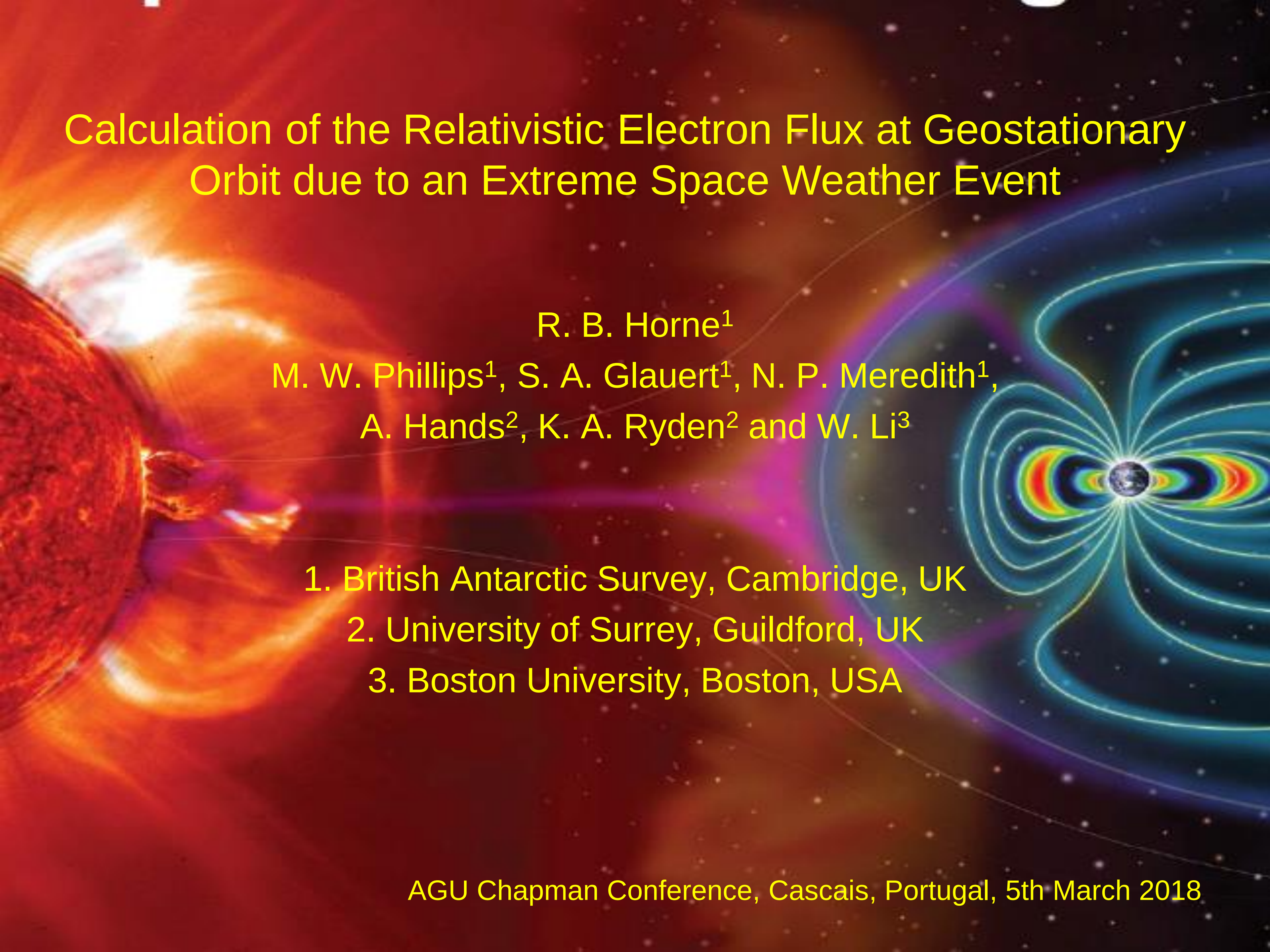

# Calculation of the Relativistic Electron Flux at Geostationary Orbit due to an Extreme Space Weather Event

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# Extreme Space Weather Events

- Satellite Designers and Operators need to design for a 'reasonable worst case'

- At Geostationary orbit – electron flux > 2 MeV is a key quantity

- Current analysis based on extreme value statistics [Koons, 2001; Meredith et al., 2015]

- Most risk assessments consider a CME driven event – e.g. 1859 'Carrington storm'

