High-Energy Electrons

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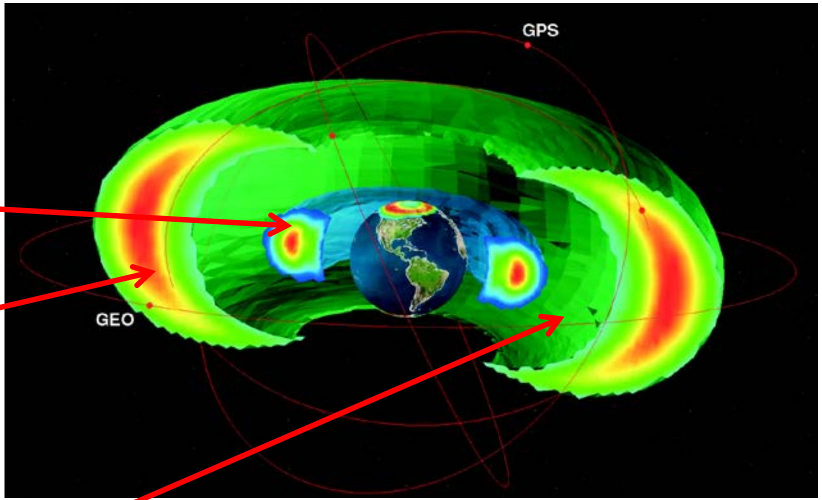
High-energy electrons in the radiation belts

- Brief introduction to modelling high-energy electrons
- Recreation of the electron flux in the radiation belts for the last 30 years
- What would happen during and following an extreme CME

Electron Radiation Belts

- High energy electrons trapped by Earth's magnetic field

- Two torus shaped regions:
  - Inner belt
    Between 1.2 and 2 Earth radii
    Fairly stable
  - Outer belt
    Between 3 and 7 Earth radii
    Highly dynamic



- Slot region between the two belts
  - Usually 'empty' but can 'fill' during strong storms

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BAS Radiation Belt Model

- State-of-the-art model developed at BAS over the last 5 years
  - Diffusion equation for the drift averaged phase-space density
- Includes:
  - Radial transport
  - Wave-particle interactions
  - Loss to the atmosphere
  - Loss to the magnetopause
- Waves:
  - Chorus waves
  - Plasmaspheric hiss
  - 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. [2014a, 2014b], Horne et al. [2013],
Meredith et al. [2012, 2014], Kersten et al. [2014]

Recreating the radiation belts for the last 30 years

Motivation

- Understanding the radiation environment at medium Earth orbit (MEO) is becoming increasing important
  - GPS, Galileo, O3B
  - Electric orbit raising
- Modern satellites expected to have a lifetime of about 15 years
- No data set at MEO covers this length of time

Aim

- Use available data and modelling to recreate the MEO high-energy electron environment
  - 1 January 1986 to 1 January 2016
  - Energies responsible for internal charging (E > ~500 keV)

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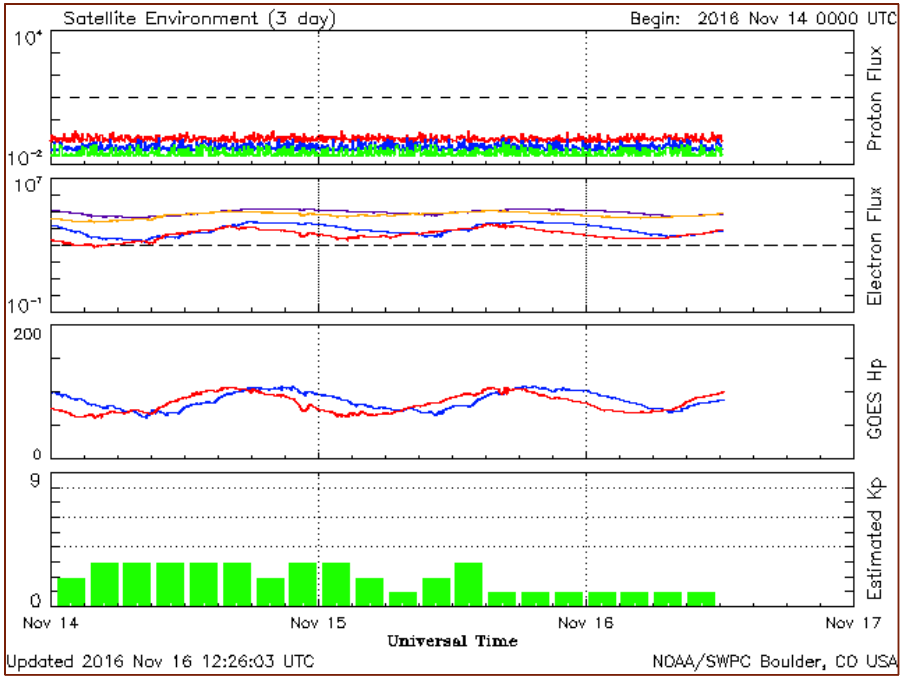
Drivers for the model

