Validating very long-term simulations with the BAS Radiation Belt Model using GIOVE-B data

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Outline

- Motivation
- Background on the model
- Boundary conditions
- Results
- Comparison with data
- Conclusions

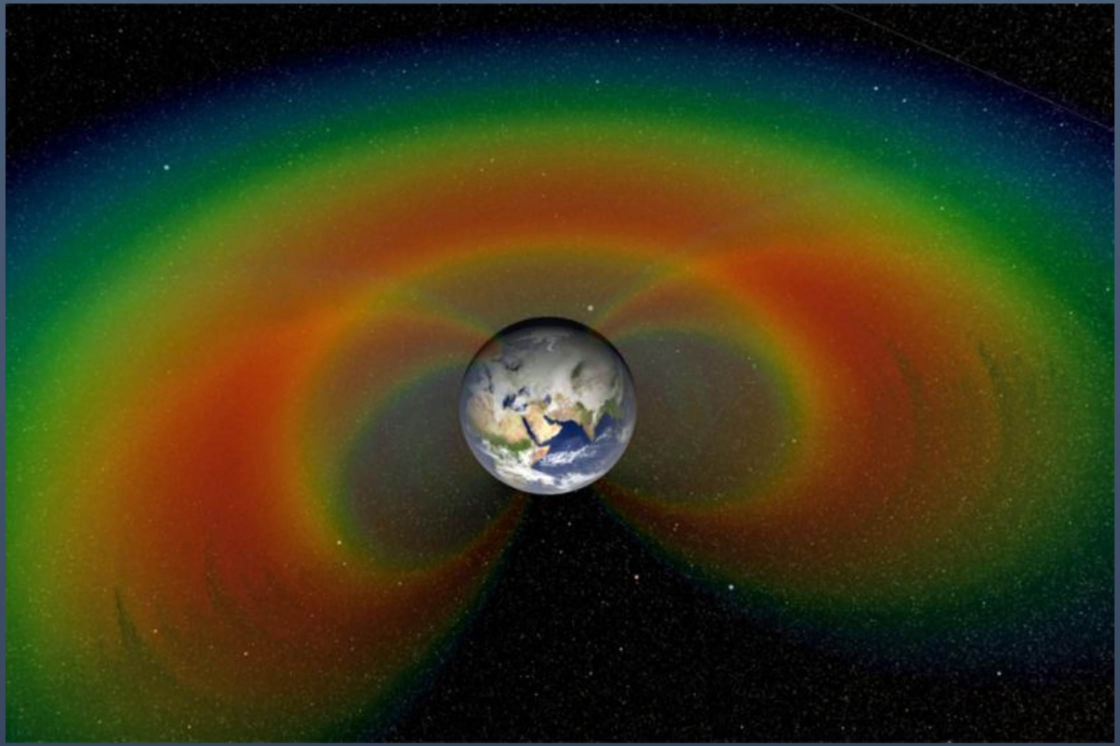

Image: NASA

Context

EU FP7 project SPACESTORM

- April 2014 – March 2017
- Aim: *To model severe space weather events and mitigate their effects on satellites*
- Reconstruct the high-energy electron radiation environment inside GEO for 30 years

Motivation

- Understanding the MEO environment is becoming increasingly important
  - GPS, Galileo
  - O3B at 8000km
  - Electric orbit raising
- Modern satellites expected to have a lifetime of about 20 years
- No data set at MEO covers this sort of time period
- A 30 year reconstruction would provide a resource for designers, operators and insurers

BAS Radiation Belt Model

- Diffusion equation for the drift averaged phase-space density
  - pitch-angle (α), Energy (E), L^* (L)
- Includes:
  - Wave-particle interactions
  - Radial transport
  - Loss to the atmosphere and magnetopause
- Waves:
  - Upper and lower band chorus
  - Plasmaspheric hiss and lightning-generated whistlers
  - EMIC waves

$$\frac{\partial f}{\partial t} = \frac{1}{g(\alpha)} \frac{\partial}{\partial \alpha}\bigg|_{E,L} g(\alpha) \left(D_{\alpha\alpha} \frac{\partial f}{\partial \alpha}\bigg|_{E,L} + D_{\alpha E} \frac{\partial f}{\partial E}\bigg|_{\alpha,L} \right) + \frac{1}{A(E)} \frac{\partial}{\partial E}\bigg|_{\alpha,L} A(E) \left(D_{EE} \frac{\partial f}{\partial E}\bigg|_{\alpha,L} + D_{\alpha E} \frac{\partial f}{\partial \alpha}\bigg|_{E,L} \right) + L^2 \frac{\partial}{\partial L}\bigg|_{\mu,J} \left(\frac{1}{L^2} D_{LL} \frac{\partial f}{\partial L}\bigg|_{\mu,J} \right) - \frac{f}{\tau}$$

$$g(\alpha) = \sin 2\alpha \left(1.3802 - 0.3198\left(\sin\alpha + \sin\alpha^{1/2}\right)\right)$$

$$A(E) = (E + E_0)\left(E(E + 2E_0)\right)^{1/2}$$

Glauert et al. [2014 a, b]
Horne et al. [2013]
Meredith et al. [2014]
Kersten et al. [2014]

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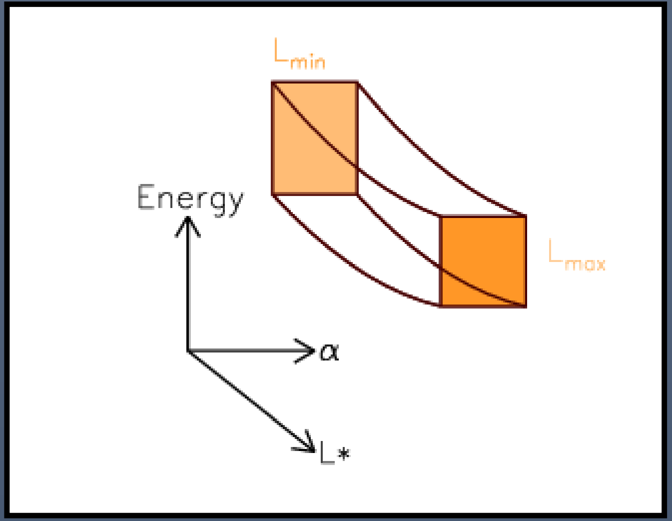
Model boundaries

- Model includes radial diffusion
  - —Energy range varies with L*
- 6 boundaries:
  - —α = 0^o, 90^o $\partial f/\partial\alpha = 0$
  - —$E_{max}(L^*) = 0$ $f = 0$
  - —E_{min} = 100 keV at L_{max}
  - —$L_{min} = 2$ Statistical boundary condition from CRRES data [*Glauert et al.*, 2014b]
  - —$L_{max} = 6.1$



