Forecasting the High Energy Electron Radiation Belts Using Physics Based Models

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Presented by

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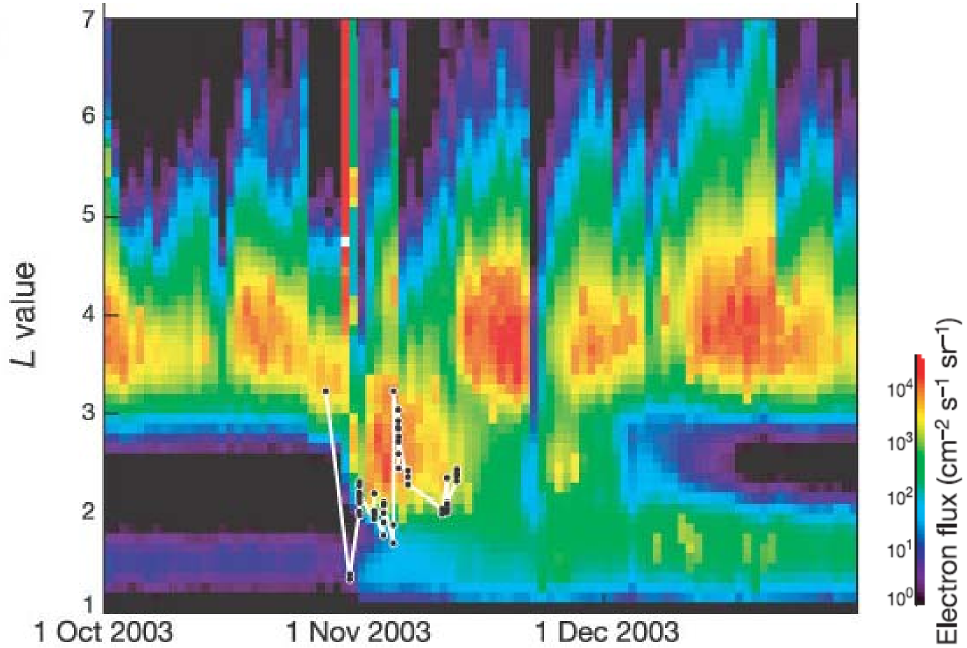
Invited talk, Fall AGU, 4th December 2012

Magnetic Storms – Radiation Belts

- The outer radiation belt is highly variable
- The flux of relativistic electrons can change by several orders of magnitude on a variety of timescales

> 2 MeV electron flux



Baker *et al*., Nature [2004]

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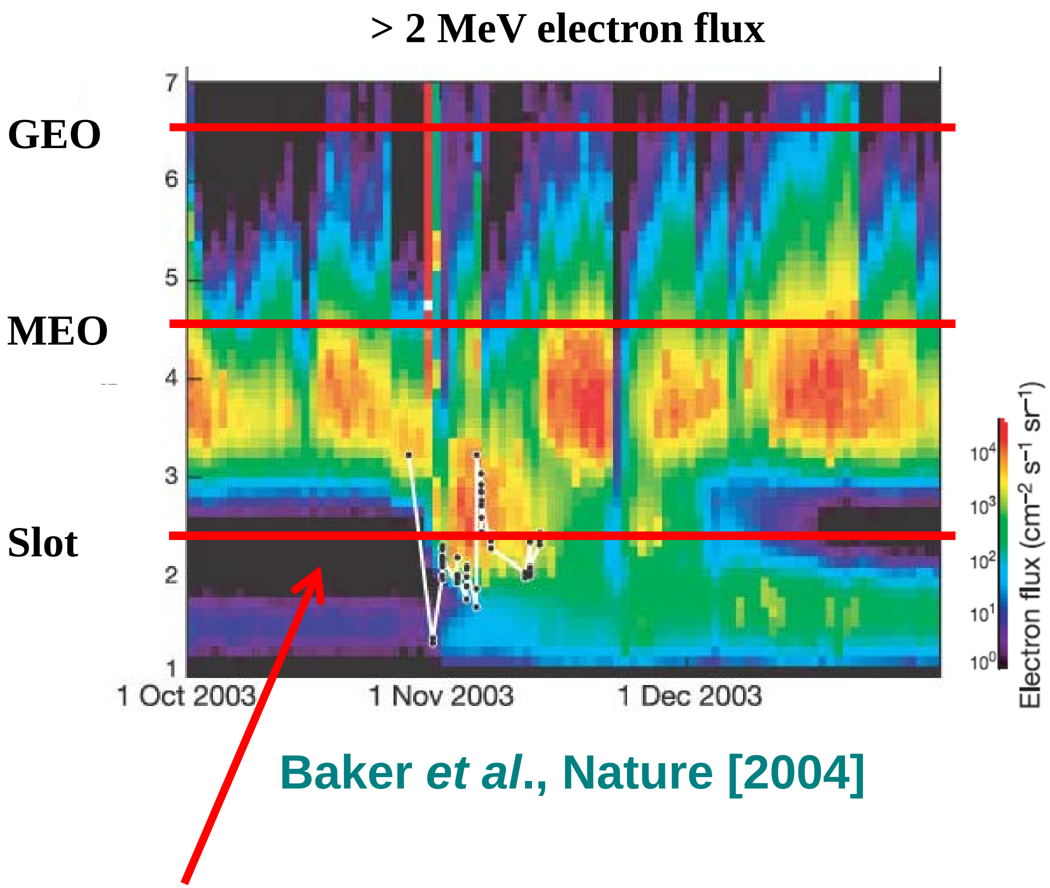
Magnetic Storms – Radiation Belts

- Satellites in MEO such as the GPS satellites experience higher radiation than those at GEO
- Boeing – use plasma thrusters to get from GTO to GEO – 1-2 months in the heart of the radiation belts
- O3b constellation of 8 satellites to be launched into the slot region in 2013



Baker *et al*., Nature [2004]

Slot region

Usually benign – except during large storms

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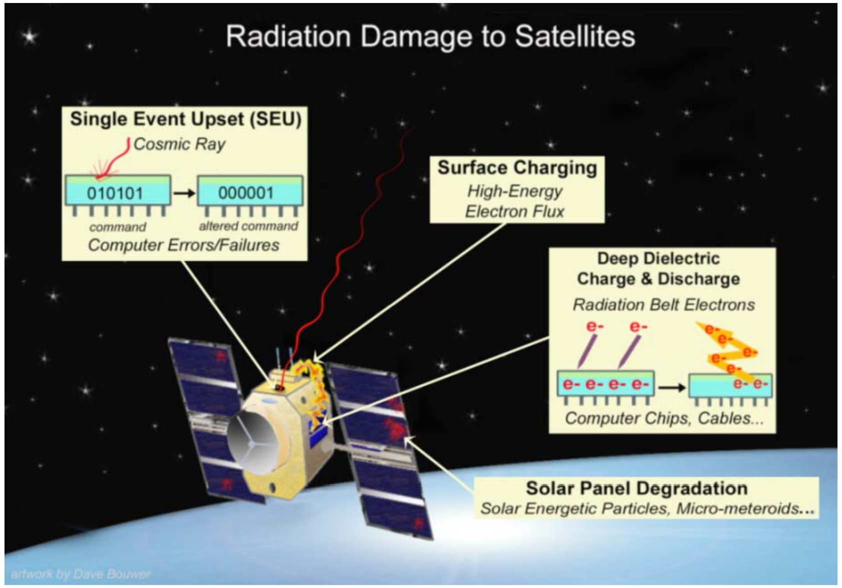
Radiation Damage to Satellites

- Relativistic electrons cause internal charging
- Internal charging can lead to high electric fields the subsequent discharge of which can lead to:
  - damage to the dielectric
  - component failure
  - phantom commands
- Significant correlation between satellite anomalies and the E > 2 MeV electron flux at GEO [**Iucci *et al*., 2005**]



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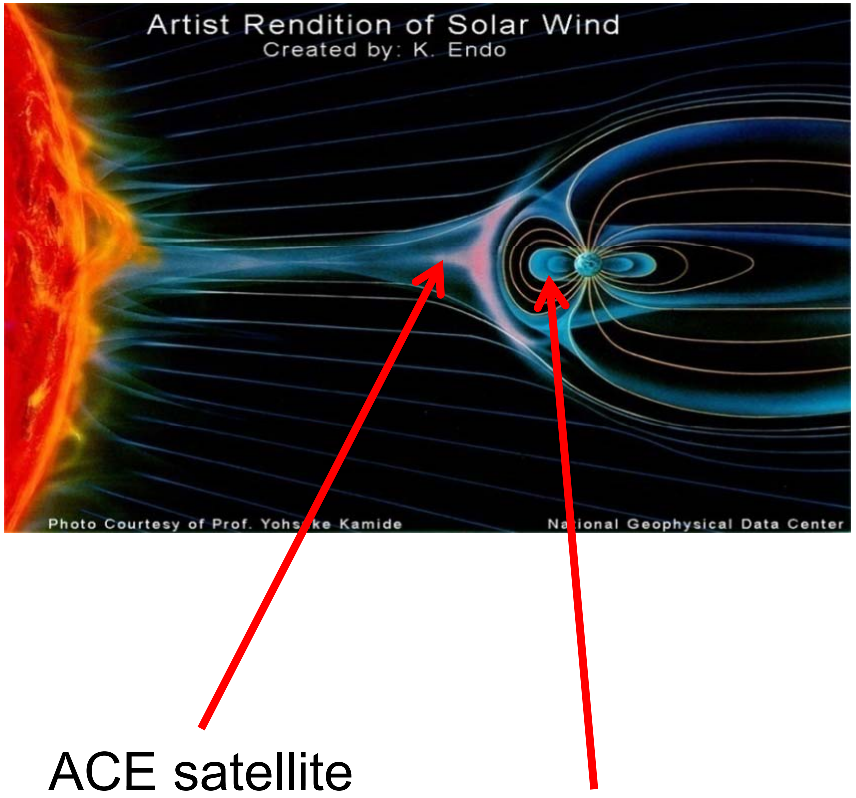
Radiation Belt Forecasting