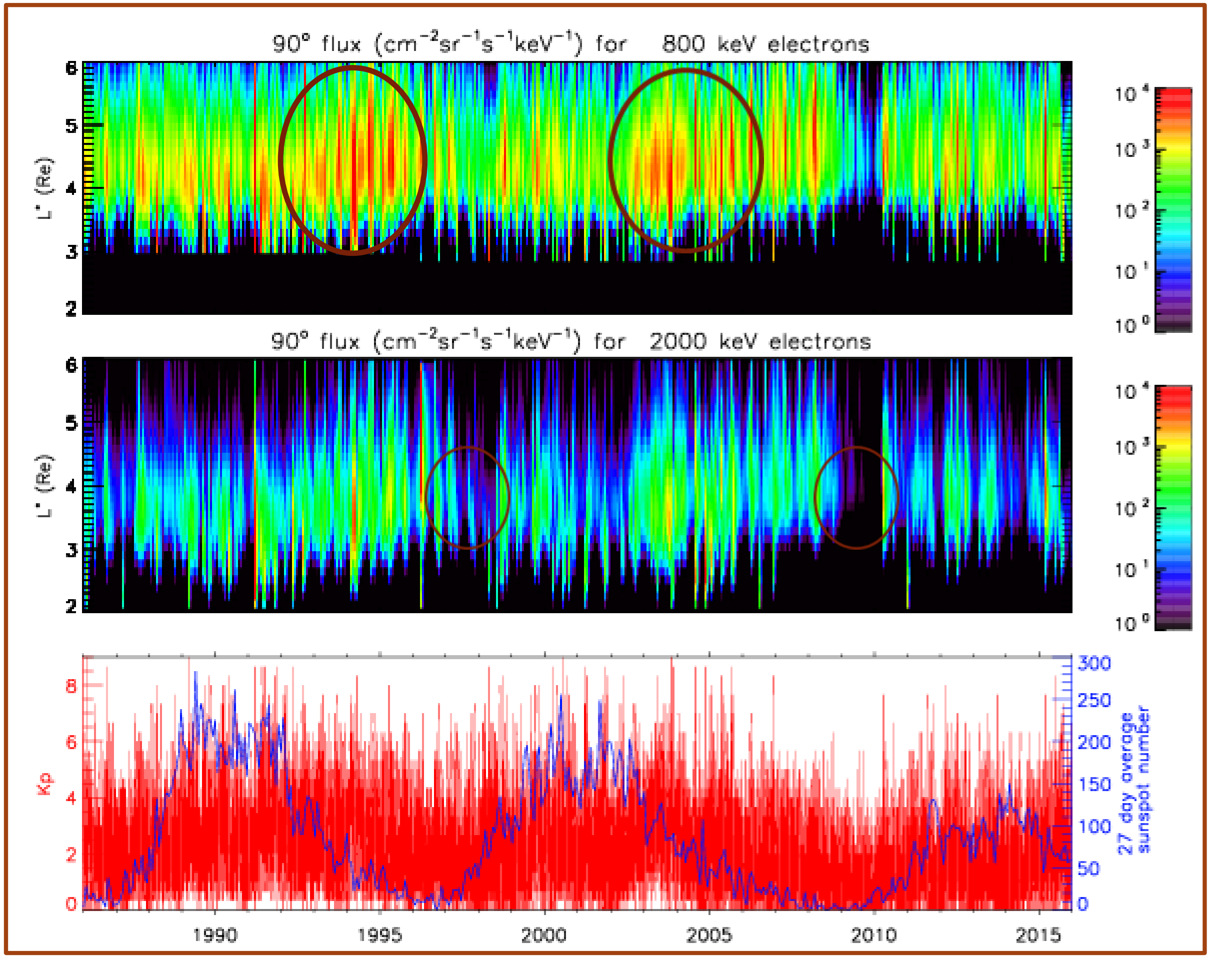
- Need 30 year long data sets
  - Kp index
  - Solar wind parameters, IMF Bz
- GOES > 2MeV electron flux
  - EPS, 5 minute resolution