Outer L* boundary

- Need a data set that covers 30 years
  - GOES > 2MeV electron flux (EPS, 5 minute resolution)

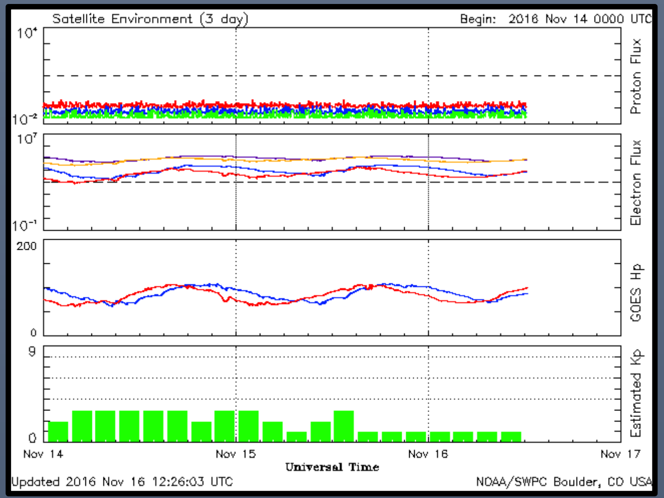


Image: SWPC

GOES provides:	Model requires:
Integral flux	Drift-averaged differential flux
At GEO - varying L*	Fixed L*
>2 MeV flux only	Full spectrum from 100 keV

- Need to
  1. Map to fixed L* and remove diurnal variation
  2. Approximate differential energy spectrum from one integral flux measurement

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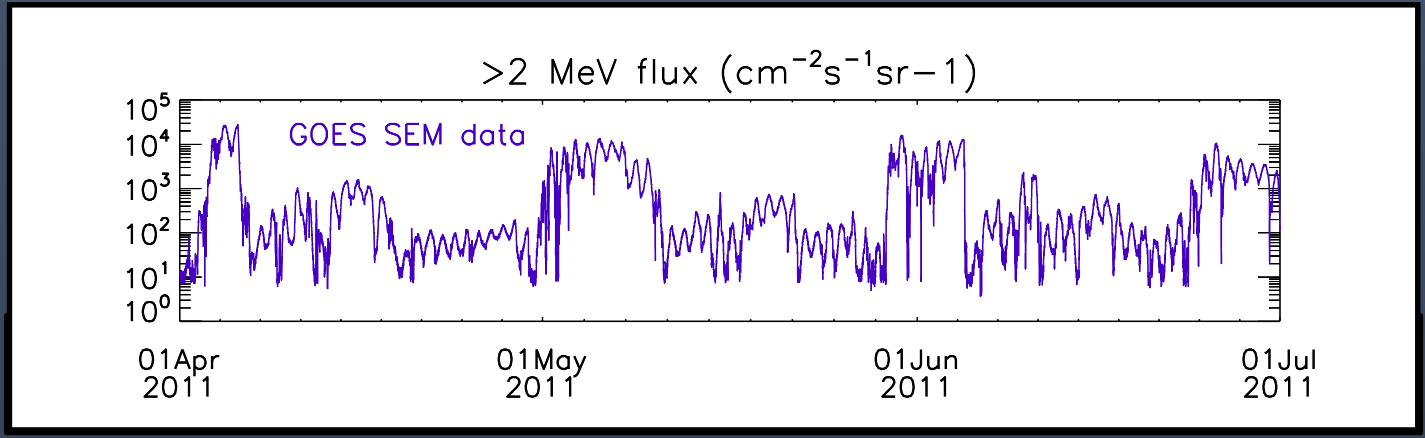
Mapping to fixed L*

Statistical Asynchronous Regression (SAR) [*O'Brien at al,2001*]

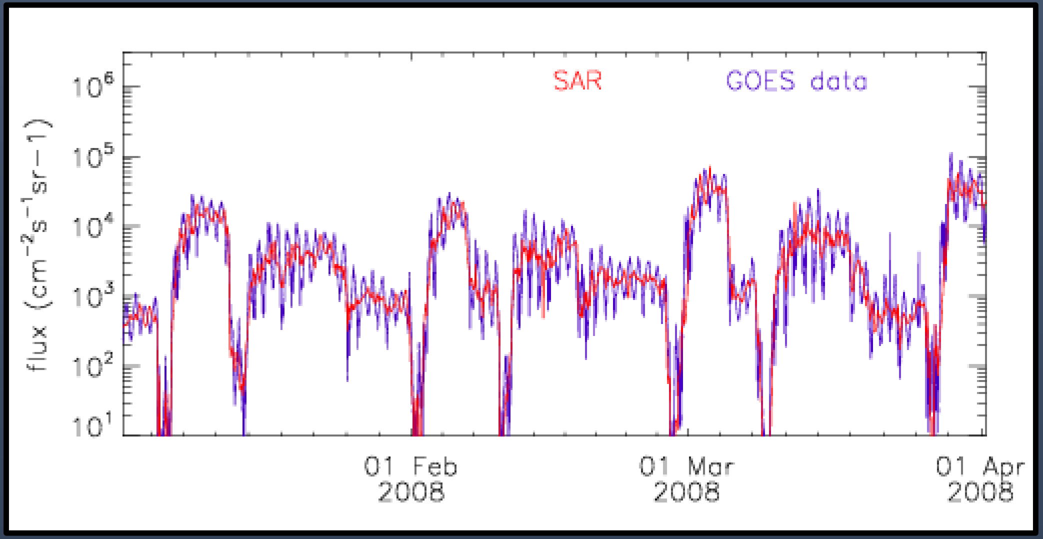
- Finds a function that maps the flux measurement at any MLT, to the flux that would be measured by the same instrument at a fixed MLT
- Removes the diurnal variation and maps to a fixed L*