- Radiation belt forecasting has a number of benefits for satellite operators.
- During periods of high risk operators can:
  - switch off non-essential systems
  - reschedule manoeuvres and software upgrades
  - ensure spare capacity is available and reroute communications traffic if necessary
- SPACECAST radiation belt models designed to forecast the high energy electron radiation belt

Forecasting Concept

- It takes ~ 40-60 minutes for the solar wind to flow from the ACE satellite to the Earth
- Access ACE satellite data in real time and use it to drive our forecasting models
- Use a forecast of Kp index from Swedish Inst. Sp. Phys. (Lund) and data from BGS(UK), Europe, USA and Japan
- We use physical models
  – Like weather forecasting



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Physical Equations

- The model is based on the solution of a diffusion equation for phase-space density
- Time-dependent Fokker Planck equation in pitch-angle (α), energy (E) and L* (L)
- The values of the diffusion coefficients D_{LL}, $D_{\alpha\alpha}$ and D_{EE} must be calculated

pitch angle diffusion — energy diffusion — radial diffusion — loss term

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

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

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

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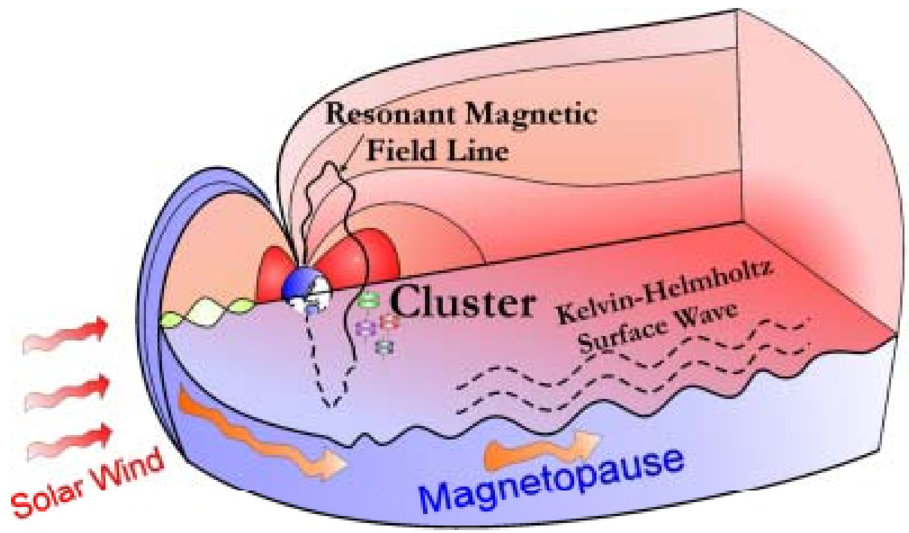
Radial Diffusion:
Transport of Electrons Across the Magnetic Field

- Radial diffusion is an important transport process in the Earth's radiation belts:
  - driven by fluctuations in the Earth's electric and magnetic fields on timescales of the drift period
  - enhanced by ULF waves [e.g., **Hudson *et al*., 1999; Elkington *et al*., 1999**]
- For radial diffusion we use the magnetic radial diffusion coefficients of **Brautigam and Albert [2000]**



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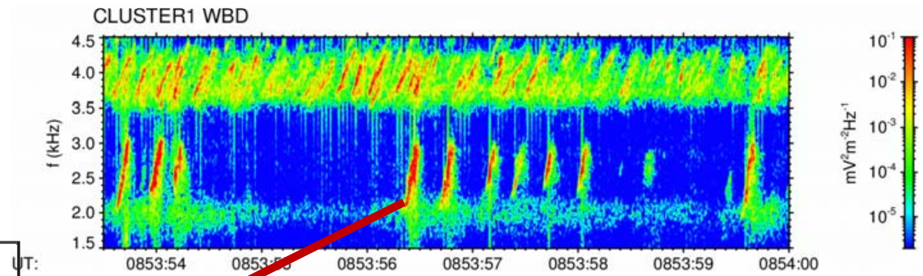
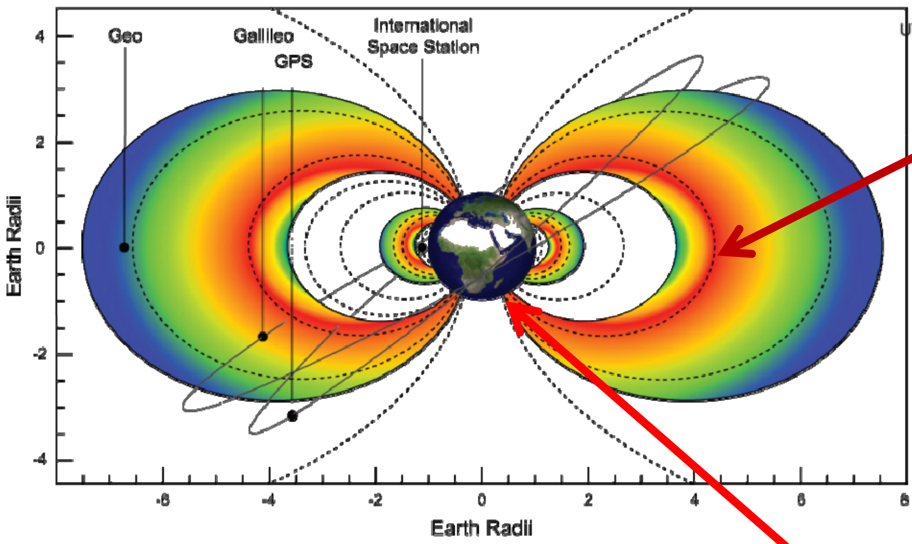
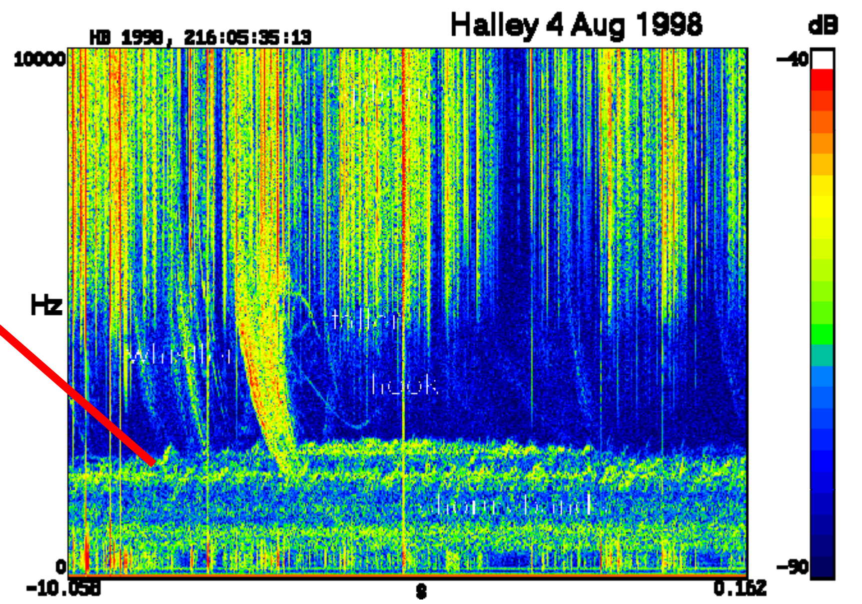
We use Physical Models that Include Wave-Particle Interactions



Satellite observations



Antarctic observations

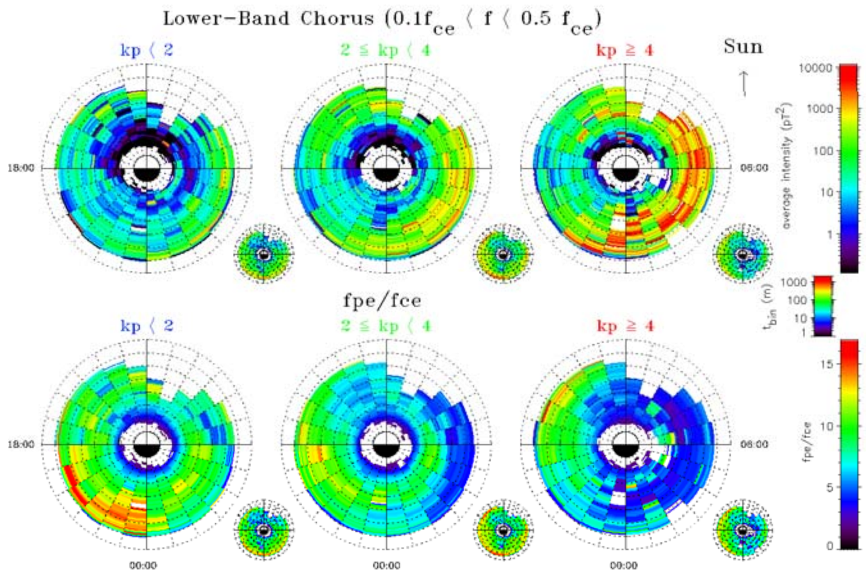


- Wave-particle interactions cause electron acceleration and loss
- Acceleration by chorus very important
- Changed ideas lasting 40 years