- New technique determines outer boundary condition from GOES data

30 year simulation

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



How reliable are our results?

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GIOVE-B data

- Galileo In-Orbit Validation Element-B (GIOVE-B)
  - MEO
  - Inclination ~56º, period ~14 hours, altitude 23,200 km
  - ~4.2 < L* < ~8.8
- ~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

How reliable are our results?

- 2010
- L* = 4.5, 5 and 5.5

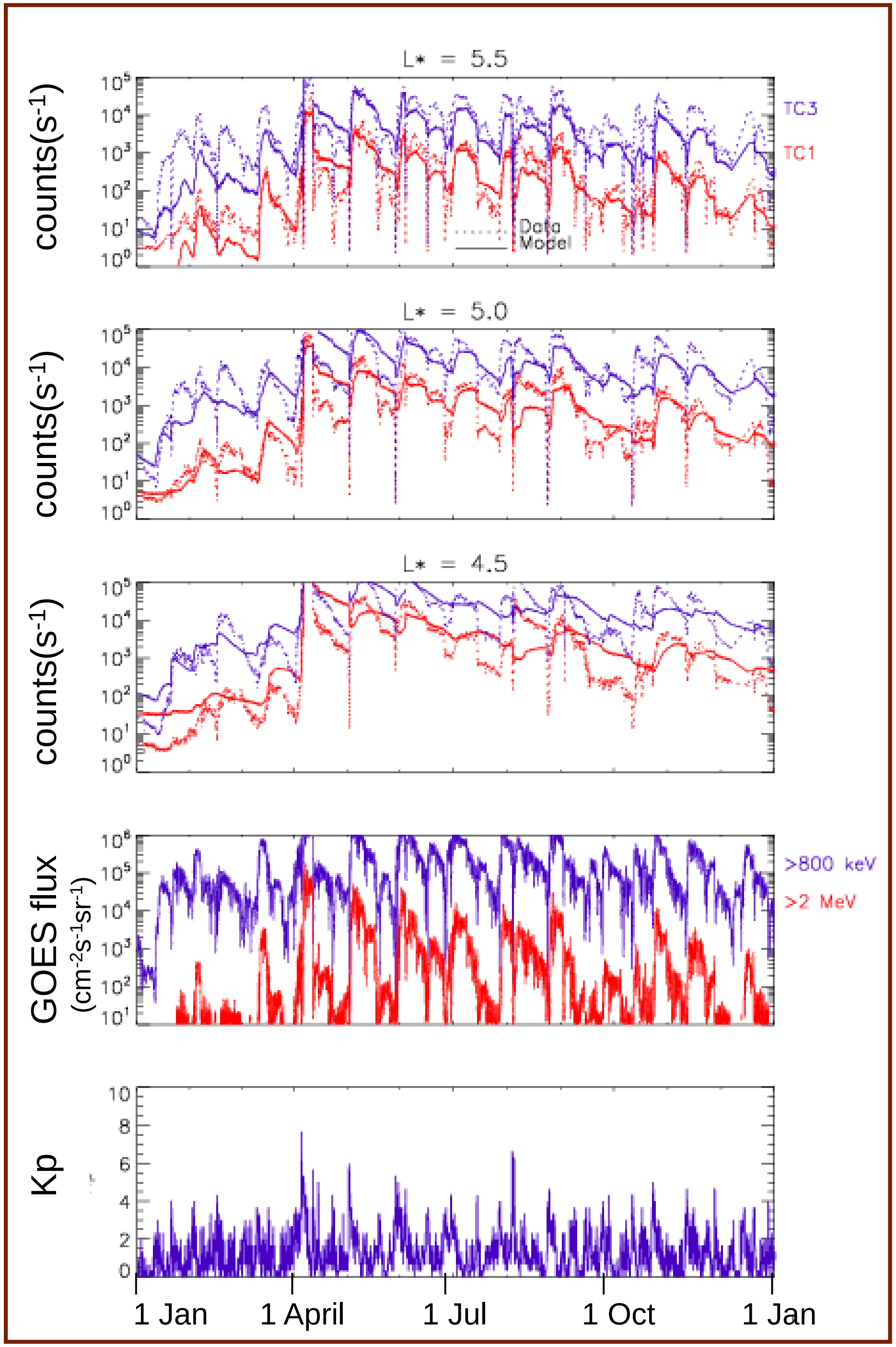
L*	Skill score for TC1
4.5	0.71
5	0.74
5.5	0.68