Apply SAR to GOES >2MeV data

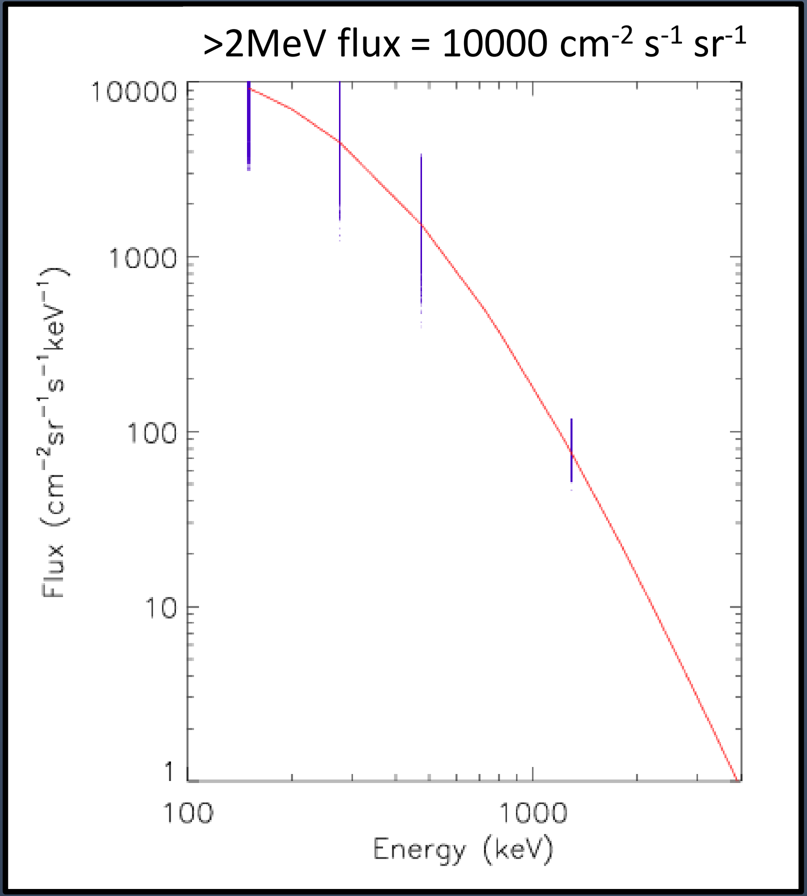
- Average the flux into 2 hour MLT bins for 3 levels of Kp
  - $0 \leq Kp < 2$, $2 \leq Kp < 4$, $4 \leq Kp$
- Calculate Kp dependent mappings
  - for both dawn and dusk
- Map flux to dawn and dusk and then average
- Separate mappings for each GOES spacecraft

Example: GOES 11
1 Jan. to 1 April 2008



Approximating the spectrum

- Have to derive the differential flux spectrum from >2MeV flux
- Need to know what the spectra look like at GEO
    - —GOES 15 MAGED
        - 150 keV, 275 keV and 475keV differential flux
    - —Difference >800 keV and >2 MeV flux
    - —Bin flux by level of >2MeV flux
        - Bins: 8, 30, 500, 10000 $cm^{-2}\ s^{-1}\ sr^{-1}$ +/- 10%
    - —Fit kappa distribution to PSD in each bin
    - —Get differential flux spectra
    - —Calculate integral spectra

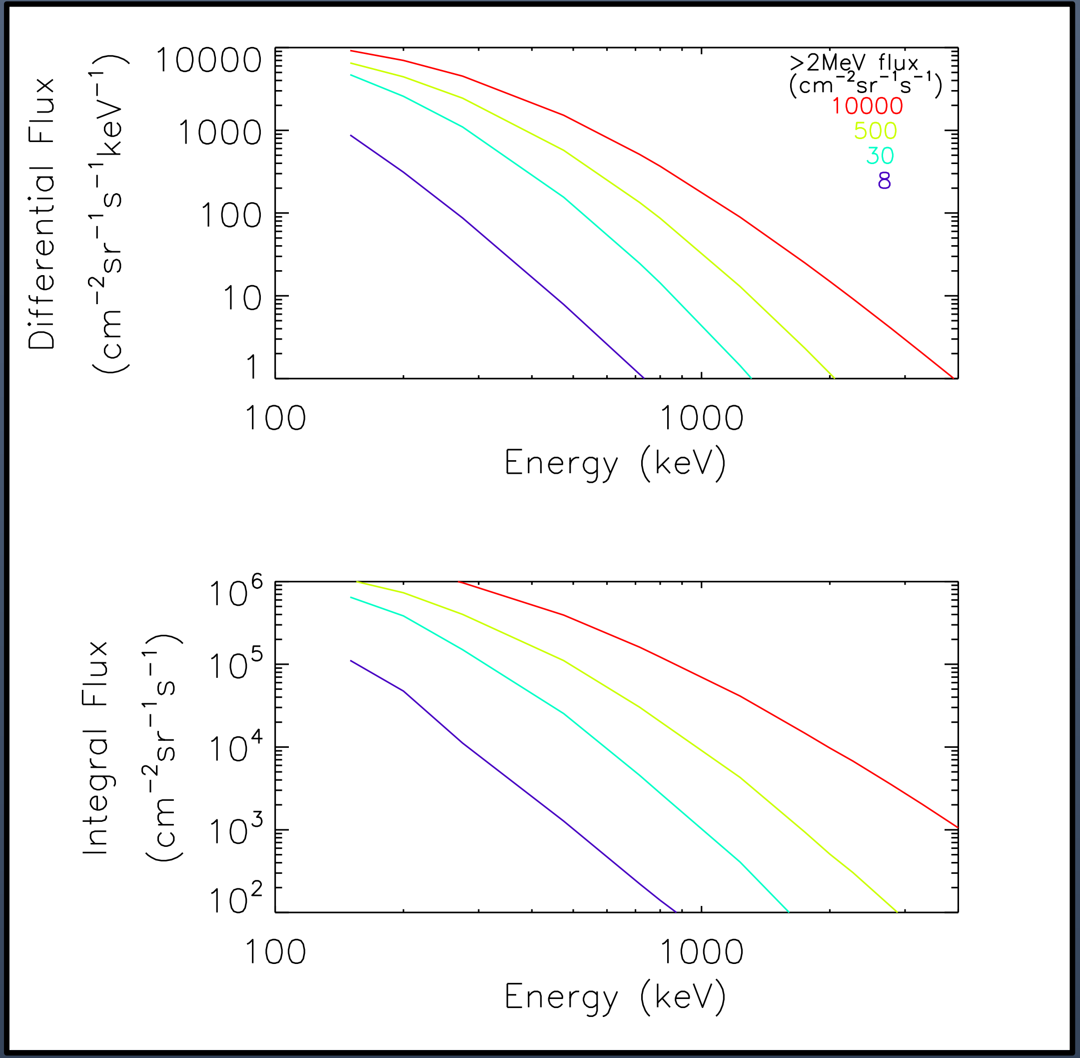


Spectra at GEO

- Shape of spectra changes as >2MeV flux increases
  - —'High energy tail' develops

- Differential spectra from >2MeV flux
  - —Find spectra that lie above and below the >2MeV flux
  - —Find weighting for these spectra so >2MeV flux matches
  - —Apply same weights to differential spectra