Whistler Mode Chorus

- Pitch angle and energy diffusion coefficients calculated using the PADIE code [**Glauert and Horne, 2005**]

- For whistler mode chorus the drift-averaged diffusion coefficients are based on CRRES statistical maps of lower band chorus and fpe/fce scaled by Kp



Meredith *et al*., GRL [2003]

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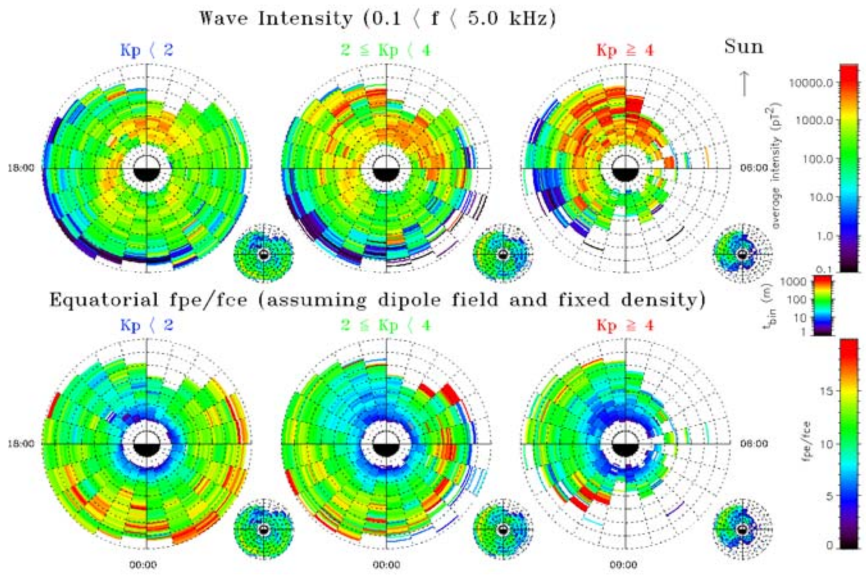
Plasmaspheric Hiss and Lightning Generated Whistlers

- For plasmaspheric hiss and lightning generated whistlers the drift-averaged diffusion coefficients are based on CRRES statistical maps of the relevant wave power and fpe/fce scaled by Kp



Meredith *et al.*, JGR [2007]

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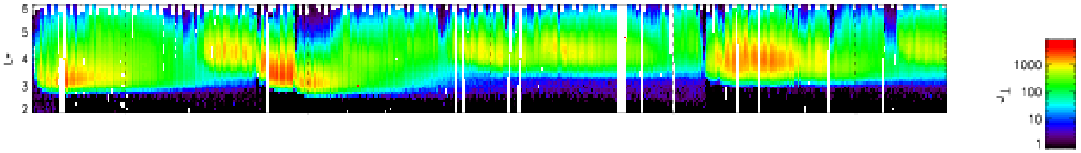
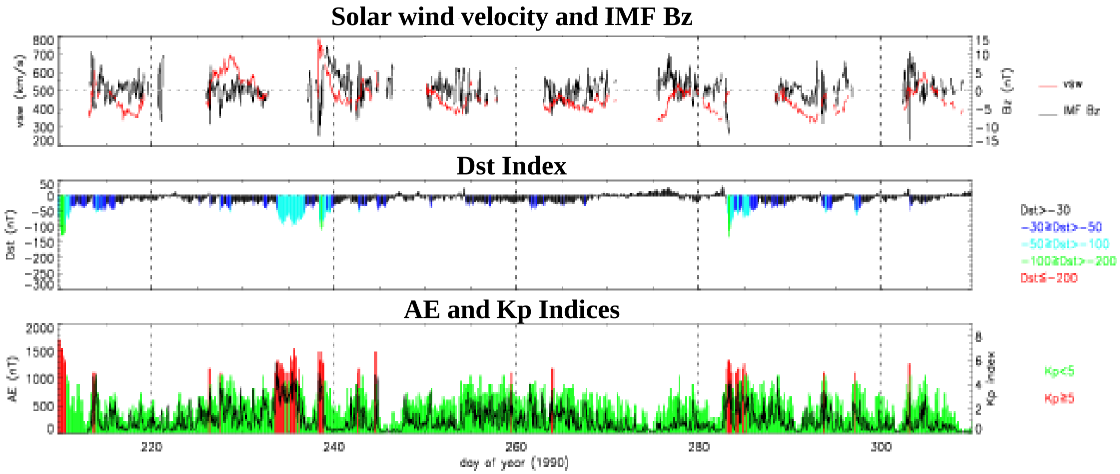
Simulation of a long time period

- Model 100 days during the CRRES mission

E = 1.09 MeV

CRRES Data





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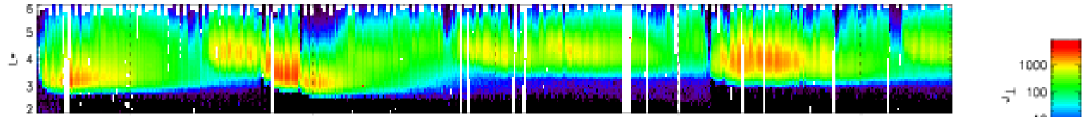
Simulation of a long time period

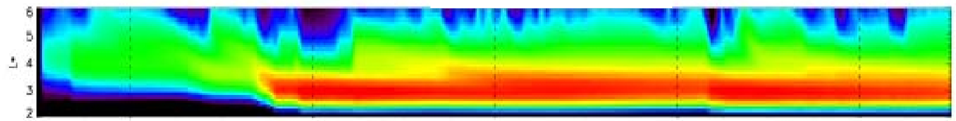
- Model 100 days during the CRRES mission
- Radial diffusion alone overestimates flux and does not predict the slot

