Space Weather Charging Environments Especially Radiation Belts

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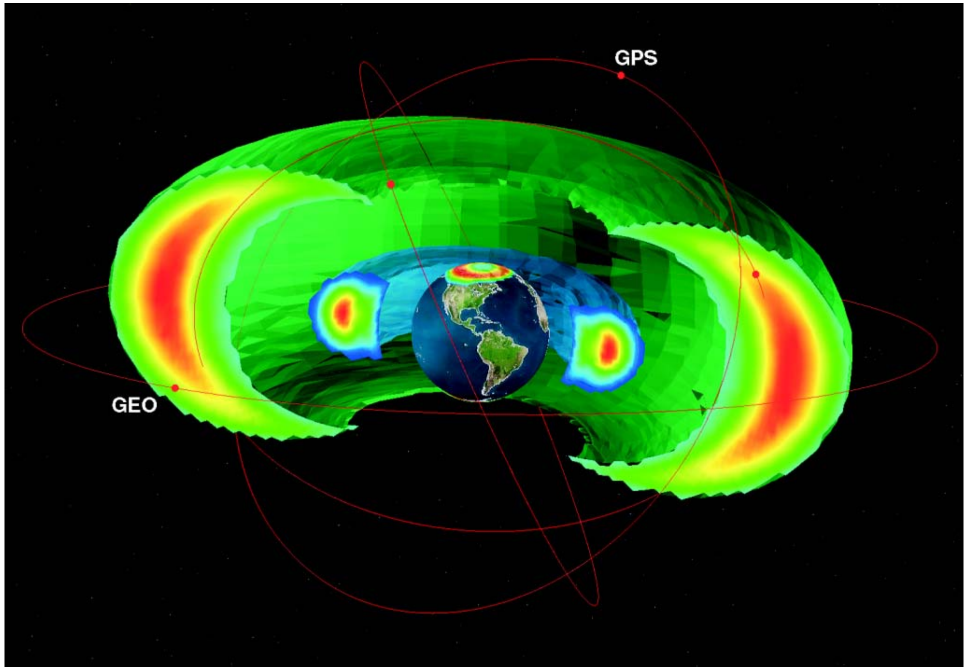

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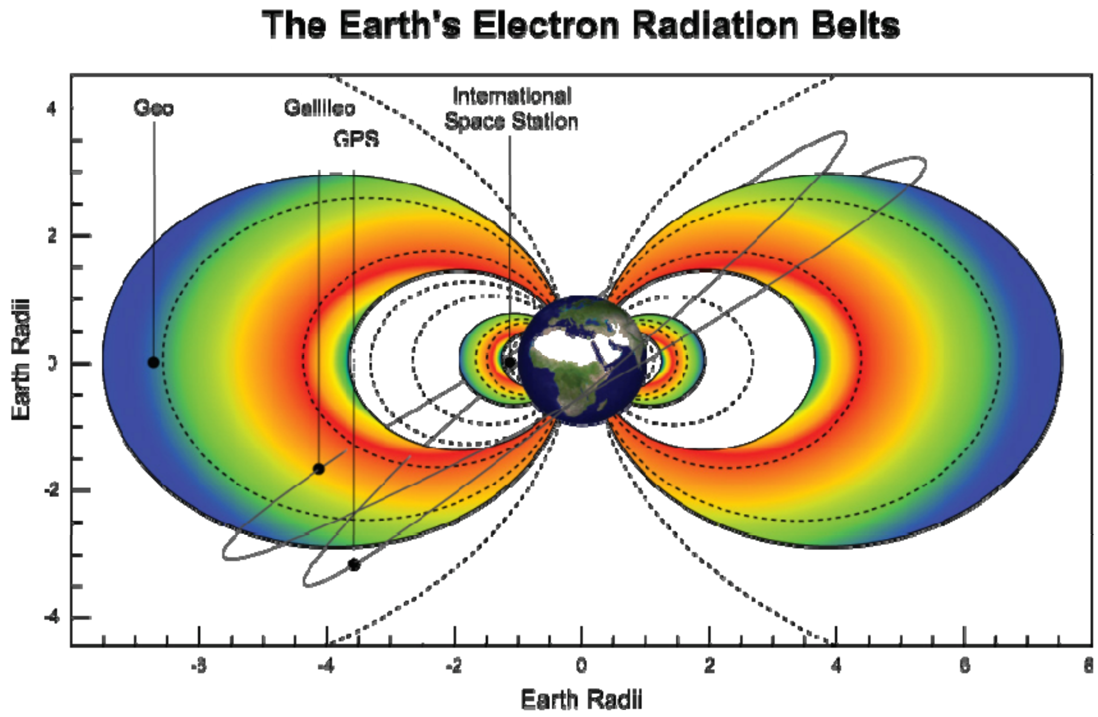
SEREN workshop on Physical Pathways to Space Weather Impacts, London, 10-12 Feb 2015