=> Spectrum on boundary



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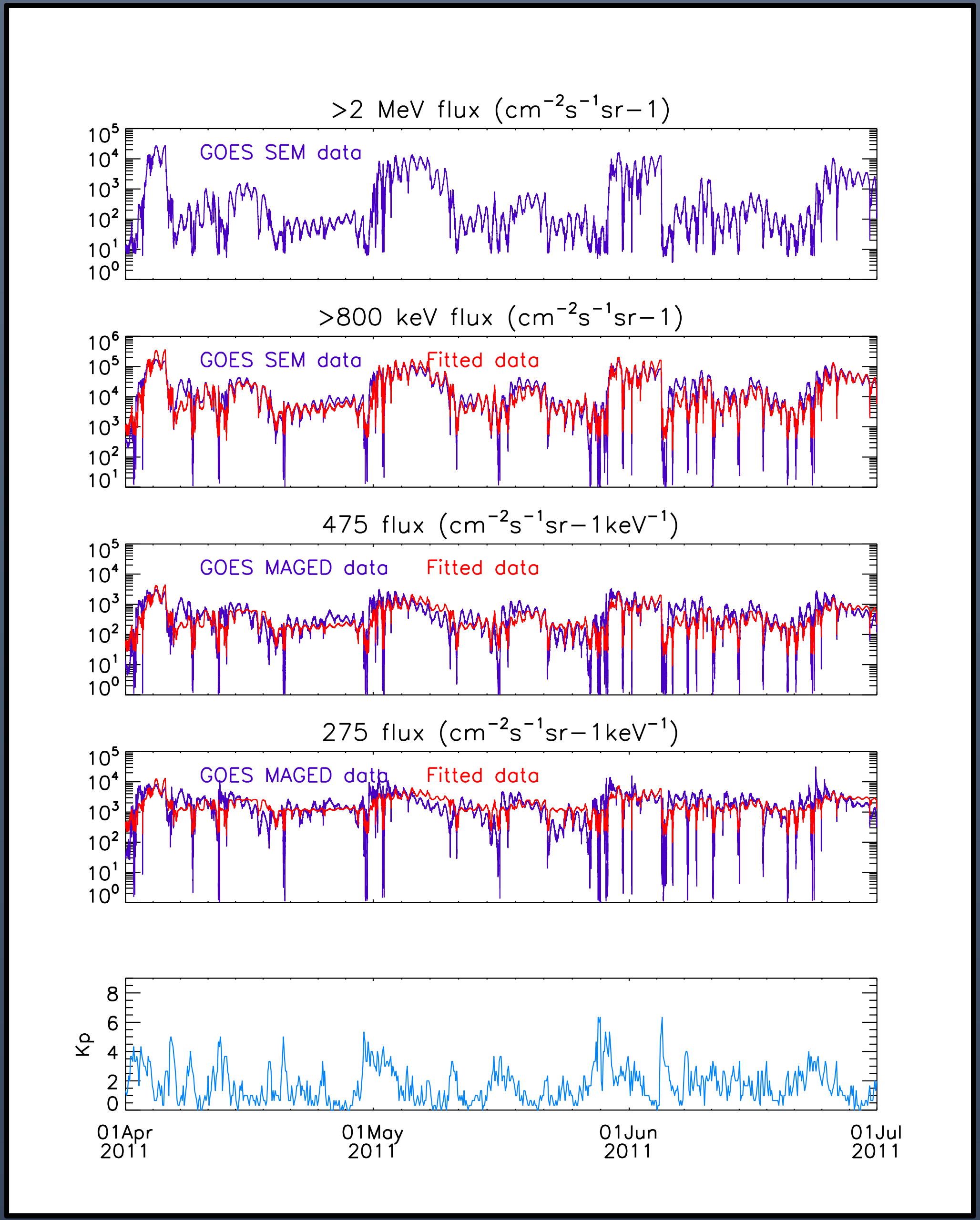
Fitting spectra

April - July 2011



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L_{max} and E_{min} boundary conditions

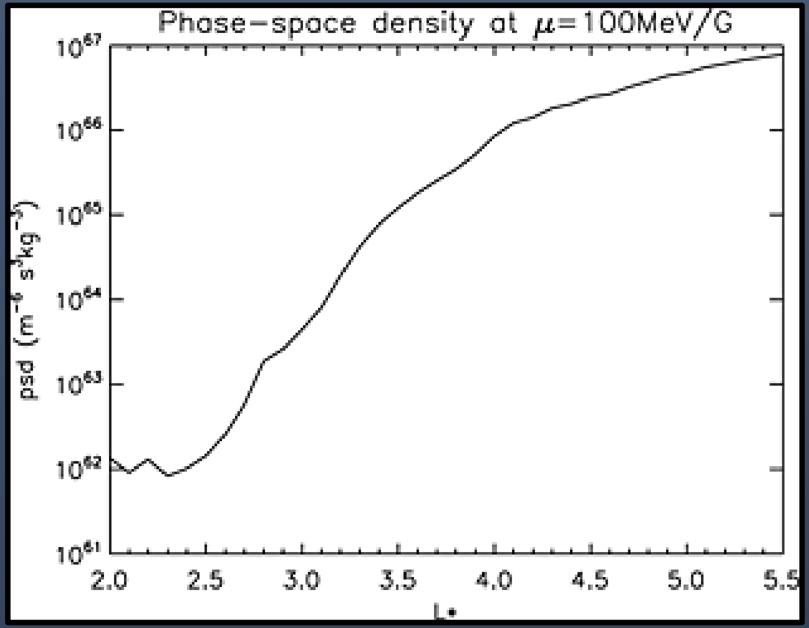
Outer radial boundary:

- Apply SAR to get drift average >2MeV flux at fixed L^*
- Use spectra to get all energies
- Move boundary adiabatically to L*=6.1

Minimum energy boundary:

- Average psd as a function of L*
  - —From CRRES for μ= 100 MeV/G
- Scale this profile to match outer boundary

Glauert et al., 2014



GOES satellites

Usually more than one GOES spacecraft providing data

- Prefer to use GOES West
- Nearer the magnetic equator

GOES	Start Date
6	01-01-1986
7	06-03-1987
9	01-04-1996
10	28-07-1998
11	01-07-2006
15	01-01-2011