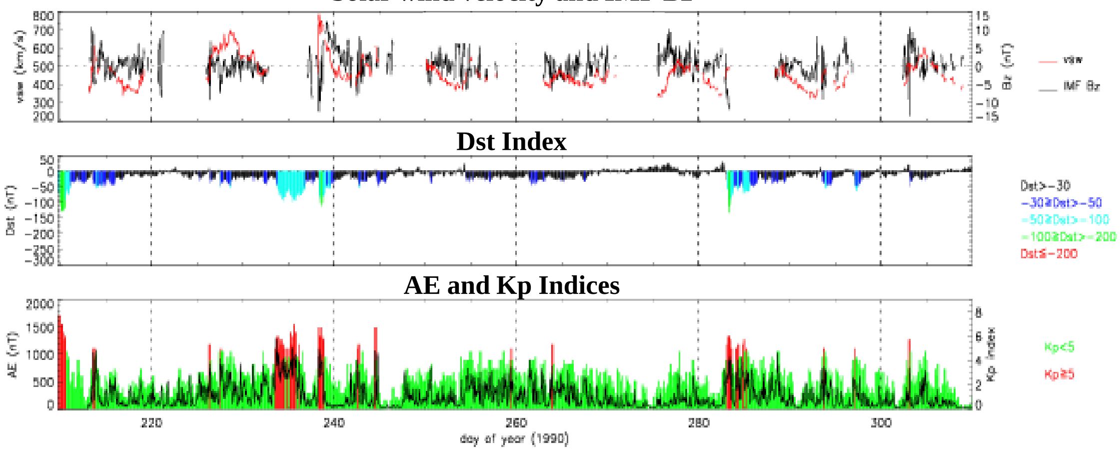
E = 1.09 MeV

CRRES Data



Radial Diffusion only





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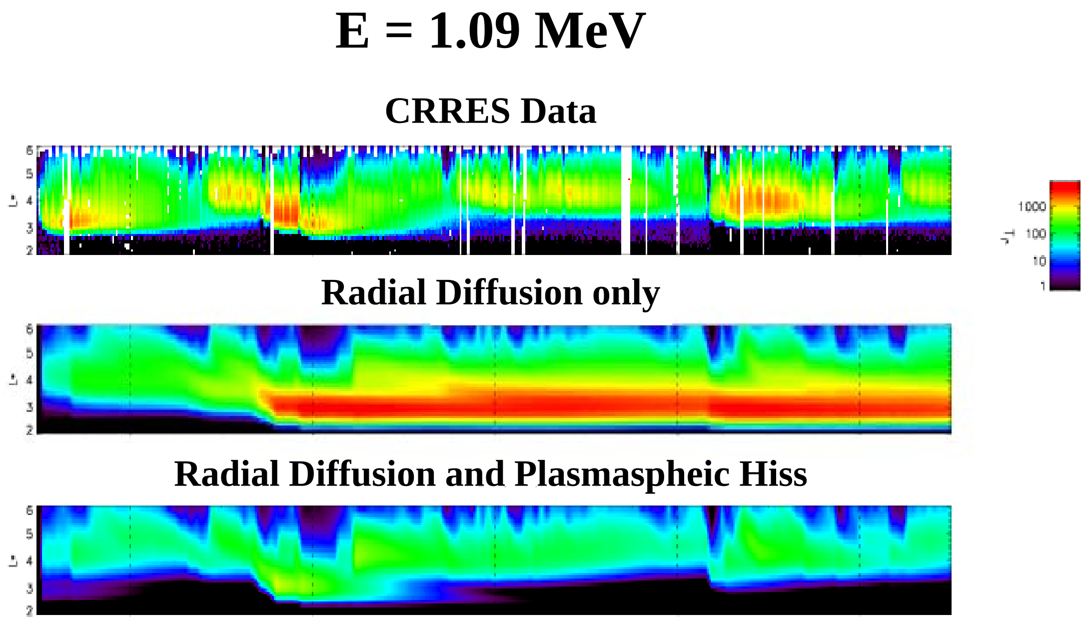
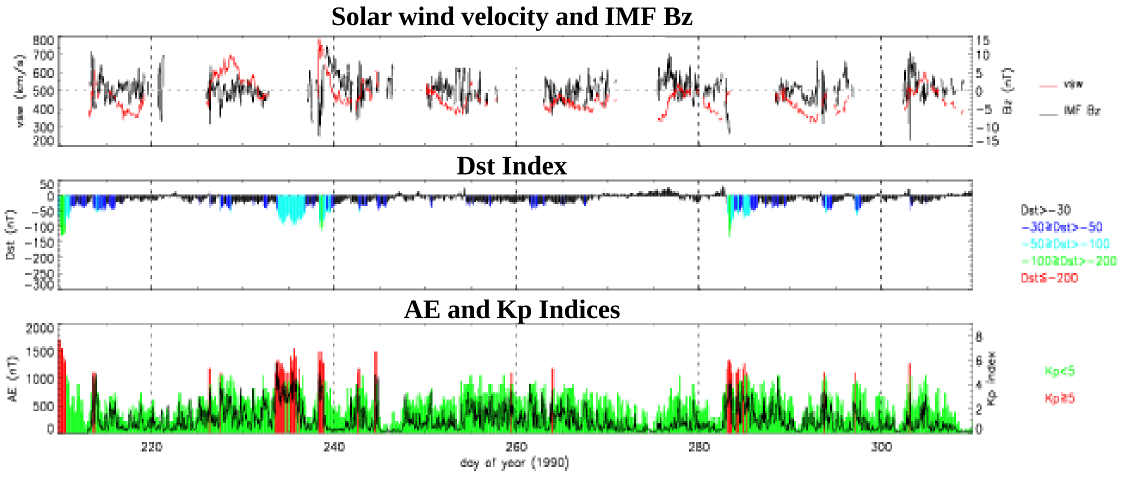
Simulation of a long time period

- Model 100 days during the CRRES mission

- Radial diffusion alone overestimates flux and does not predict the slot

- Radial diffusion and hiss predicts the slot but underestimates flux due to lack of local acceleration





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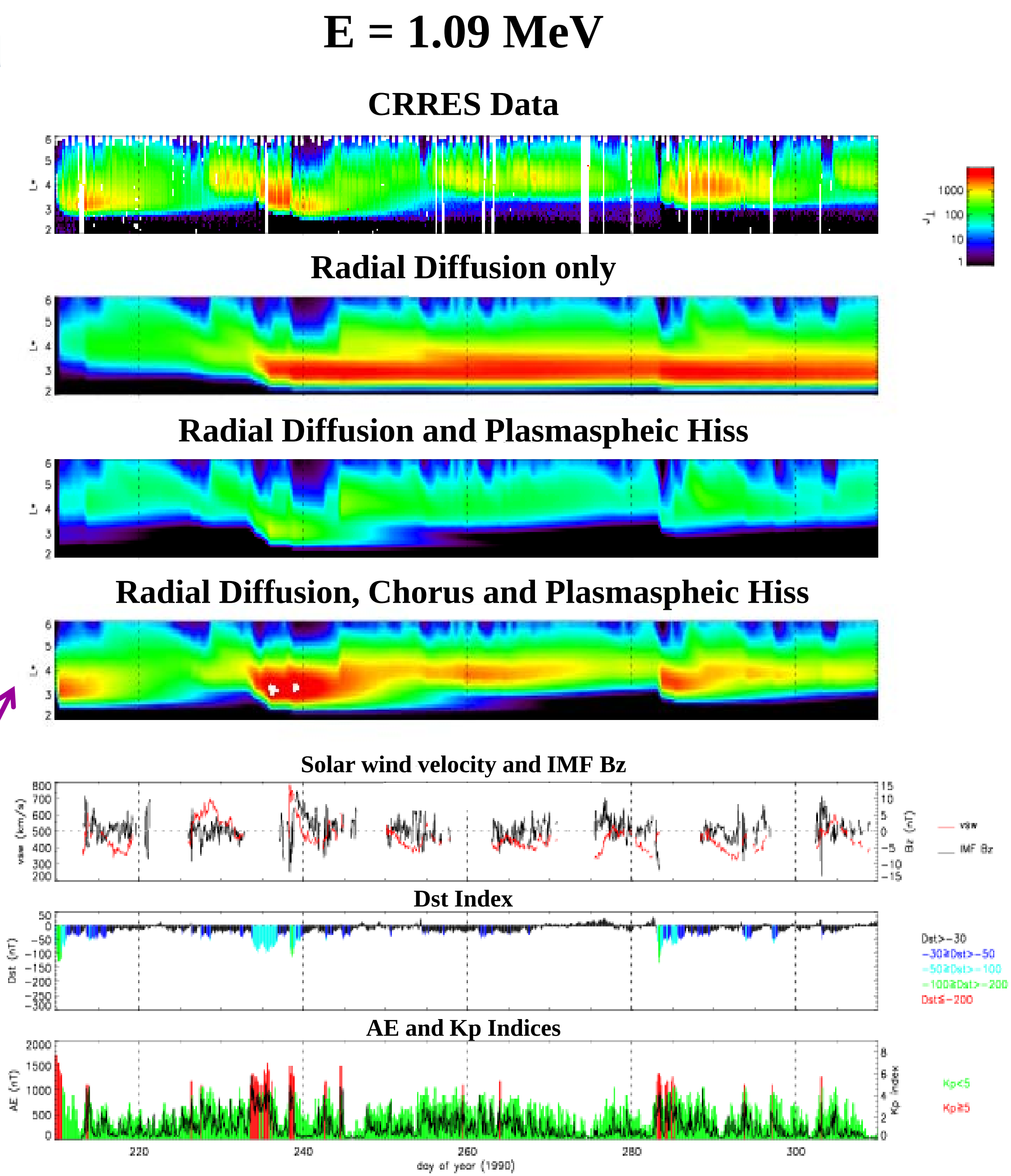
Simulation of a long time period

- Model 100 days during the CRRES mission
- Radial diffusion alone overestimates flux and does not predict the slot
- Radial diffusion and hiss predicts the slot but underestimates flux due to lack of local acceleration
- Radial diffusion, chorus and hiss best reproduce structure of the radiation belts



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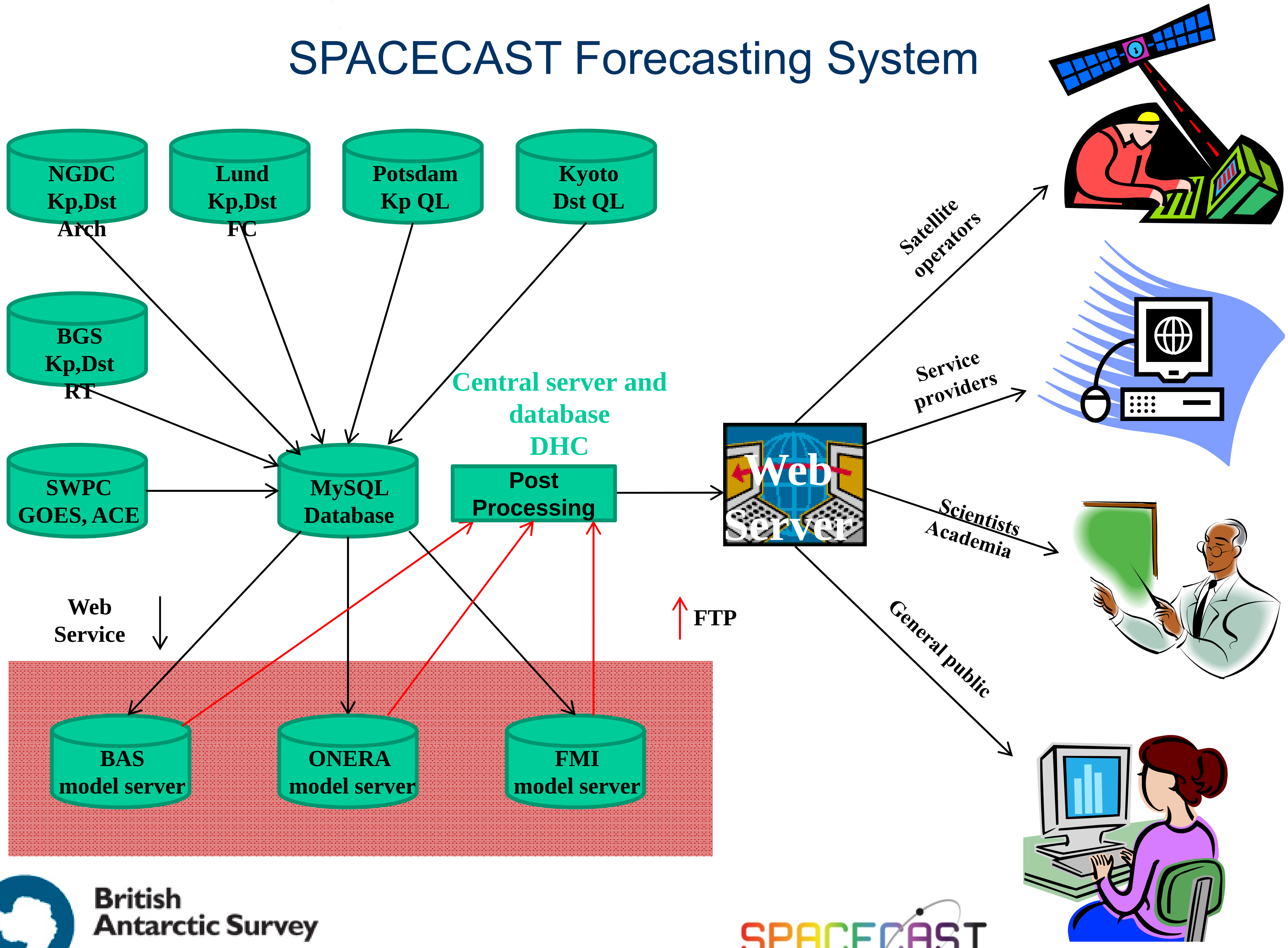
SPACECAST Forecasting System