- But – what about other types of events? – Fast solar wind streams

- Here - use our physical understanding – to calculate >2 MeV electron flux

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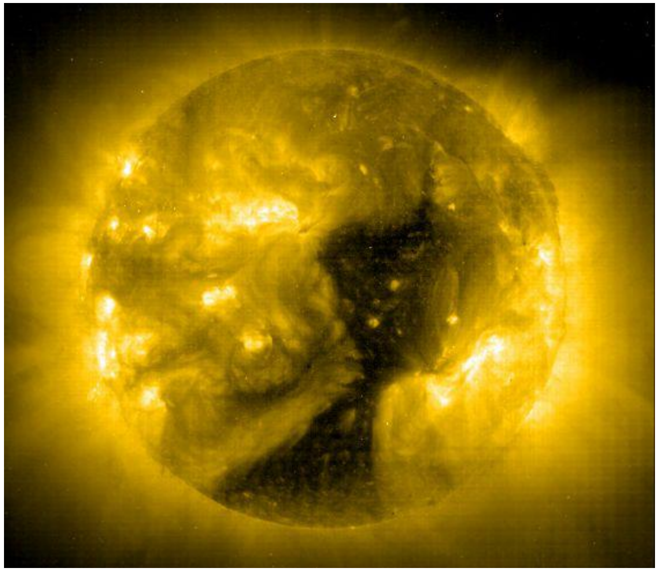
# Coronal Holes - Source of Fast Solar Wind

- Coronal Holes - Regions of lower temperature, lower density  and open magnetic flux on the Sun
- Source of fast solar wind – typically twice the average speed
- Co-rotate with the Sun – 27 day recurrence period
- Most common during the declining phase of the solar cycle



Coronal hole – in an X-ray image of the Sun

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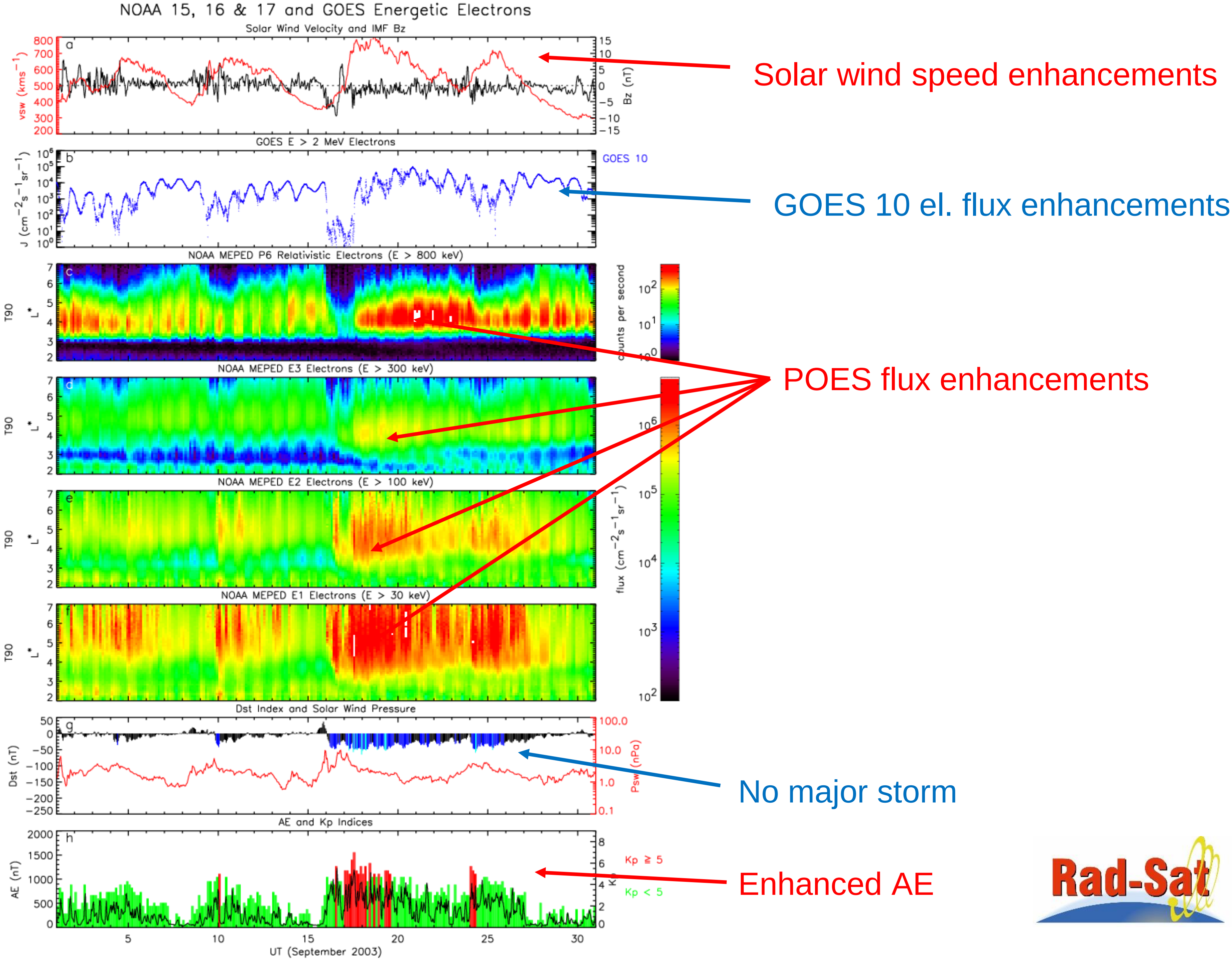