Satellite Orbits and the Earth's Radiation Belts



- About 1000 satellites in orbit:
  - 420 in geosynchronous orbit GEO
  - 70 in medium Earth orbit MEO
  - 470 in low Earth orbit LEO
  - 35 in highly elliptical orbit HEO

- Earth's radiation belts contain very high energy electrons and ions that damage satellites

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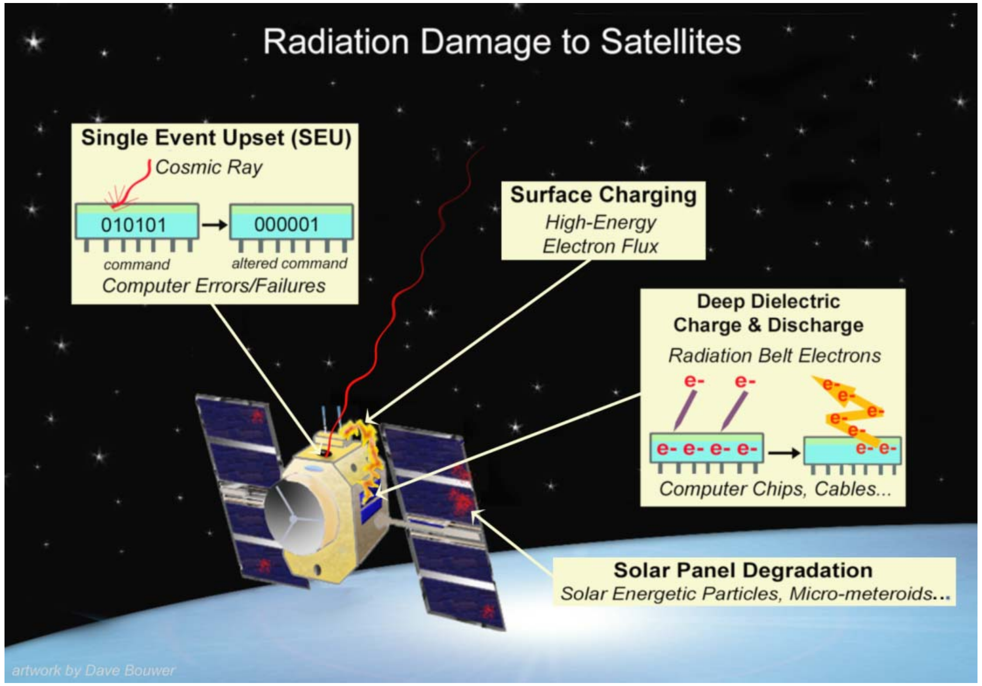
Spacecraft Damage

- Satellite charging
  - Internal charging – MeV electrons
  - Surface charging – keV electrons

- Electrostatic discharge
  - Component failure
  - Phantom commands

- Single event effects
  - Corrupt memory circuits
  - Loss of power in solar cells
  - ~ 2% in GaAs/Ge cells – SEP event
  - Parts failure

- Cosmic rays
- Solar energetic particle events (SEPs)



- Cumulative radiation dose limits spacecraft lifetime
  - Aging of surface coatings
  - Erosion
  - Reduced thermal resiliance

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Satellite Anomalies – Related to Space Weather

- 20th Jan 1994
  - Intelsat 4 and Anik E1 - recovered in a few hours
  - Anik E2 - Loss of service for 6 months
- 11th January 1997
  - Telstar 401 - Total loss – Insurance payout $132m
- 19th May 1998
  - Galaxy IV - Total loss – Insurance payout $165m
- 23rd Oct to 6th Nov 2003
  - 47 satellites reported malfunctions – 1 total loss
  - 10 satellites – loss of service for more than 1 day
- 3rd Aug 2004
  - Galaxy 10R – loss of propulsion – Insurance payout $75m
- 5th Apr 2010
  - Galaxy 15 - Loss of service for 8 months - risk of collision
- 7th March 2012,
  - Sky Terra 1 and Spaceway 3 - Safe mode, loss of service for hours – days