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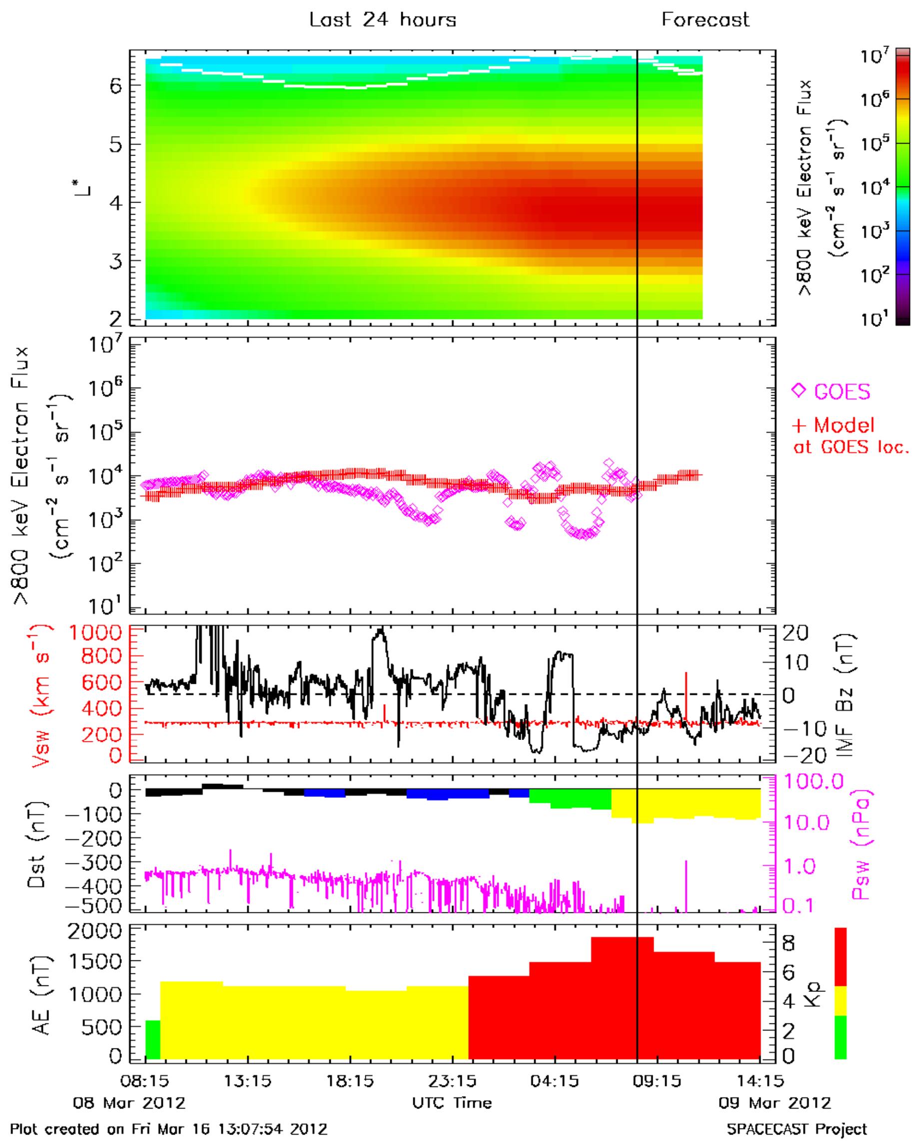
Electron Radiation Belt Forecasts

- Model
  - operates 24 hours a day in near real time and is updated every hour
  - provides 3 hourly forecasts using the Kp forecast from Lund
  - provides a risk index for GEO, MEO and the slot region
- The forecast is freely available on-line: http://www.fp7-spacecast.eu



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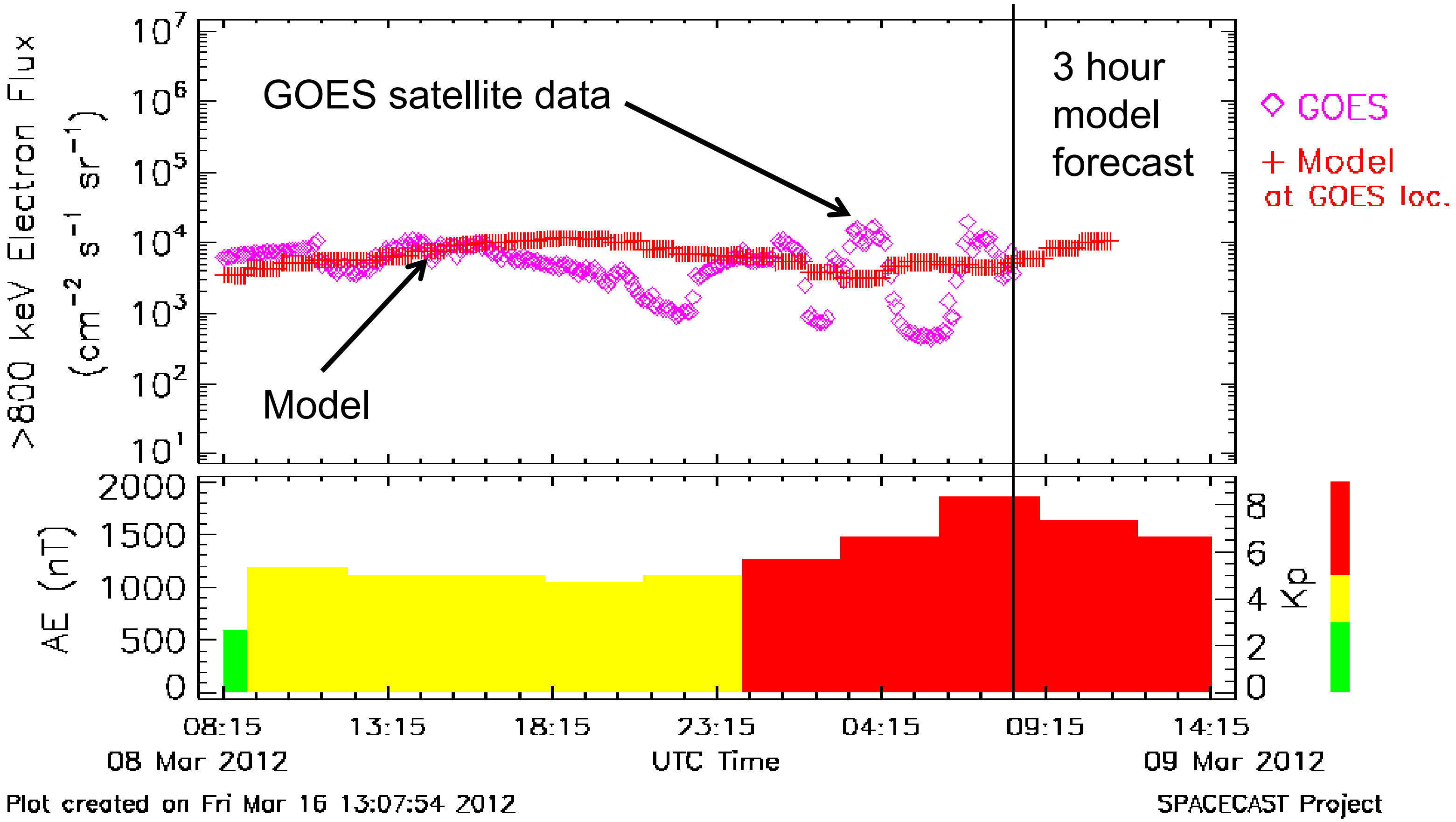
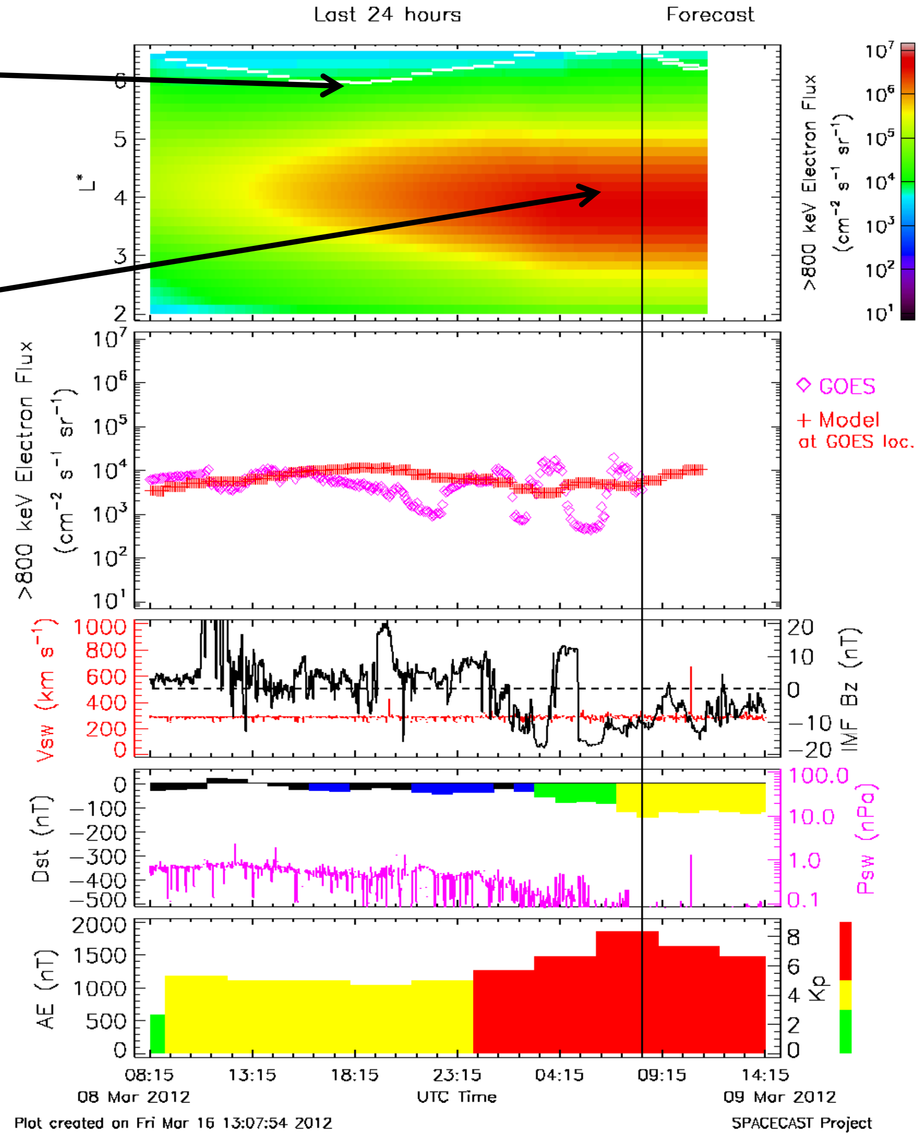
SPACECAST – Forecast >800 keV electrons