NOAA 15, 16 & 17 and GOES Energetic Electrons
Solar Wind Velocity and IMF Bz
vsw (kms$^{-1}$)
Bz (nT)
GOES E > 2 MeV Electrons
GOES 10
J (cm$^{-2}$s$^{-1}$sr$^{-1}$)
NOAA MEPED P6 Relativistic Electrons (E > 800 keV)
counts per second
NOAA MEPED E3 Electrons (E > 300 keV)
NOAA MEPED E2 Electrons (E > 100 keV)
NOAA MEPED E1 Electrons (E > 30 keV)
flux (cm$^{-2}$s$^{-1}$sr$^{-1}$)
T90 L*
Dst Index and Solar Wind Pressure
Dst (nT)
Psw (nPa)
AE and Kp Indices
AE (nT)
Kp ≥ 5
Kp < 5
UT (September 2003)
Solar wind speed enhancements
GOES 10 el. flux enhancements
POES flux enhancements
No major storm
Enhanced AE
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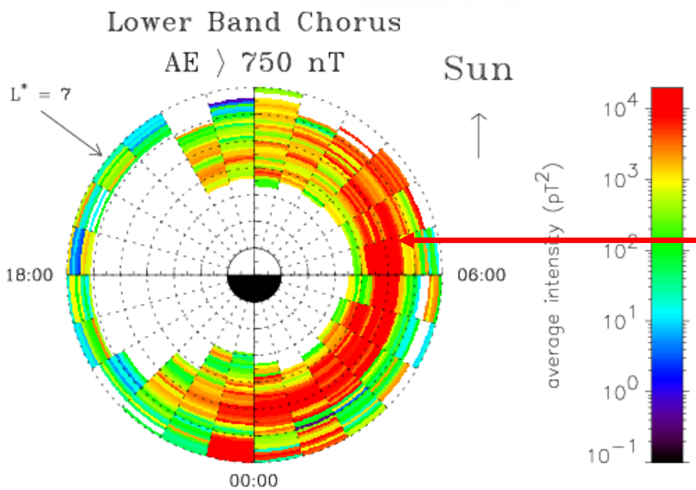
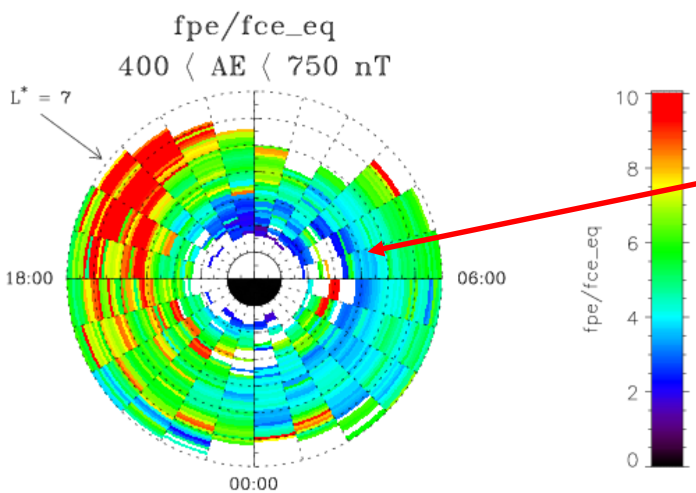
# Lower Band Chorus Waves