- Impact of 1 in 100 year event? - National Risk Register
  - Estimates vary widely (all space weather - US$0.6 – 2.6 trillion)

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Severe Space Weather Event

- Royal Academy of Engineering Report 2013
  - Based on 2003 event:
  - 10% of the entire fleet malfunctioning
  - < 10 - total loss
  - All satellites aged
  - After the event – increased failure rates

- Orbits most at risk
  - CME event – GEO, MEO, HEO and probably LEO
  - Fast solar wind stream – GEO, MEO, HEO
  - Solar energetic particles – all orbits

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Pathways

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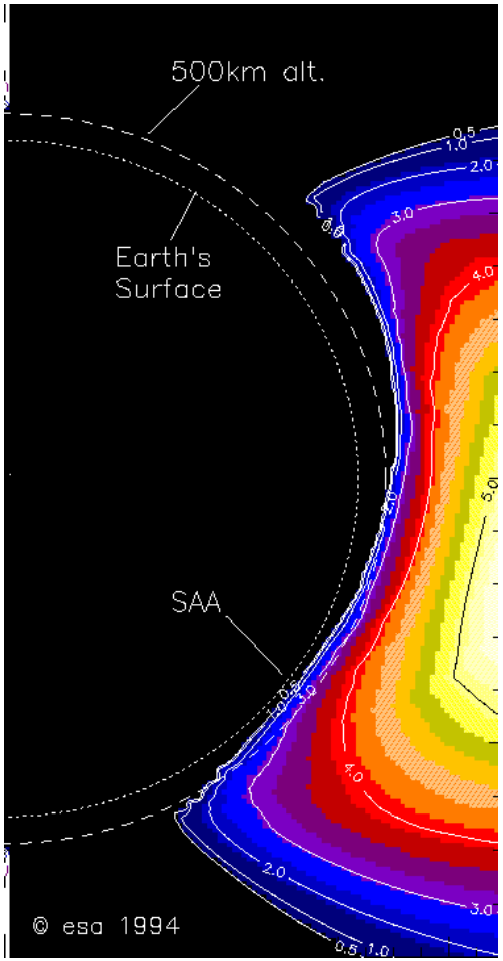
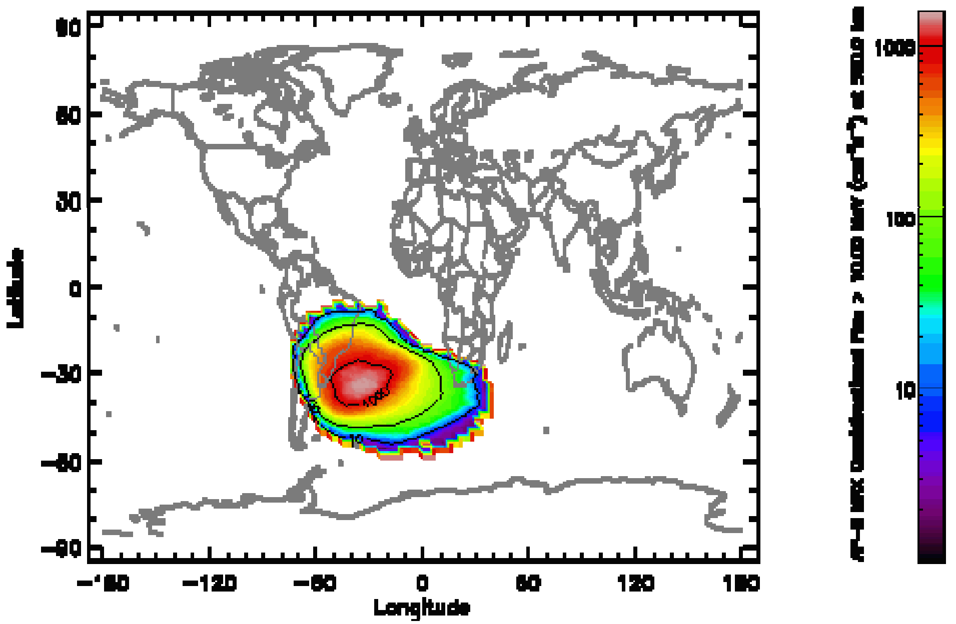
Proton Radiation Belt