- During the 9 March 2012 magnetic storm the model forecast the E > 800 keV flux at GOES 13 to within a factor of two and later in the event to within a factor of ten

SPACECAST – Forecast >800 keV electrons

GOES orbit



- Flux of E > 800 keV electrons most enhanced in the heart of the outer radiation belt around L* = 4.

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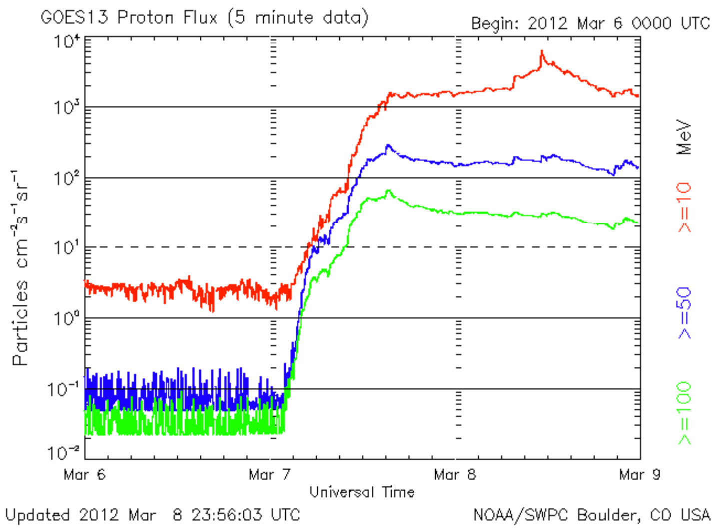
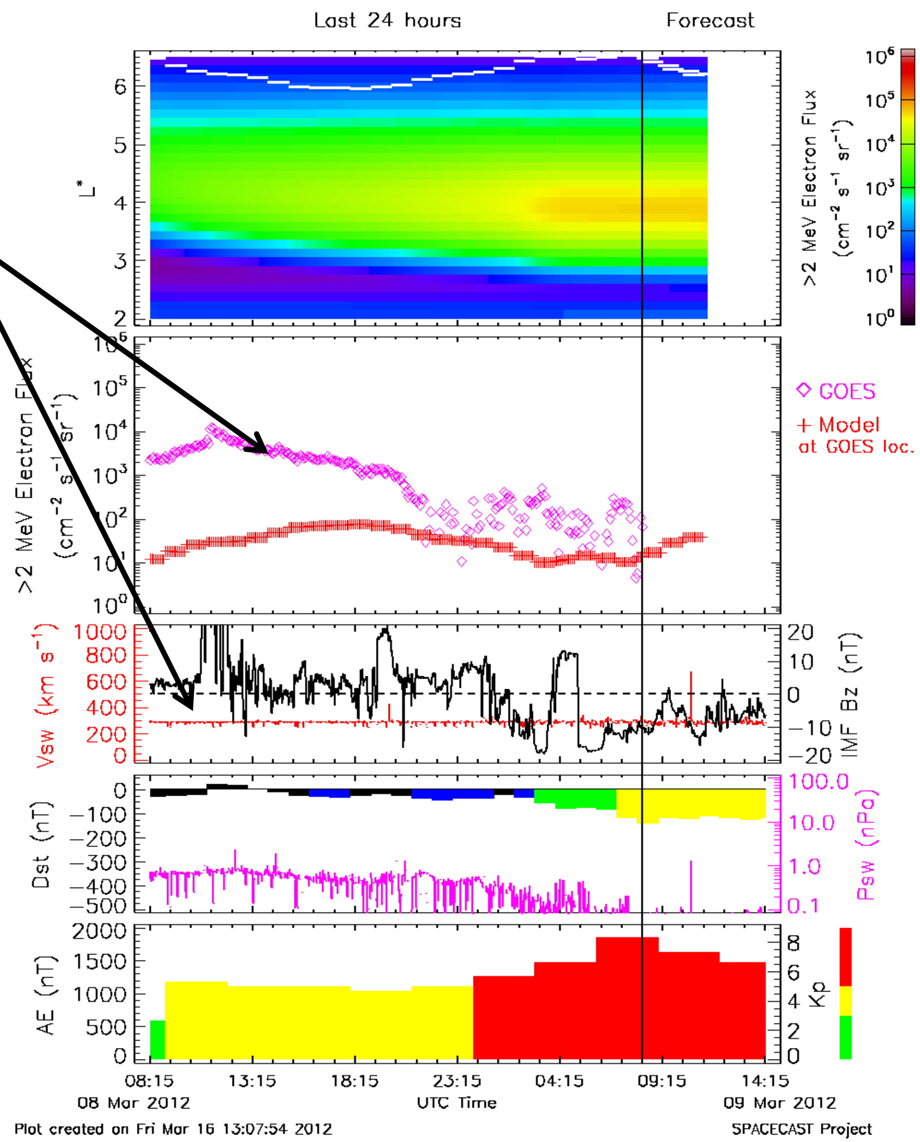
SPACECAST > 2 MeV Electrons

- ACE solar wind velocity data from and GOES E > 2 MeV flux became unreliable due to the solar proton event





- SPACECAST model switched to use a nowcast of the Kp index from BGS and continued to forecast without interruption