- Chorus wave database organised by AE index – 9 satellites
- Fast SW streams characterised by large AE (> 750 nT)
- ~12 hours of MLT
- For high AE - fpe/fce is small near dawn
- Suggests most wave acceleration of electrons inside/near GEO orbit

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# Reasonable Worst Case - Model

- Assume a fast solar wind stream last 5 days >750 km s-1 corresponding to AE > 750 nT

- Solve the Fokker-Planck Equation – [Glauert et al., 2014]

- Include:
- Doppler shifted cyclotron resonance with chorus waves
  - Pitch angle and energy diffusion
  - Use statistical wave properties – amplitudes $B_w$
  - Use statistical plasma properties – $f_{pe}/f_{ce}$
- Loss to the atmosphere – for electrons diffused into the loss cone
- Substorm injections – modulate the flux at low energies (~ 150 keV)

- Omit radial diffusion - discuss later

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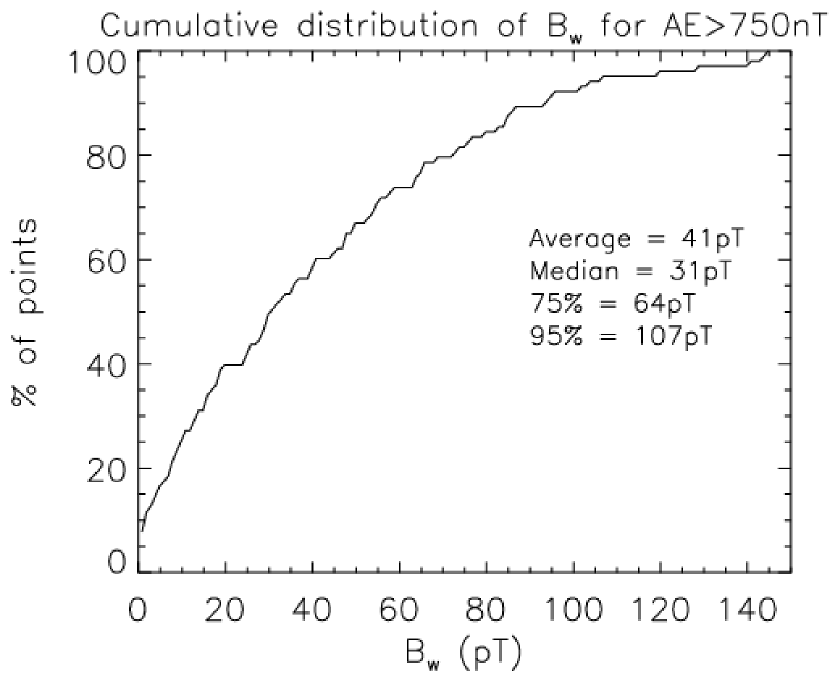
# Wave Amplitudes




- Cumulative distribution of chorus wave amplitudes
- AE > 750 nT
- < 30$^o$ latitude
- 00:00 – 12:00 MLT

- Median Bw = 31 pT
- RMS Bw = 55 pT
- Skewed distribution – take the median (31 pT)

- For 400 < AE < 750
- Median Bw = 28 pT
- Mean Bw = 39 pT

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# Wave Spectrum

- Gaussian wave spectrum for lower band chorus waves based on satellite observations [Horne et al., 2013; Sicard-Piet et al., 2014]
  - $\exp( -(X - X_m)^2/X_w^2)$
  - $f_m/f_{ce} = 0.3$ width $\delta f/f_{ce} = 0.1$
  - maximum upper frequency $f_{ucut} = f_m + 2\delta f$
  - minimum lower frequency $f_{lcut} = f_m - 2\delta f$

- Angular distribution peaked along the background field [Li et al., 2017; Agapitov et al., 2013]
  - $\exp( -(X - X_m)^2/X_w^2)$
  - $X = \tan \Psi$
  - $X_m = 0$
  - $X_w = \tan 30^o$

- Wave power up to $30^o$ latitude [Horne et al., 2013]