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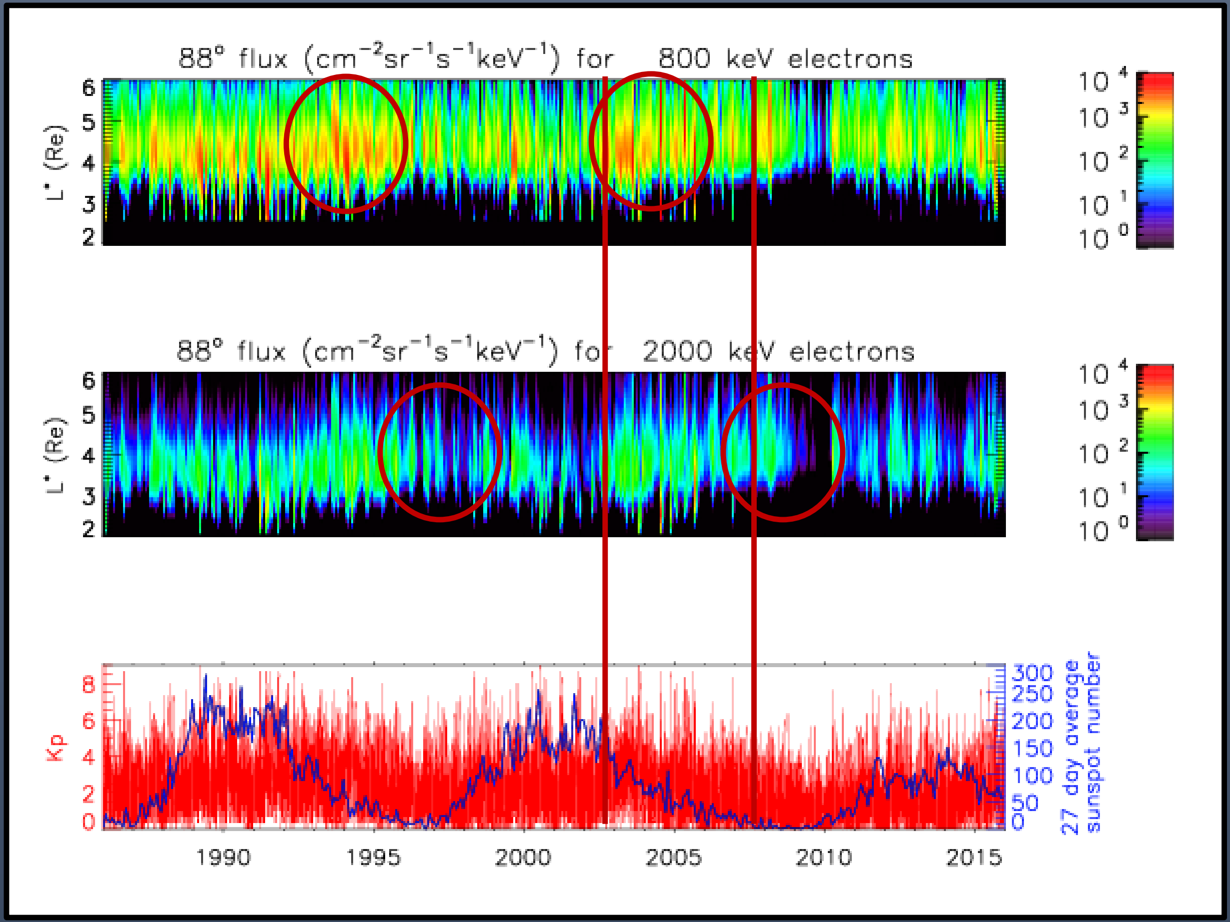
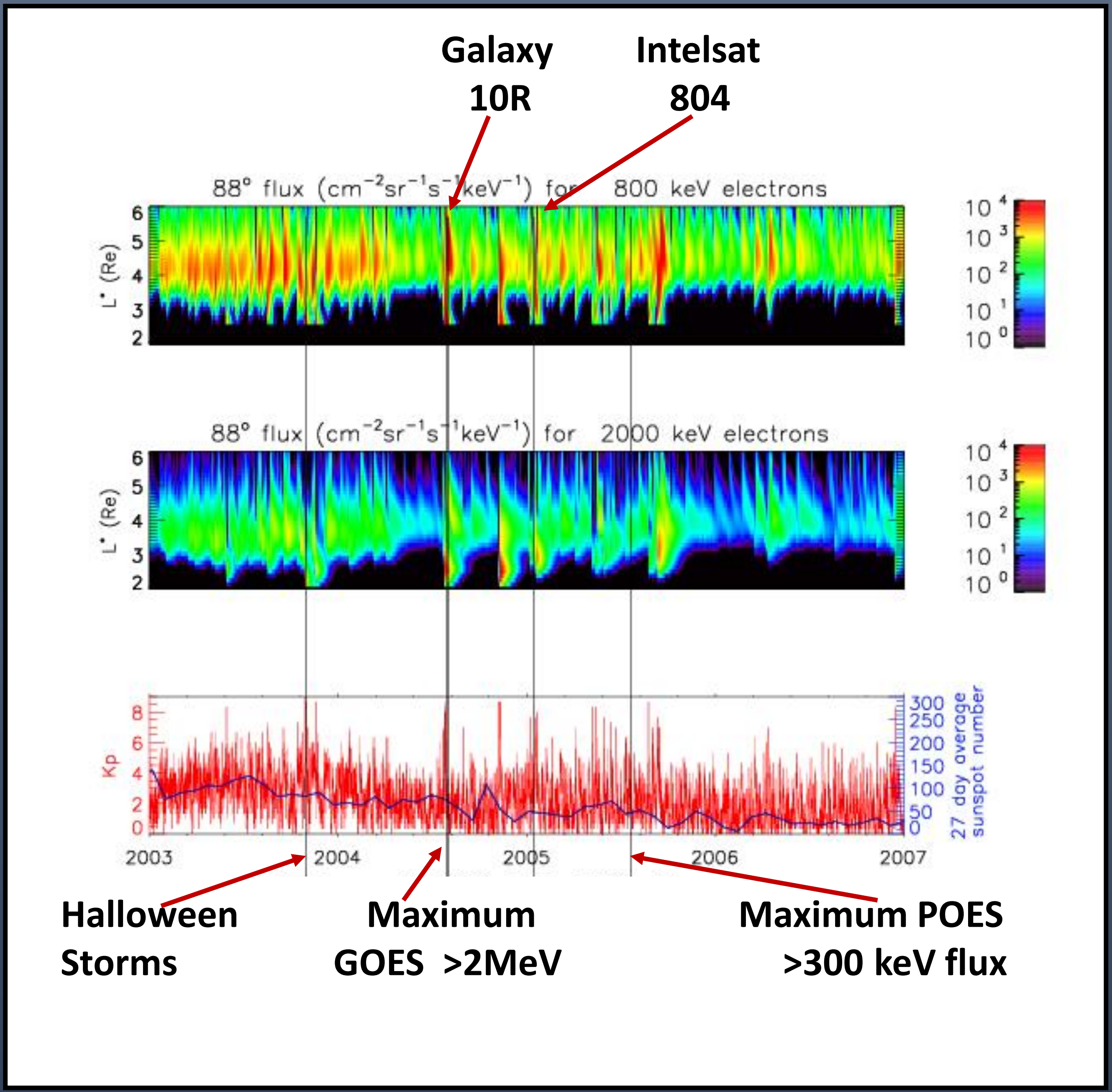
1986 - 2016