Skill score:

1 = perfect

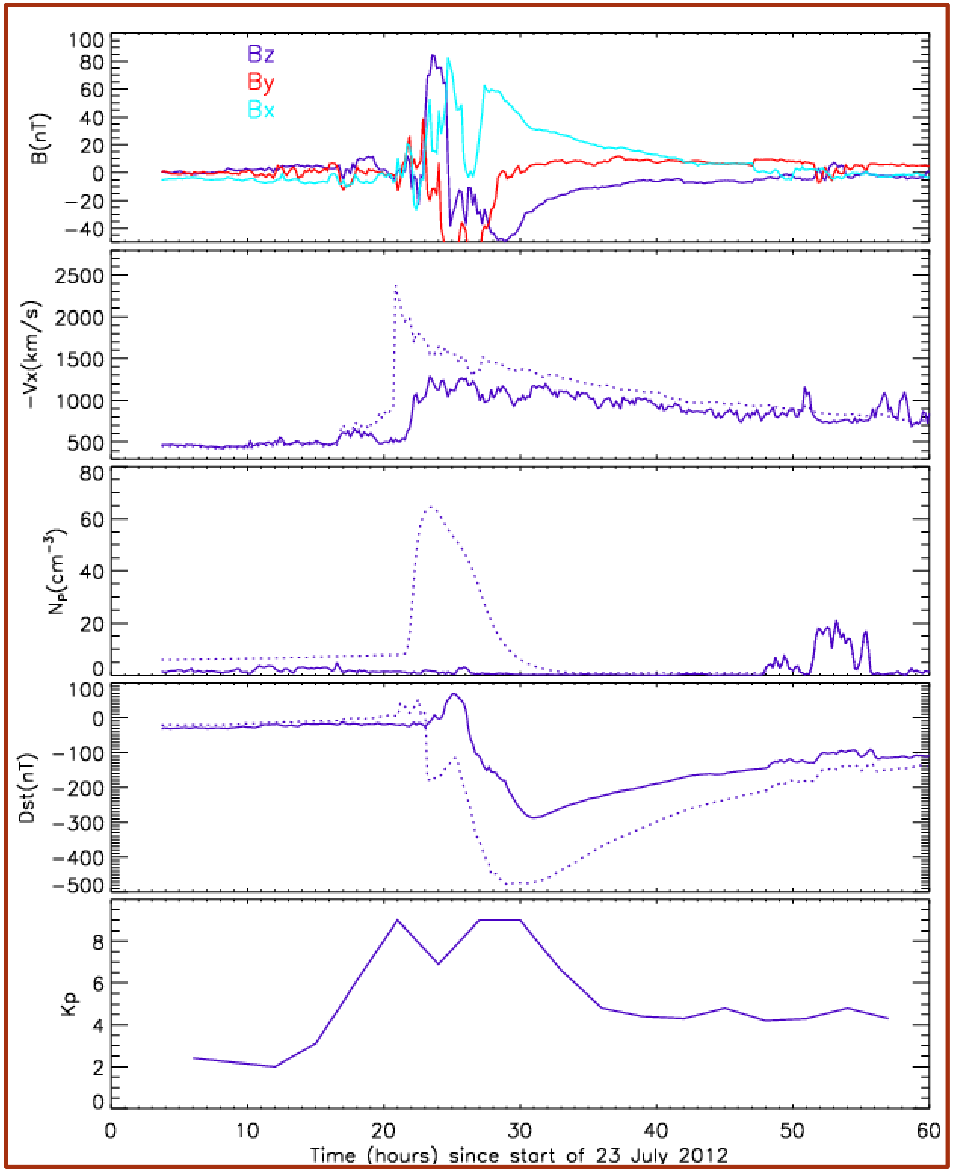
0 = as good as using average value

<0 = worse than using the average!