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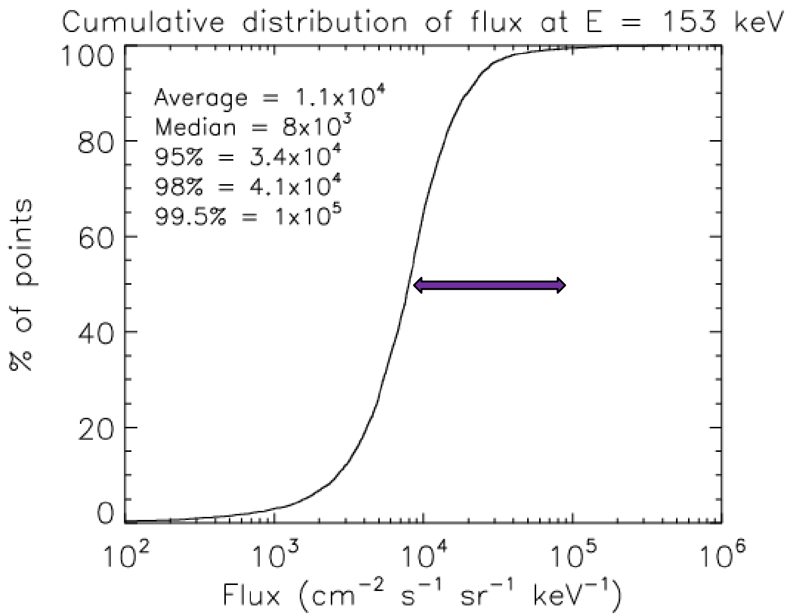
# Reasonable Worst Case – Substorms




- CRRES data, L* = 6
- Set flux to median value at low energy boundary (150 keV)
- Flux increased by a factor of 10 followed by exponential decay - so that the flux drops by a factor of 10 in 2.75 hours
- Most probable time between substorms is 2.75 hours [Borovsky et al., 1993] – so repeat every 2.75 hours for 5 days
- Ensures flux only exceeds 98 percentile level a few per cent of the time
- Flux not allowed to exceed $10^5$ pfu

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# Plasma properties

- Cumulative probability distribution for $f_{pe}/f_{ce}$

- Data taken from wave experiment on CRRES – as this is one of the most accurate measurements of fpe

- Median – $f_{pe}/f_{ce}$ = 5.16
- Mean – $f_{pe}/f_{ce}$ = 5.37
- Almost Gaussian - use the mean

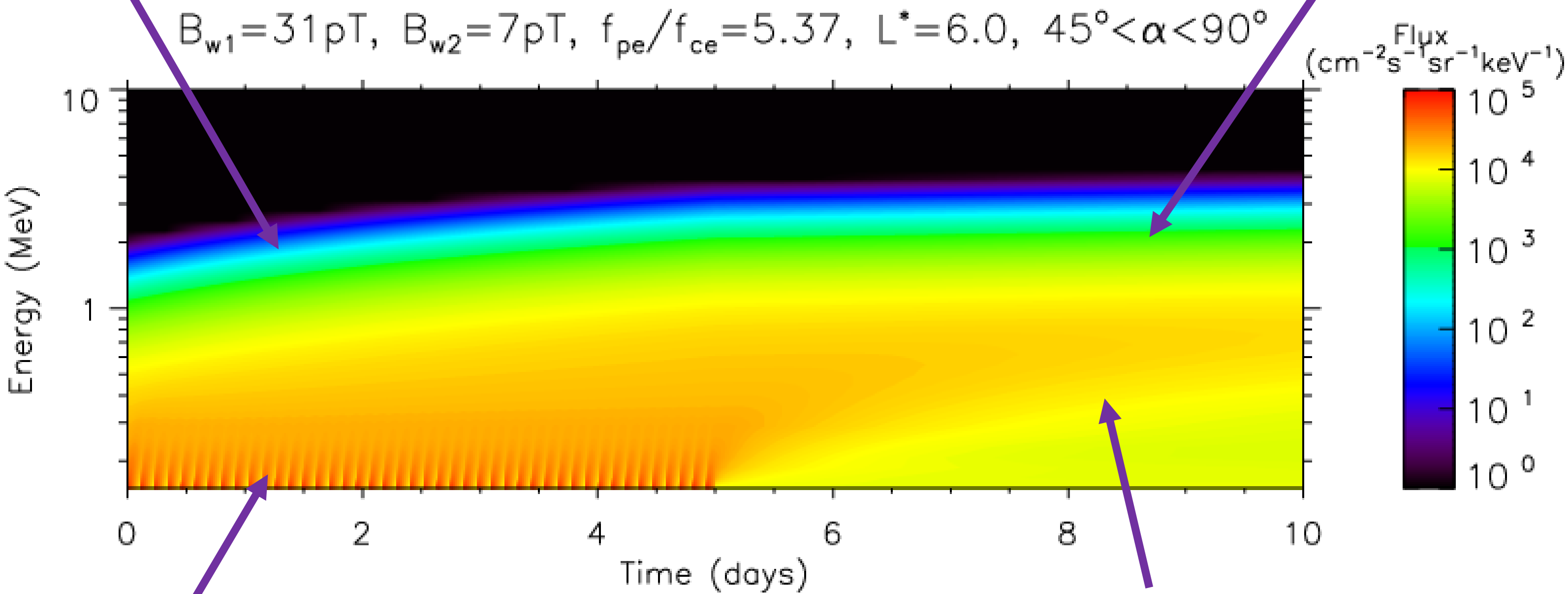
- Other studies have used $f_{pe}/f_{ce}$ = 3 [Thorne et al., 2013]
  - may occur for some locations and short periods