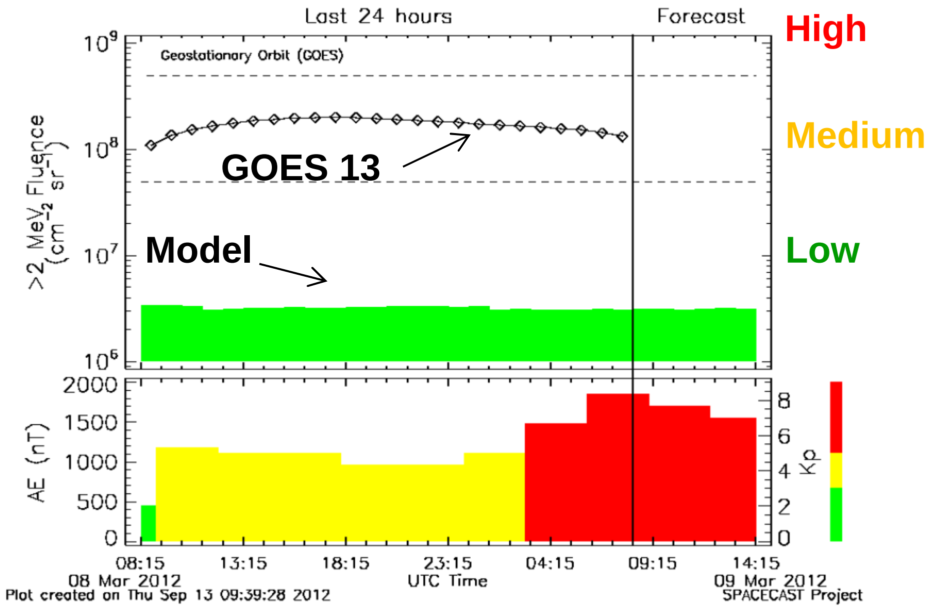
Risk of Satellite Charging - ESD

- Model results converted into a risk index based on previous satellite anomalies at geostationary orbit

- High Risk
  - fluence > $5x10^8$ cm^{-2} sr^{-1}
- Medium Risk
  - $5x10^7$ < fluence < $5x10^8$ $cm^{-2}sr^{-1}$
- Low Risk
  - fluence < $5x10^7$ cm^{-2} sr^{-1}

- Note: GOES electron daily fluence too high during this event due to contamination by > 10 MeV protons

Geostationary Orbit



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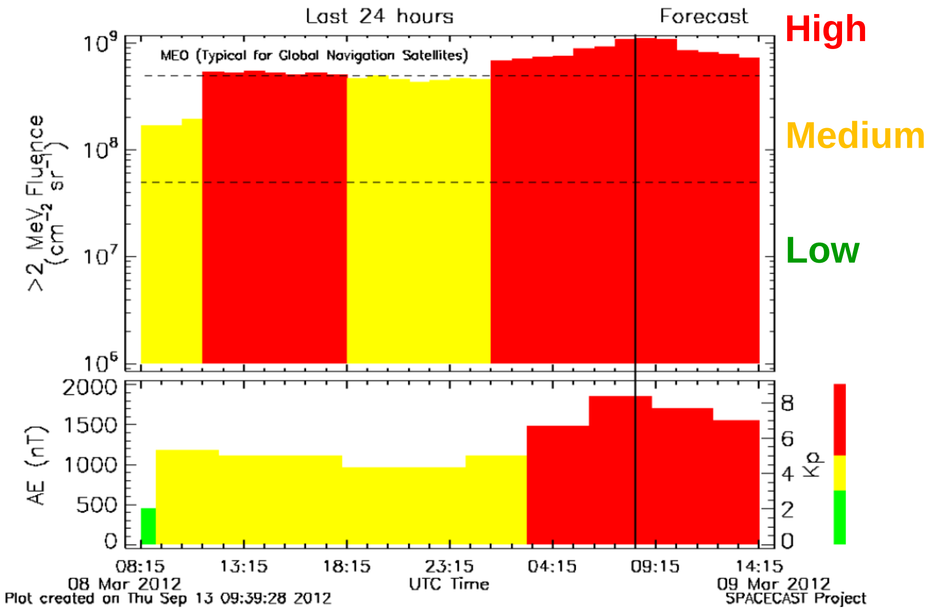
Risk of Satellite Charging - ESD

- We also calculate a risk index for MEO and the slot region
- Risk depends on satellite design
- Needs close collaboration with satellite operators and designers

GPS/Galileo Orbit



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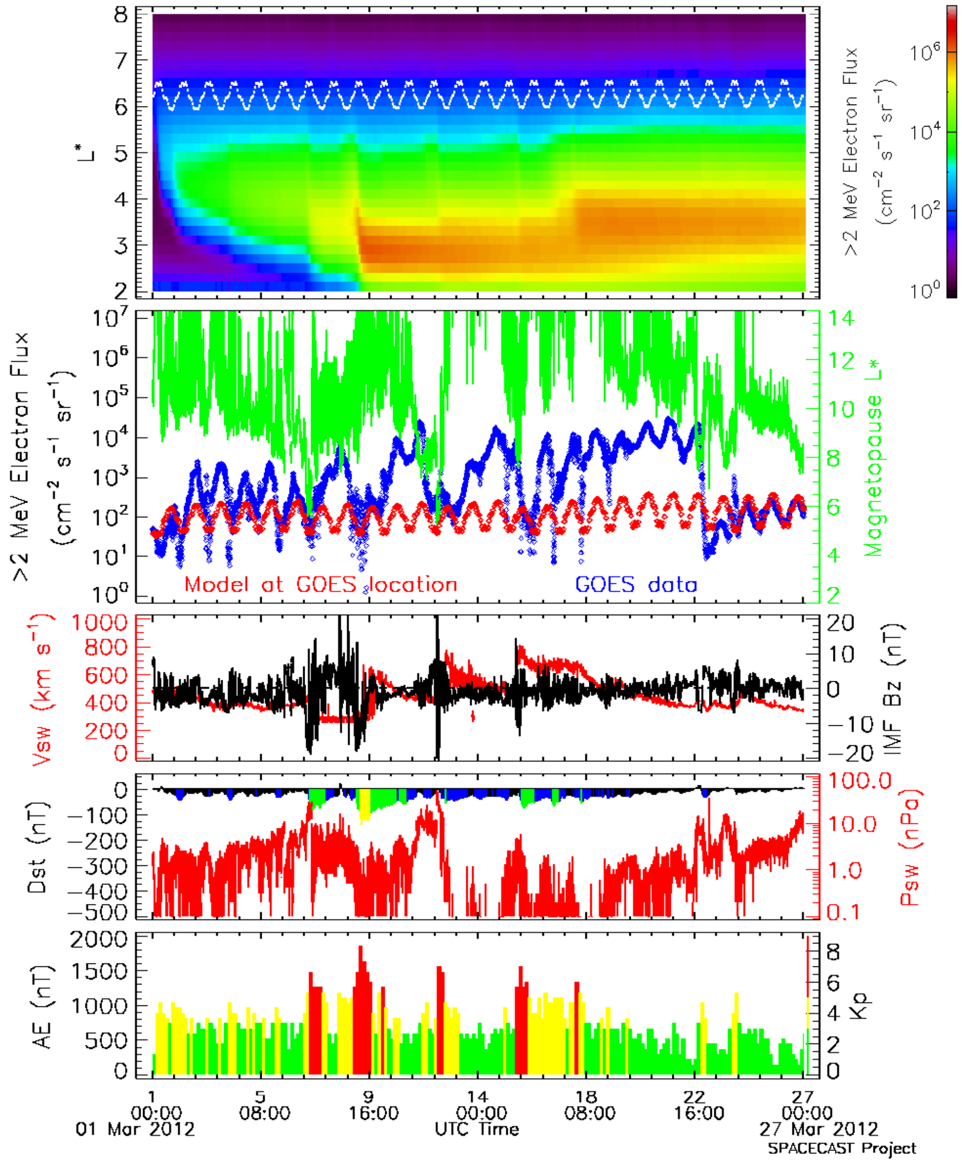
Effect of WPIs beyond GEO

- Current model includes the effects of wave particle interactions inside geostationary orbit
- Flux at GEO not always well-modelled
- To test the effect of WPIs beyond GEO we include chorus out to L* = 8



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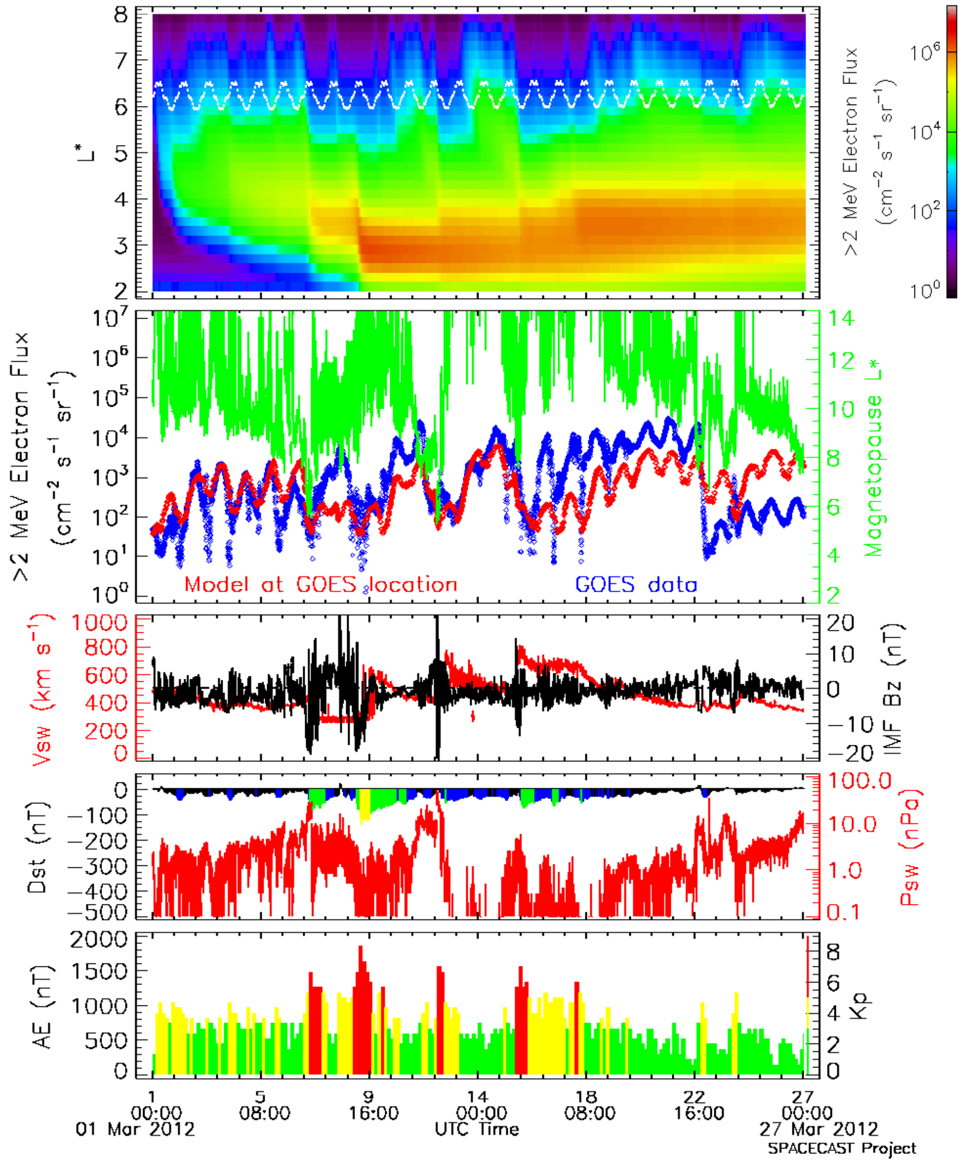
Effect of WPIs beyond GEO