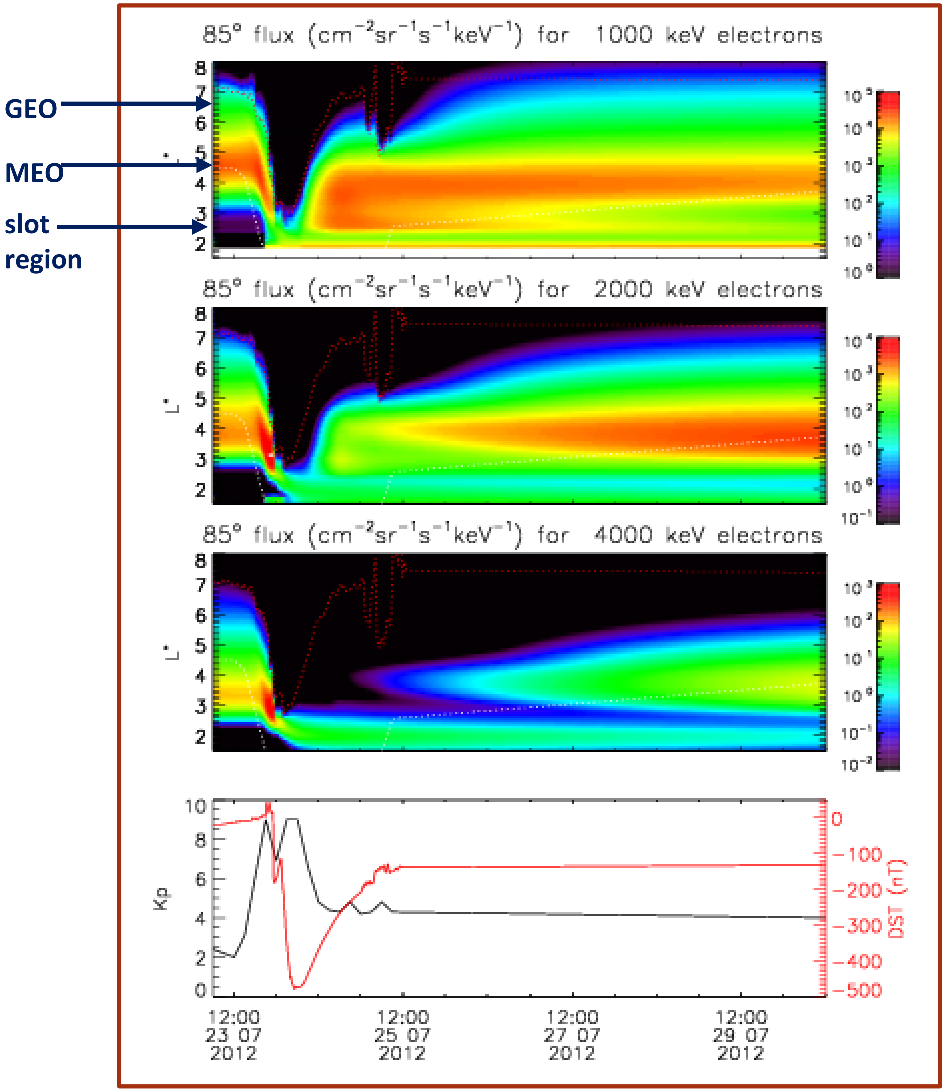
An extreme CME

- Carrington storm – not enough data
- July 2012
  - A very large CME that missed Earth
  - Observed by STEREO-A
  - *Baker et al*. [2013] estimated solar wind and other parameters
  - Dst ~-470 nT   Vsw > 2000 km/s
- What would have happened to the radiation belts if it had hit the Earth?



The July 2012 CME

- Magnetopause compression causes a flux drop-out
  - To about L*=3
- 1 MeV flux recovers rapidly
- 2 MeV flux recovers later
- Fluxes at GEO are not extreme
- Highest fluxes at MEO
- Slot region fills with MEV electrons
  - inner belt is enhanced



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Comparison with the 1 in 100 year events

- 1 in 100 year event at GOES west
  - daily averaged >2 MeV flux = 5.5 $x10^5$ $cm^{-2}s^{-1}sr^{-1}$
- Worst case from these simulations
  - ~ 10^5 $cm^{-2}s^{-1}sr^{-1}$

- 1 in 100 year event from INTEGRAL spacecraft data