- Using the mean seems more appropriate for an event lasting 5 days

# Fast Solar Wind for 5 days + 5 days Low Activity Acceleration from a Pre-existing Radiation Belt

Acceleration to > 2 MeV

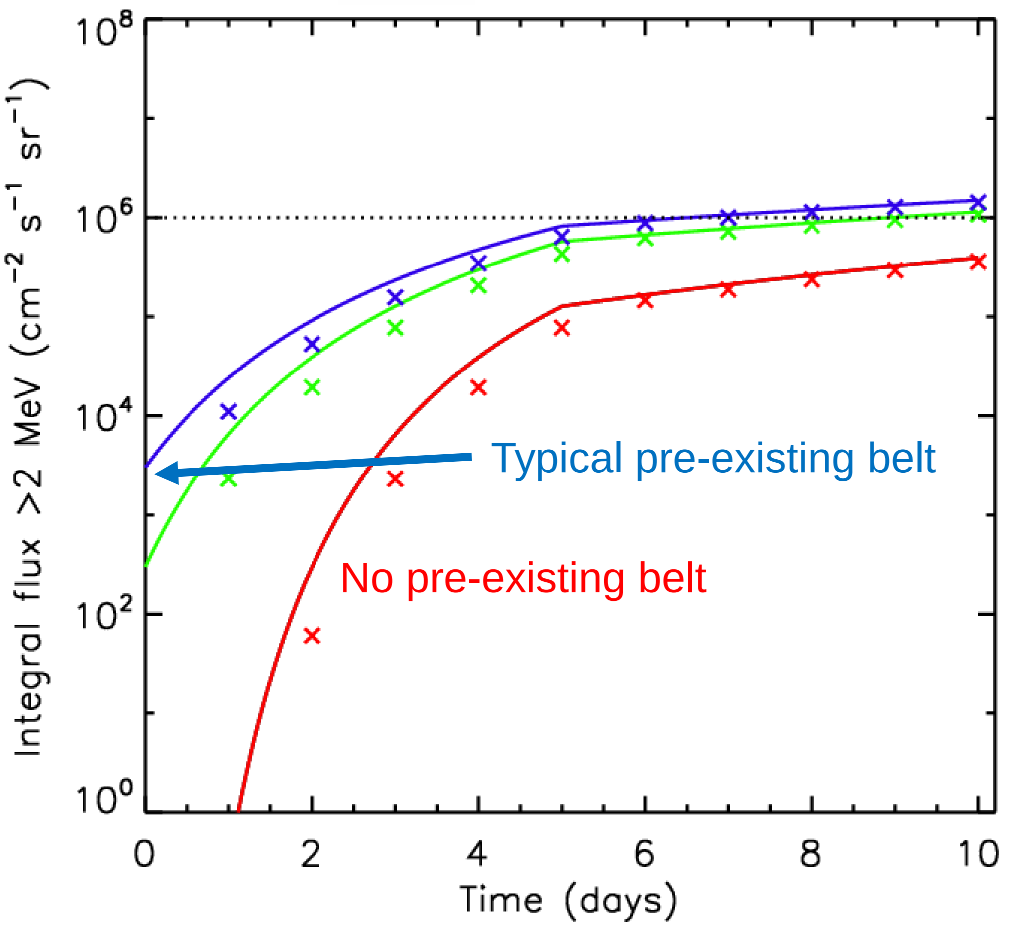
> 2 MeV flux remains high for days




Substorm injections

Decay at lower energies

# Electron flux at GEO




- Flux tends towards a limiting value
- Relatively insensitive to a pre-existing radiation belt
- $10^6$ level is from Meredith et al. [2015]