- When we include WPIs beyond GEO we find:
  - increased variability beyond GEO
  - much better agreement with GOES data
- These results suggest that inclusions of WPIs beyond GEO out to at least L*=8 will improve modelling and forecasting accuracy



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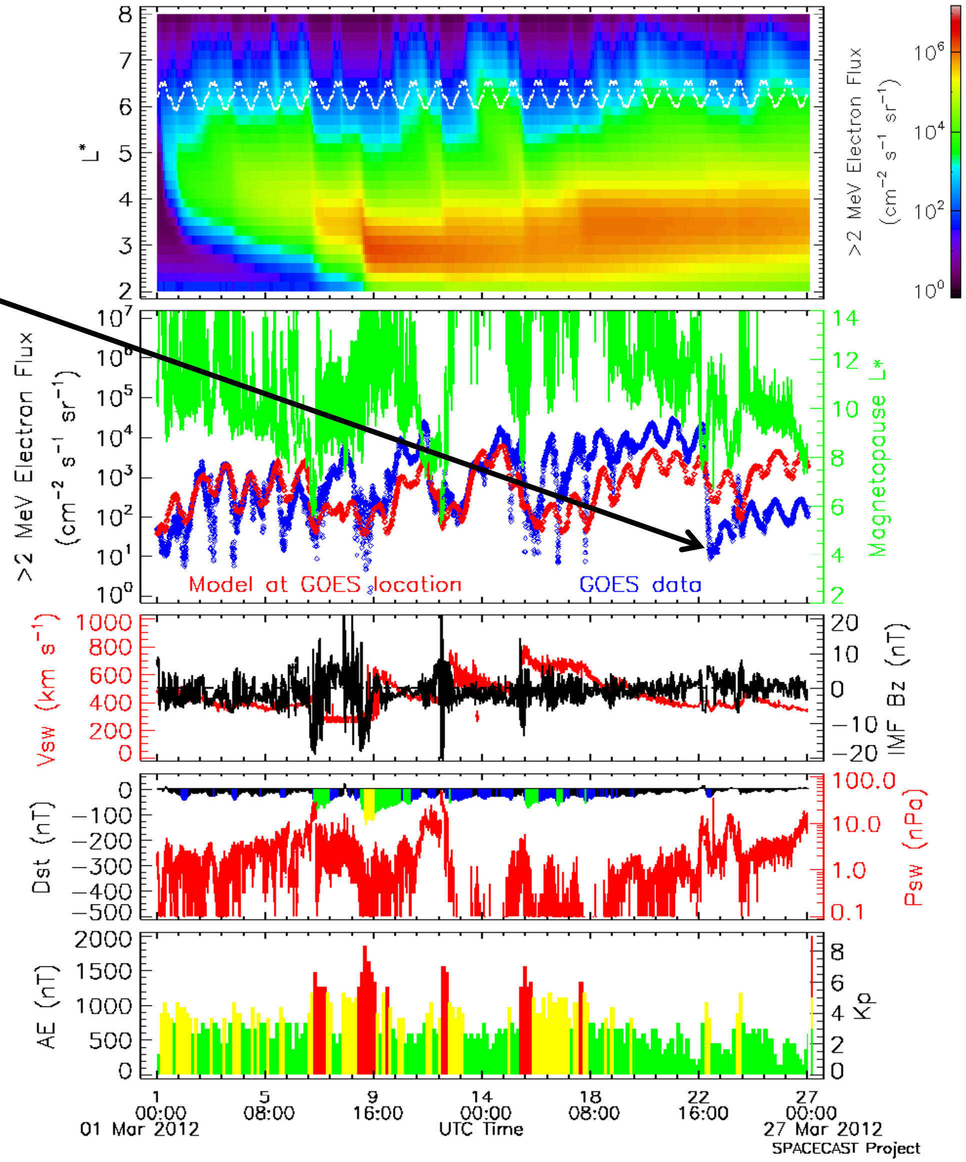
Flux Dropouts

- Rapid drop in GOES flux on 22 March not captured by model
- Drop out occurred just after solar wind pushed magnetopause inside L* = 8
- Observation suggests including the effects of the magnetopause on radial transport and loss likely to improve models and forecasts



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Benefits of Physical Models

- Forecast what is likely to happen – enables mitigation
- Reconstruct what happened in the past - identify the cause of satellite anomalies
- Construct data where there are little/no observations – GNSS orbits
- Calculate extreme conditions based on physical principles
- Calculate number of particles precipitating into the atmosphere - effects on low altitude satellites, ionization and GPS signals

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Next Steps

- Current work is focussed on developing the underlying models. Key next steps include:
  - Better treatment of the outer boundary
  - Improved diffusion coefficients for hiss and chorus
  - Improved initial condition
  - Improved radial diffusion coefficients
  - Better low energy boundary condition
  - Model validation by comparison with GOES, RBSP and Galileo data
- Improvements to the SPACECAST forecasts will be introduced on 1st March 2013

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Conclusions

- SPACECAST makes real time forecasts of the radiation belts for satellite operators

- Forecast for 3 hours, updated every hour, and translated into a risk index

- Unique features
  - Physical models, that include wave-particle interactions
  - Forecast for the whole radiation belts – including GPS/Galileo orbits
  - European led – with USA and Japan

- Forecasts can be improved by
  - Coupling the solar wind/magnetopause to the radiation belts
  - Including low energy electrons – surface charging

- Options to model extreme events and orbits where there is little or no data

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Acknowledgement

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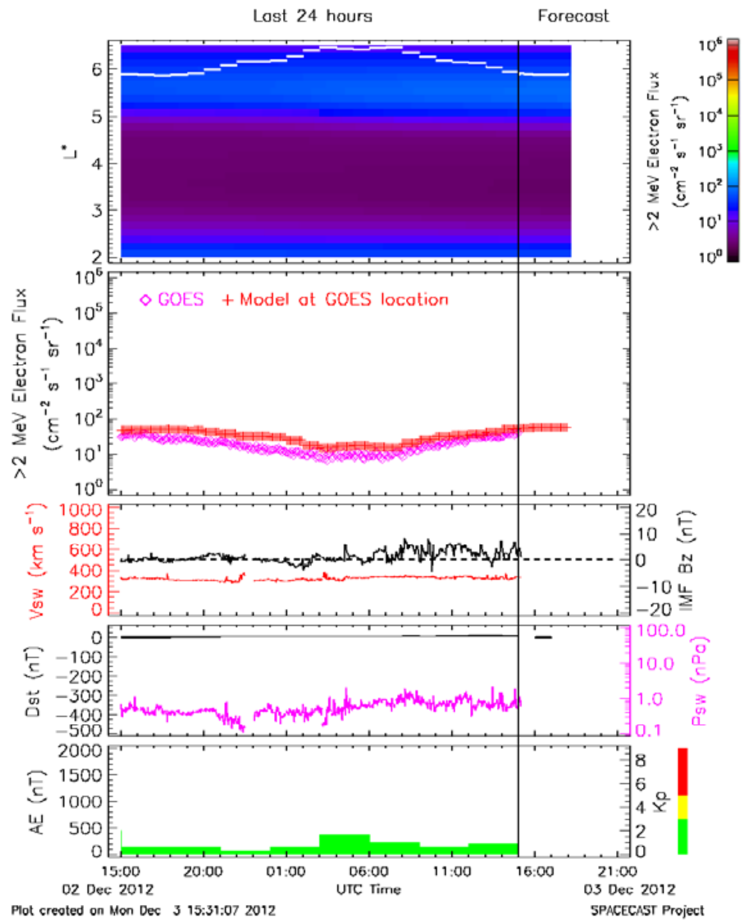
E > 2 MeV Electrons



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