	1 in 100 year event from INTEGRAL data		Maximum flux from extreme CME	
Energy	**788 keV**	**2.05 MeV**	**800 keV**	**2 MeV**
L* = 4.5	$9.3x10^3$	$5.8x10^2$	$8.6x10^3$	$9.7x10^2$
L* = 6.0	$3.0x10^3$	$1.6x10^2$	$6.0x10^2$	$3.0x10^1$

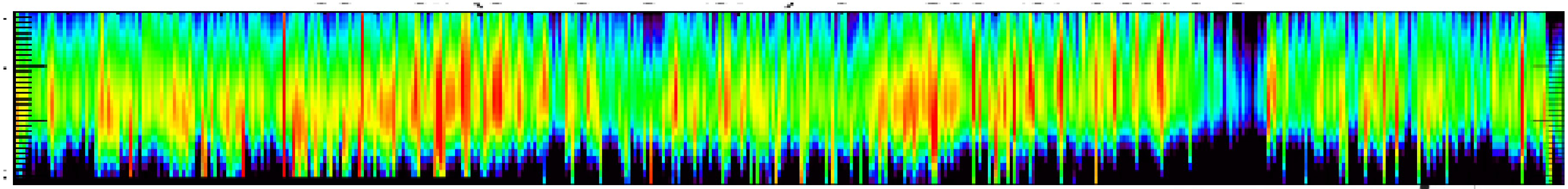
- Suggests that the extreme event at L*=4.5 (MEO) may be explained by a CME

Conclusions – High-energy electrons

- Recreated the radiation belts for the last 30 years
  - First long term simulation of the radiation belts
  - Shows considerable long-term variation throughout the belts
    - Solar cycle variations are clearly visible
  - Good agreement with independent data from GIOVE-B

- Simulated the effects of an extreme CME
  - Electron flux at GEO may not be extreme in this case
  - Orbits most at risk are MEO and the slot region

Flux spectrum encountered by a satellite in a Galileo-type orbit for the last 30 years is available on request.