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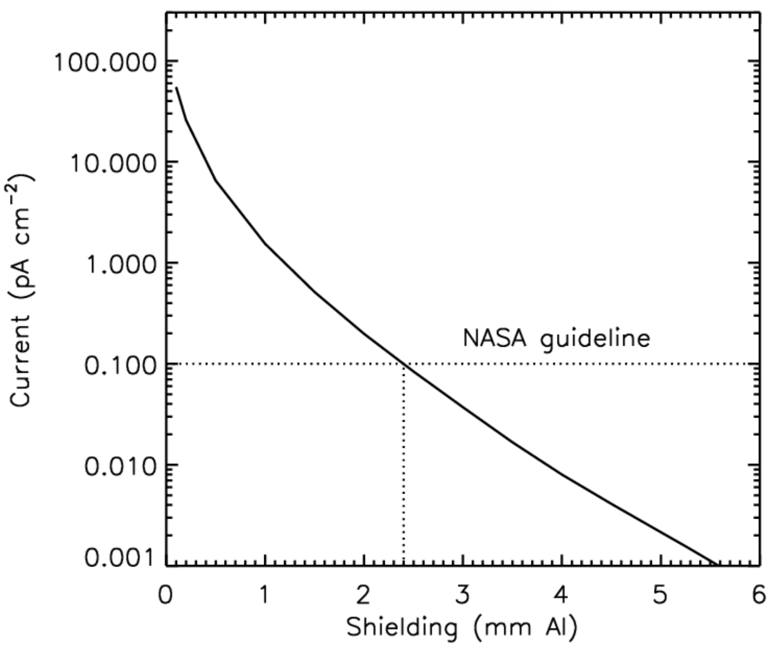
# Shielding Electronic Components




- The integral flux > 2 MeV corresponds to a current of 0.22 pA cm$^{-2}$
- Exceeds the NASA recommended guideline of 0.1 pA cm$^{-2}$
- So how much shielding do we need?
- Use the AE 8 max electron spectrum and scale to get the correct flux > 2 MeV
- Use DICTAT code to calculate radiation transport through Al and assume planar geometry
- Need about 2.4 mm of Al shielding

