 1 in 10 year flux ranges 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
• 1 in N year fluxes at equatorial MEO are a factor of 3-4 greater than those at GEO
Limiting Flux

- The limiting fluxes at $L^* = 4.5$ are up to a factor of 2.3 times larger than the 1 in 10 year fluxes.
Comparison with CRRES Worst Case

- CRRES spectrum of worst cases at $L^* = 4.5$ occurred on 28/29\textsuperscript{th} March 1991

- CRRES worst case spectrum is similar in magnitude to the IREM 1 in 10 year fluxes
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 $L^*$
- For each energy the 1 in 10 year fluxes are roughly constant in the region $4.0 \leq L^* \leq 5.0$ and then decrease with increasing $L^*$
• Results can also be used to determine the 1 in 100 year electron flux as a function of energy and $L^*$

• The 1 in 100 year fluxes are typically up to a factor of 2 times larger than the 1 in 10 year fluxes
In the US the National Science and Technology Council called for the development of space weather benchmarks in 2015 – including the 1 in 100 year event for the near-Earth radiation environment.

“Space Weather Phase 1 Benchmarks” draft produced in January 2017 – included 1 in 100 year events:
- from LANL [O’Brien et al., 2007] and from GOES [Meredith et al., 2015]
- from HEO1 and HEO3 [O’Brien et al., 2007] in HEO

New results can be included in the next draft of the SW Benchmarks.
Summary

• The 1 in 100 year event levels can be used as space weather benchmarks as defined by the SWORM subcommittee of the NSTC.

• The benchmarks can be used to:
  – determine the likely impact of an extreme event
  – improve the resilience of future satellites
  – evaluate potential disaster scenarios
  – assess the reserves to be set aside to pay claims in the event of a worst case event

• The benchmarks may also be used for:
  – comparison with any short time constant event (1 day, 1 hr, or otherwise)
  – the purposes of situational awareness and operational risk assessments
  – comparison with theoretical maximum fluxes
Acknowledgements

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Preliminary Comparison with MagEIS-B Highest Fluxes

- Instructive to compare results with the worst fluxes recorded by MagEIS

- Use spin-averaged, background corrected, L-binned (OP77Q, 0.1L bins), B/Beq < 1.1 at L = 4.45 from MagEIS-B

- 01/04/2013 - 31/12/2017

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<th>Time (UT)</th>
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Data courtesy of Seth Claudepierre
GOES E> 2MeV Electrons

- Eighth largest daily average flux of E> 2MeV electrons occurred on 11 May 2016
- Extreme value analysis suggests that this is a 1 in 5 year event
• Largest electron fluxes during mission at $L^* = 6.0$ observed on 11 May 2016

• No coverage at $L^* = 4.5$ for this event
Calibration Factors

- Use MagEIS spin-averaged data (Release 03, Level 2, Version 4.X)
- Period: 19/08/2013 – 07/08/2015
- Conjunction Criteria
  - $\Delta L^* < 0.1$ in range $3 < L^* < 6$
  - $\Delta (B / B_{eq}) < 0.1$ and $B / B_{eq} \approx 1$
  - $4 < MLT < 8$ and $16 < MLT < 20$
  - $\Delta t < 1$ h

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<th>Energy (MeV)</th>
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Comparison with Other Data Sets