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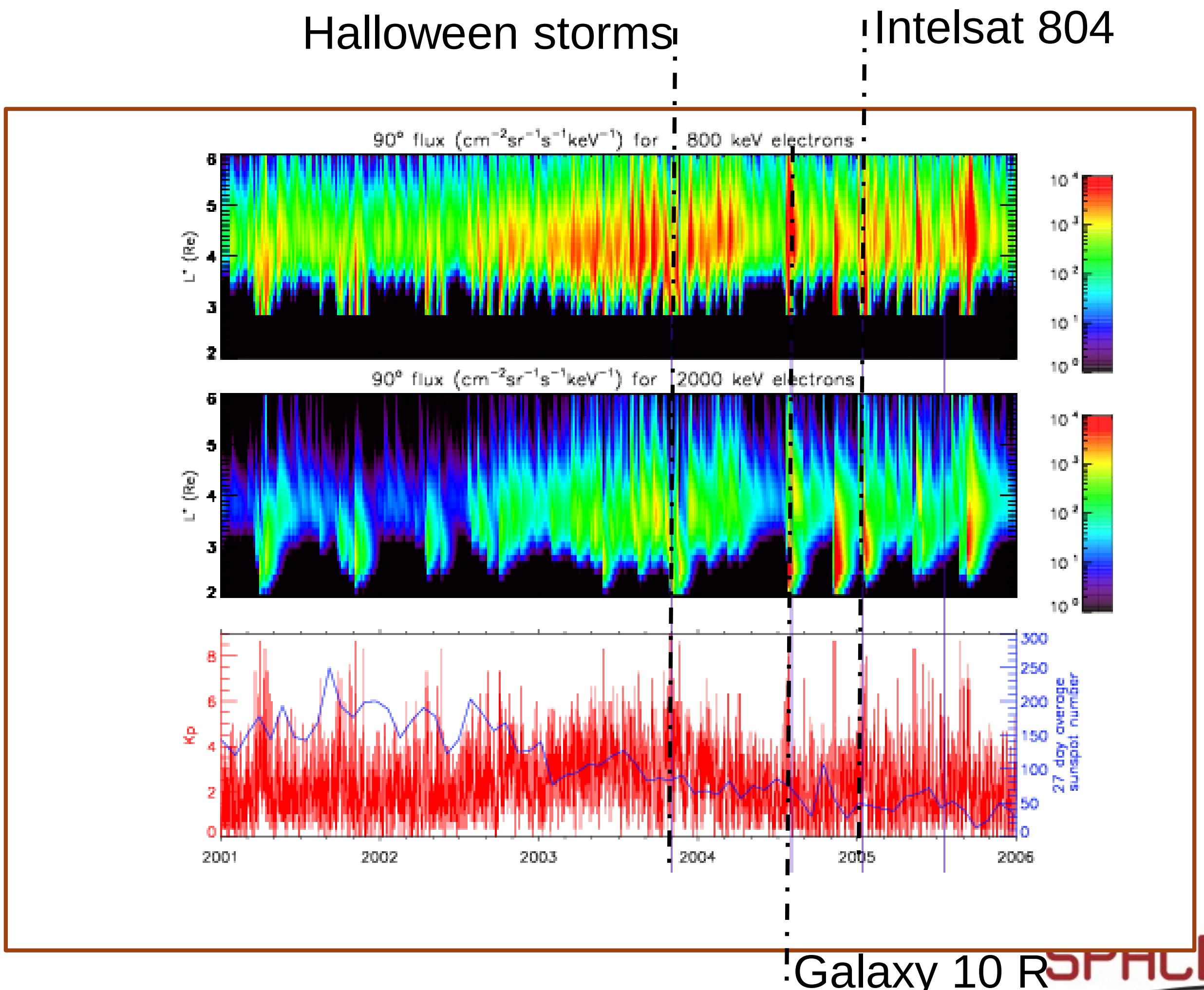
2001-2006



Halloween storms
Intelsat 804
90° flux (cm⁻²sr⁻¹s⁻¹keV⁻¹) for 800 keV electrons
90° flux (cm⁻²sr⁻¹s⁻¹keV⁻¹) for 2000 keV electrons
L* (Re)
Kp
27 day average sunspot number
2001
2002
2003
2004
2005
2006
Galaxy 10 R