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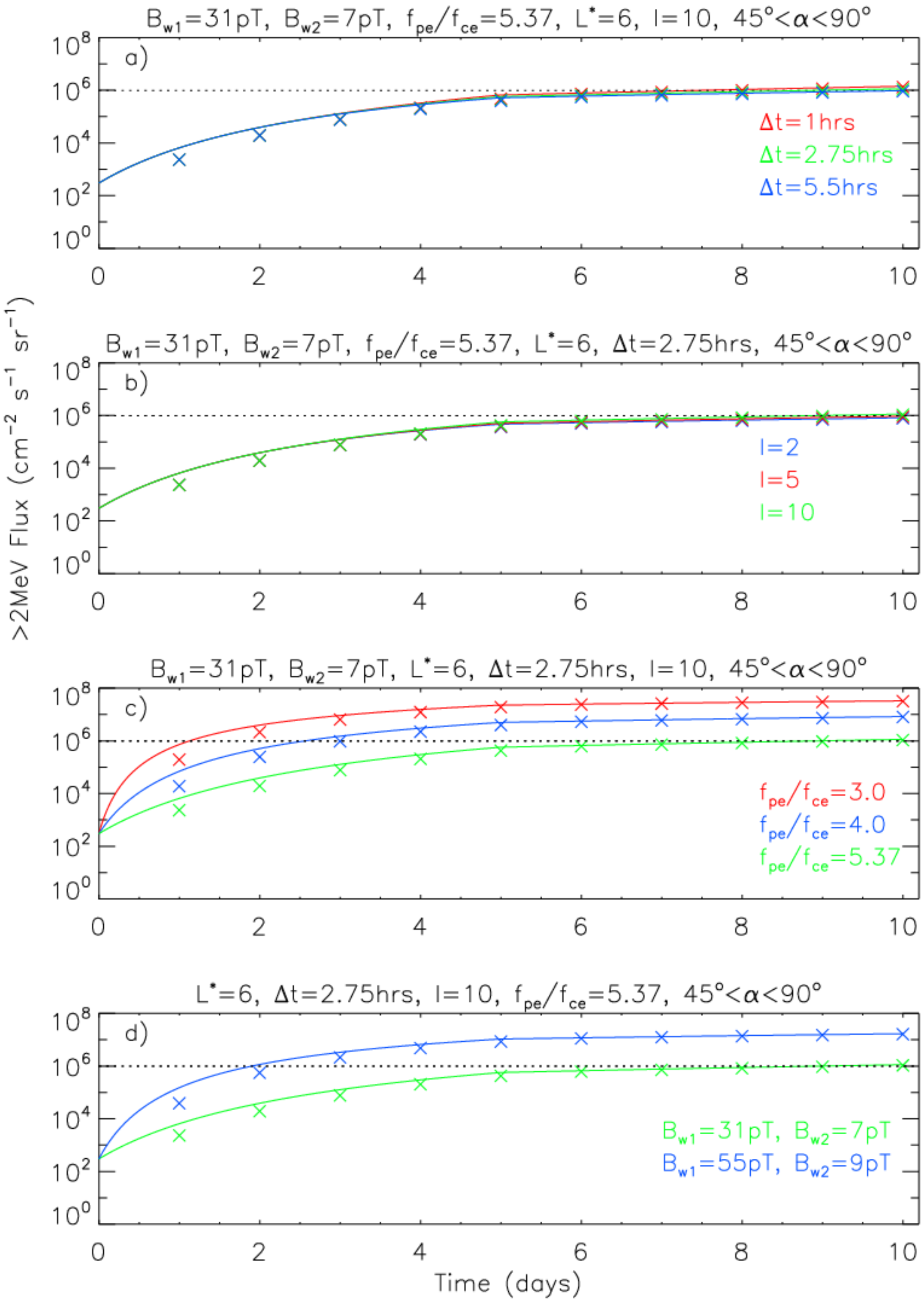


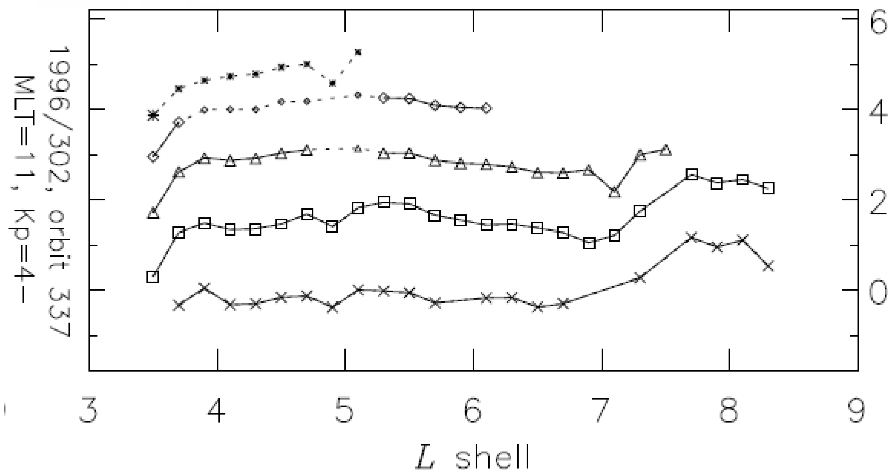

# Sensitivity

Most sensitive to:

- The ratio $f_{pe}/f_{ce}$

- Wave amplitude $B_w$

# Effects of Radial Diffusion




- We have assumed that the flux is determined by wave acceleration

- During frequent particle injections the PSD gradient is flat [Selesnick and Blake, 1997]
  - Implies radial diffusion is very efficient

- If wave acceleration is higher at another L* - this could set a higher level if RD is very efficient

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# Conclusions

- Present a 'reasonable worst case' for a fast solar wind stream lasting 5 days
- Wave acceleration increases the trapped flux > 2MeV at GEO towards a limiting value
  - Exceeds the NASA recommended guidelines for electrostatic charging
  - Need about 2.4 mm of Al shielding – between 0.5 - 1 mm more than current design
- Flux level is most dependent on wave power and fpe/fce
- CME driven storm compresses the magnetosphere - reduced flux at GEO
- Thus, satellites at GEO are more at risk from a fast SW stream lasting 5 days or more than they are from a CME driven storm

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