- Short term variability
- Long term variability
  - —Most intense in declining phase 1993-1994, 2003-2005
  - —Quiet start to new cycle 1998, 2009
- Electron desert 2009



2003 - 2007

- Declining phase of solar cycle
- Includes
  - —Halloween storms
  - —GOES >2MeV maximum flux [*Meredith et al.*, 2015]
  - —POES >300keV maximum flux at L*=4.5 [*Meredith et al.*, 2016]
  - —Galaxy 10 R anomaly
  - —Intelsat 804 anomaly



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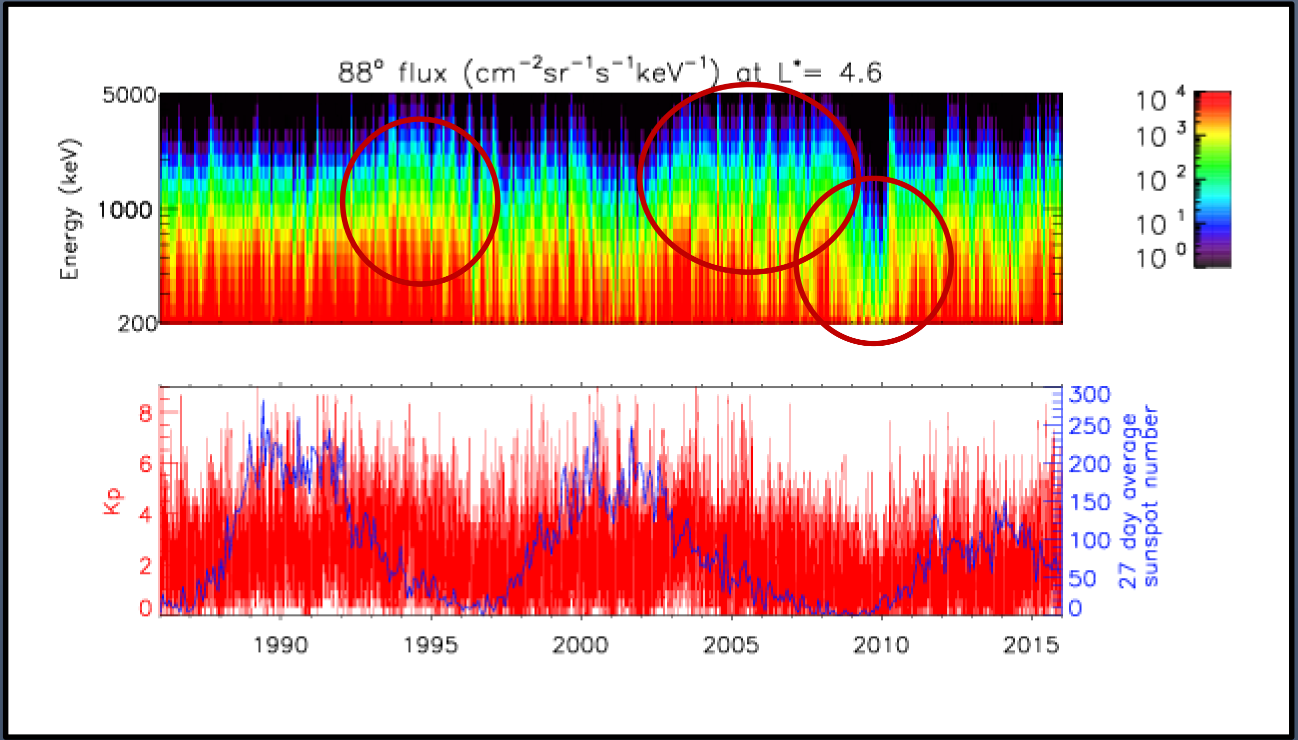
Spectra

- L* = 4.6
- Harder spectrum during declining phase
- Very soft spectrum during the ‘electron desert’



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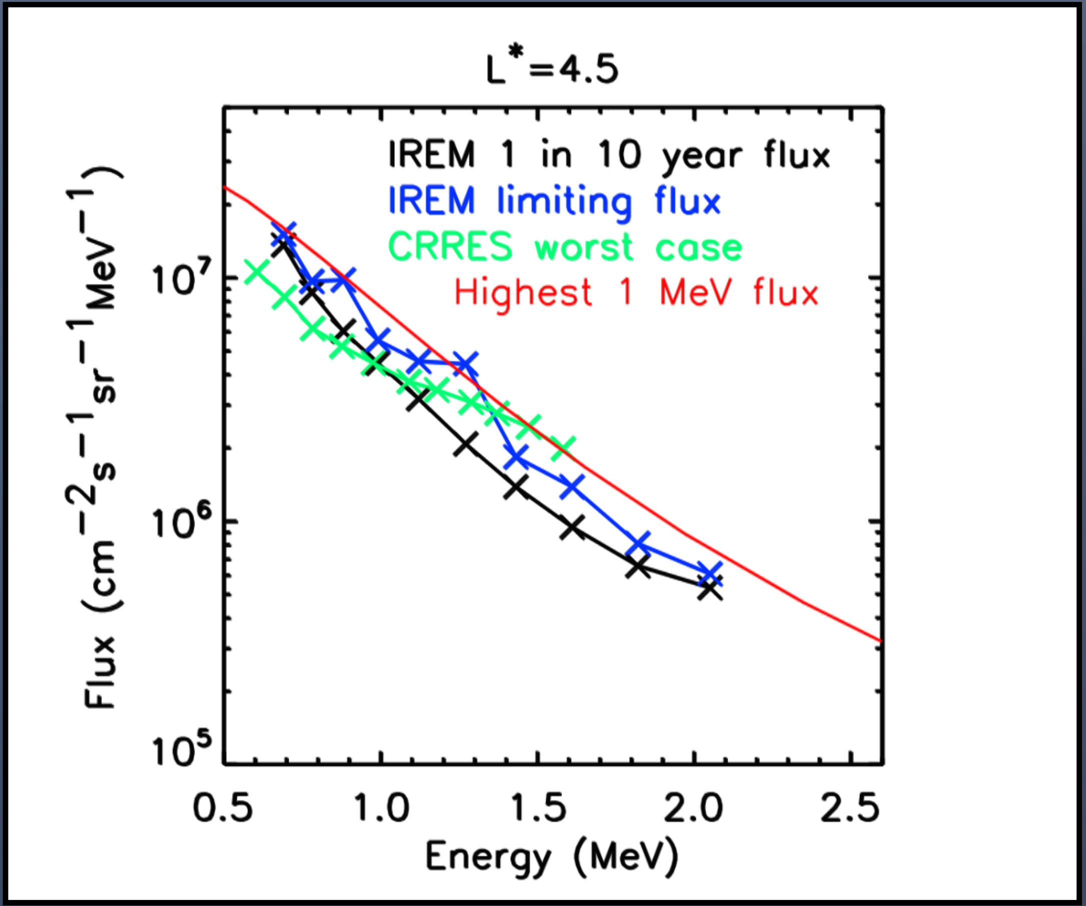
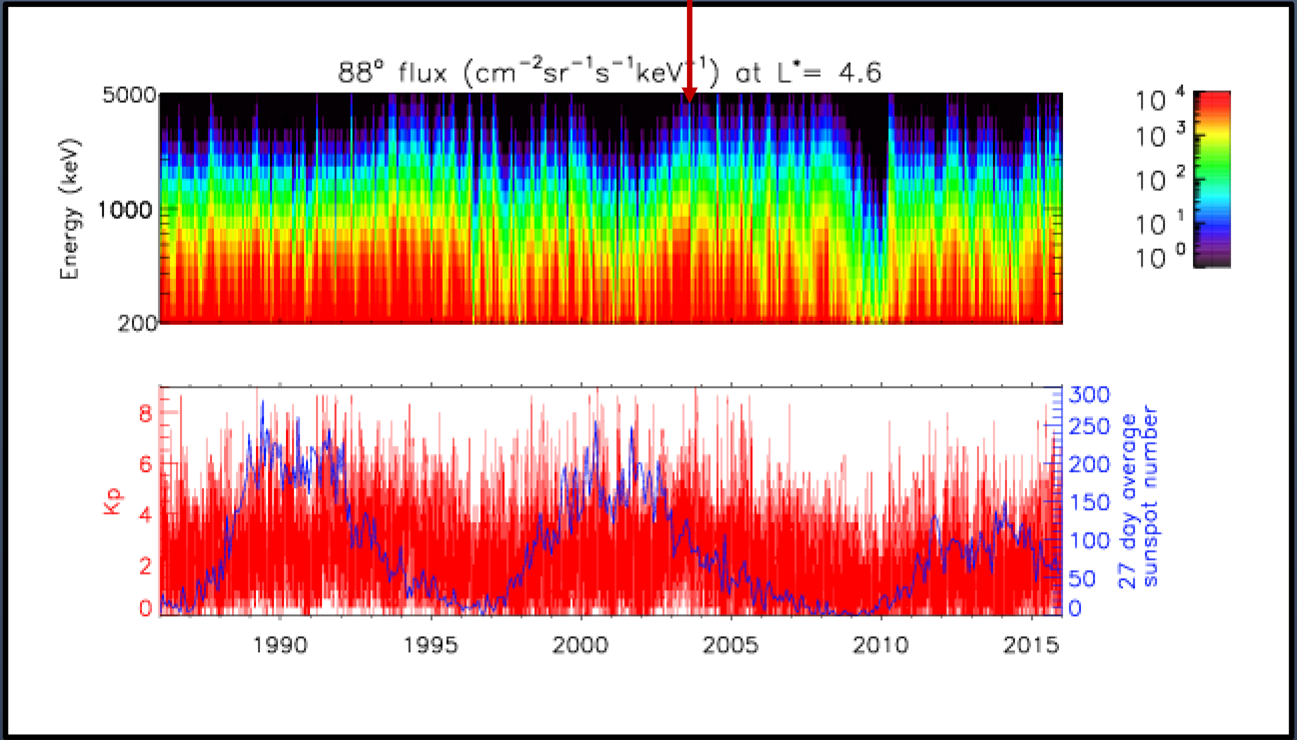
Comparison to extreme fluxes



Meredith et al., SW, 2018

2 August 2004



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GIOVE-B spacecraft

Image: ESA

- Galileo In-Orbit Validation Element-B (GIOVE-B)
  - —Inclination ~56^{o}, period ~14 hours, altitude 23,200 km
  - —~4.2 < L* < ~8.8 (Olson-Pfitzer)
  - —~4 years of data (May 2008 – July 2012)
- Standard Radiation Environment Monitor (SREM), [*Evans et al*.,2008]
  - —15 channels:
    - TC1 channel E >2 MeV
    - TC3 channel E >800 keV.
- Use response functions to convert model output to SREM count rates
  - —Giove-B response functions not available - use Rosetta

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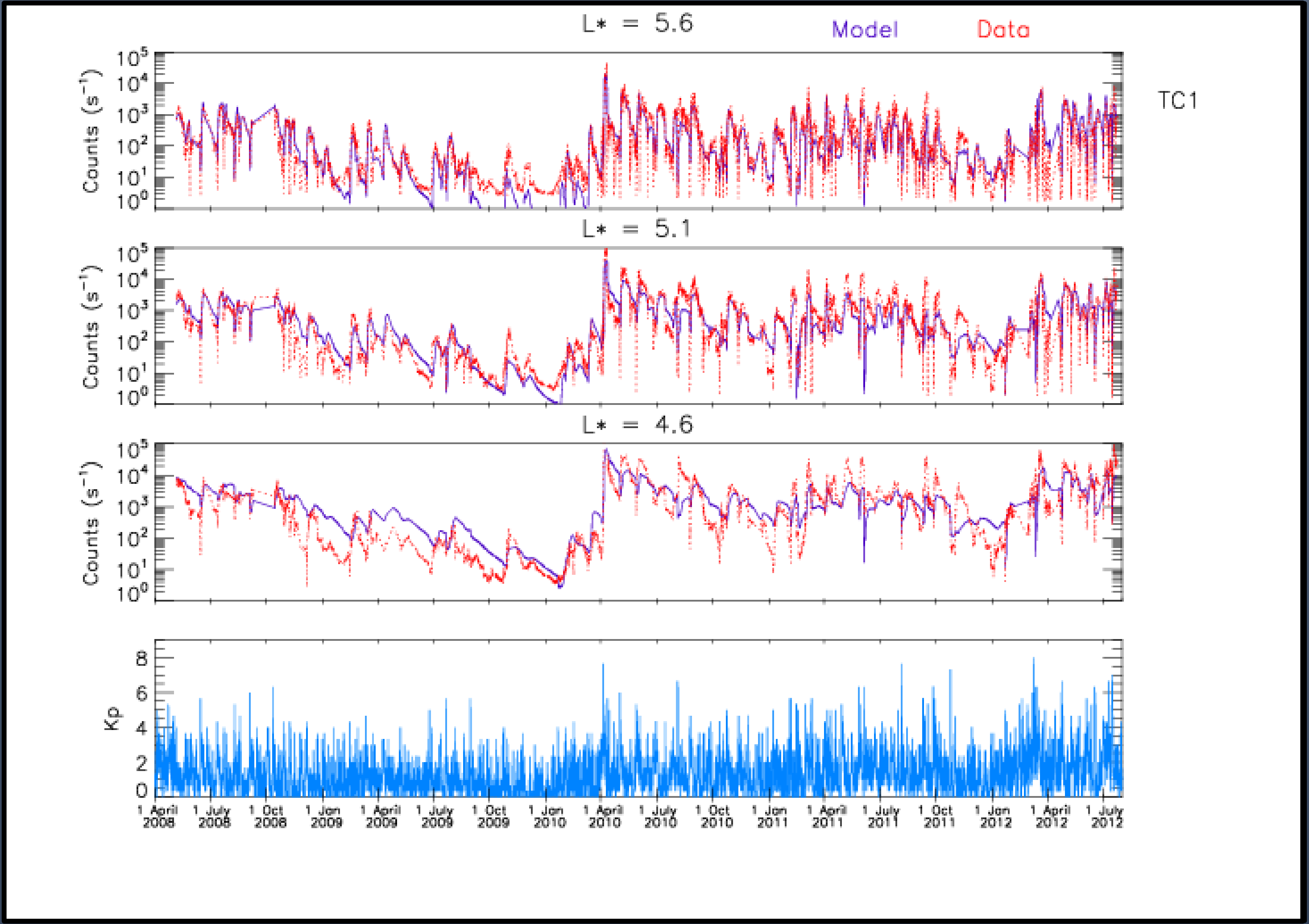
Comparison with GIOVE-B data

- L* = 4.6, 5.1 and 5.6
- TC1 ~ > 2MeV
- TC3 ~ >800 keV



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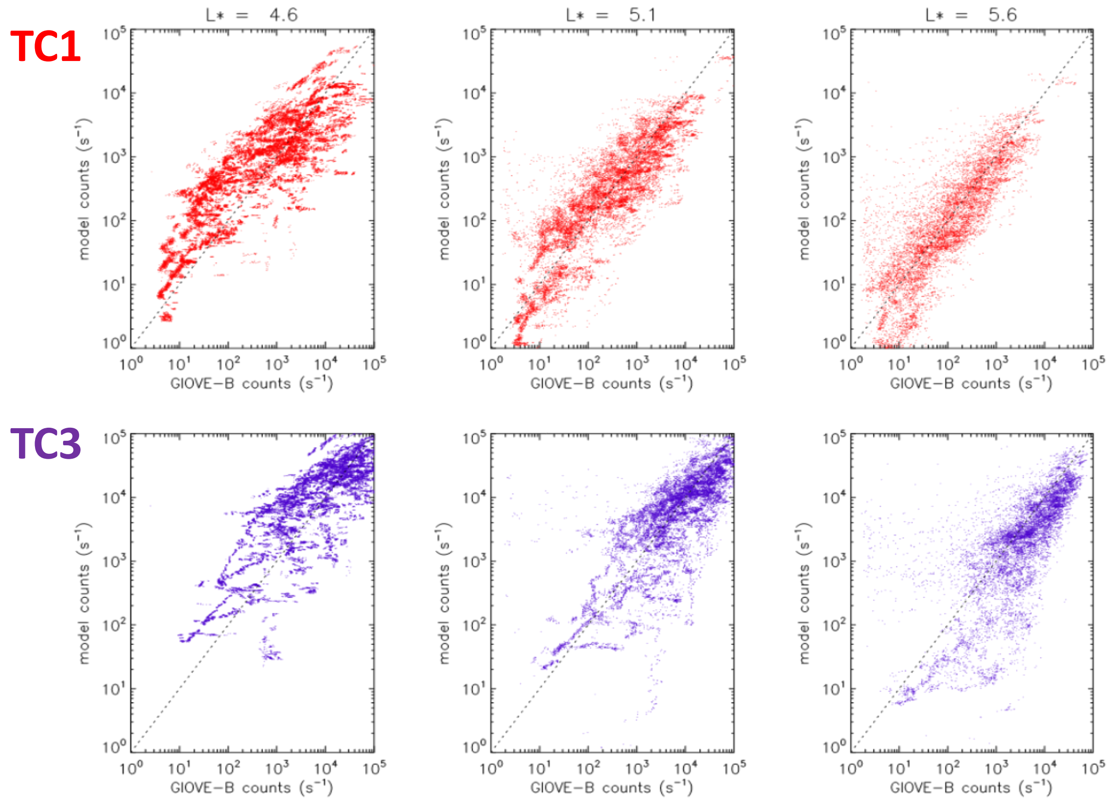
Model vs data

Correlation coefficients		
L*	**TC1**	**TC3**
4.6	0.85	0.82
5.1	0.86	0.79
5.6	0.85	0.74

Reasonably good correlation?



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Metrics

Median symmetric accuracy
Morley et al., 2018

TC1

L*	Mean abs. error (counts)	Median error (counts)	% within a factor of 4	50% of errors less than a factor of	Skill Score vs average
4.6	3279.	557.	70.8	2.61	0.69
5.1	949.	144.	80.0	2.1	0.73
5.6	291.	41.	75.9	2.1	0.59

TC3

L*	Mean abs. error (counts)	Median error (counts)	% within a factor of 4	50% of errors less than a factor of	Skill Score vs average
4.6	1846.	7509.	64.0	2.54	0.65
5.1	1005.	3929.	80.0	1.96	0.59
5.6	4764.	2016.	76.2	2.15	0.37

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Conclusions

- Have a 30 year long simulation of the radiation belts
- Reasonable agreement with data
- Applications
  - — Look at environment when anomalies occurred
  - —Worst case fluxes
  - — 'Fly through' for typical conditions along an orbit

Thank you

Acknowledgements

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Skill Score

$$SS = 1 - \frac{\sum_1^N (X_i - Y_i)^2}{\sum_1^N (X_i - \overline{X})^2}$$

X_i = data values

Y_i = model results

X = average data

N = number of points

- -∞ < SS ≤ 1
  - —SS = 1 implies a perfect model
  - —SS = 0 implies average from model equals average from data
  - —SS < 0 you should use the average value instead of your model
- We compare log (fluxes) – [*Balakin et al*., 2016]

Next steps

- Recalculate using >800 keV flux on outer boundary (from 1994)
- Use POES data for low energy boundary (from 1998)
- Compare with other data sets – e.g. VAP
- Compare with AE8/AE9