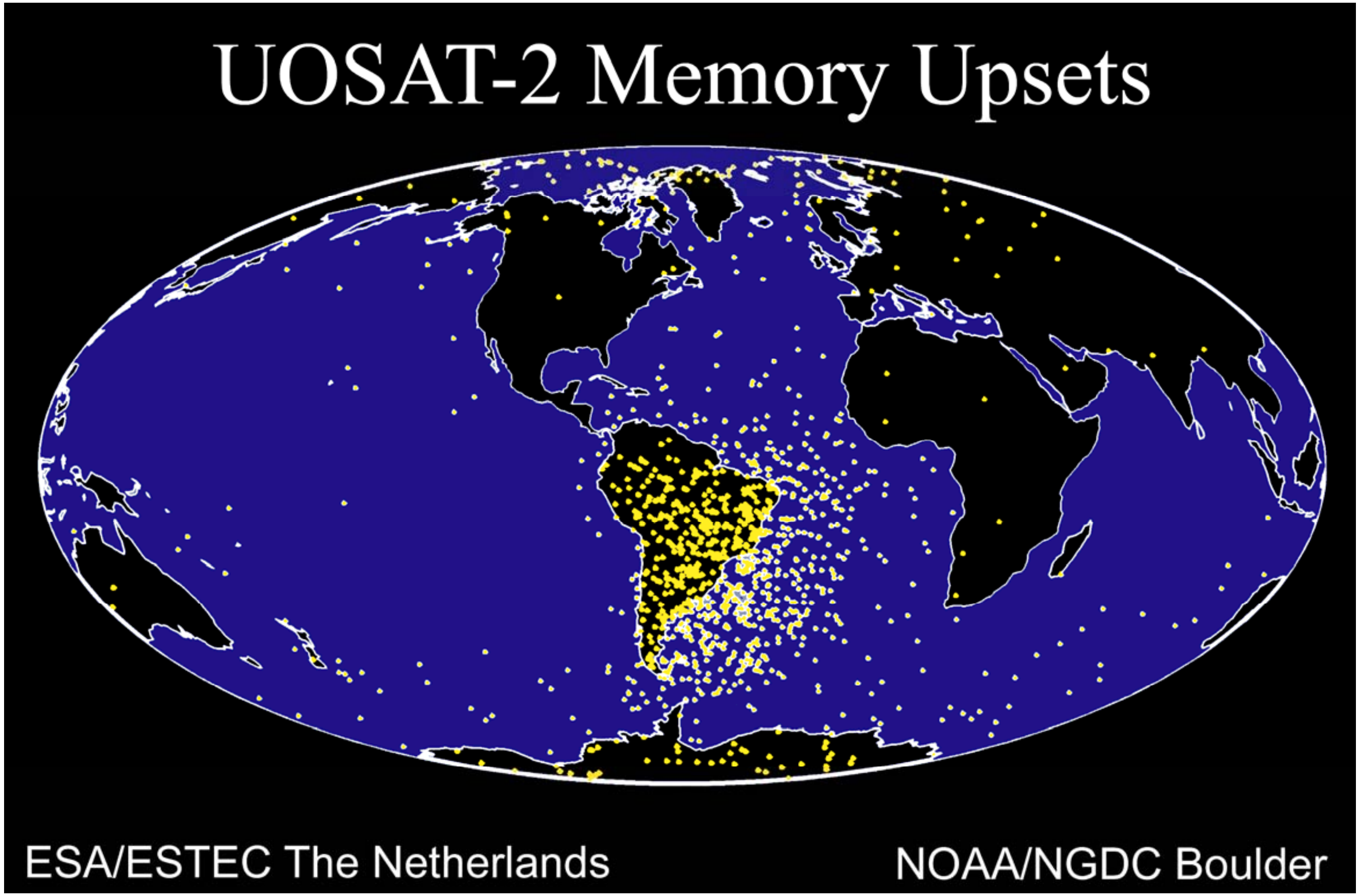


- Proton belt penetrates closer to the atmosphere over the south Atlantic due to the weakness in the magnetic field

- Hazard to low altitude satellites



Memory Upsets in the South Atlantic Anomaly



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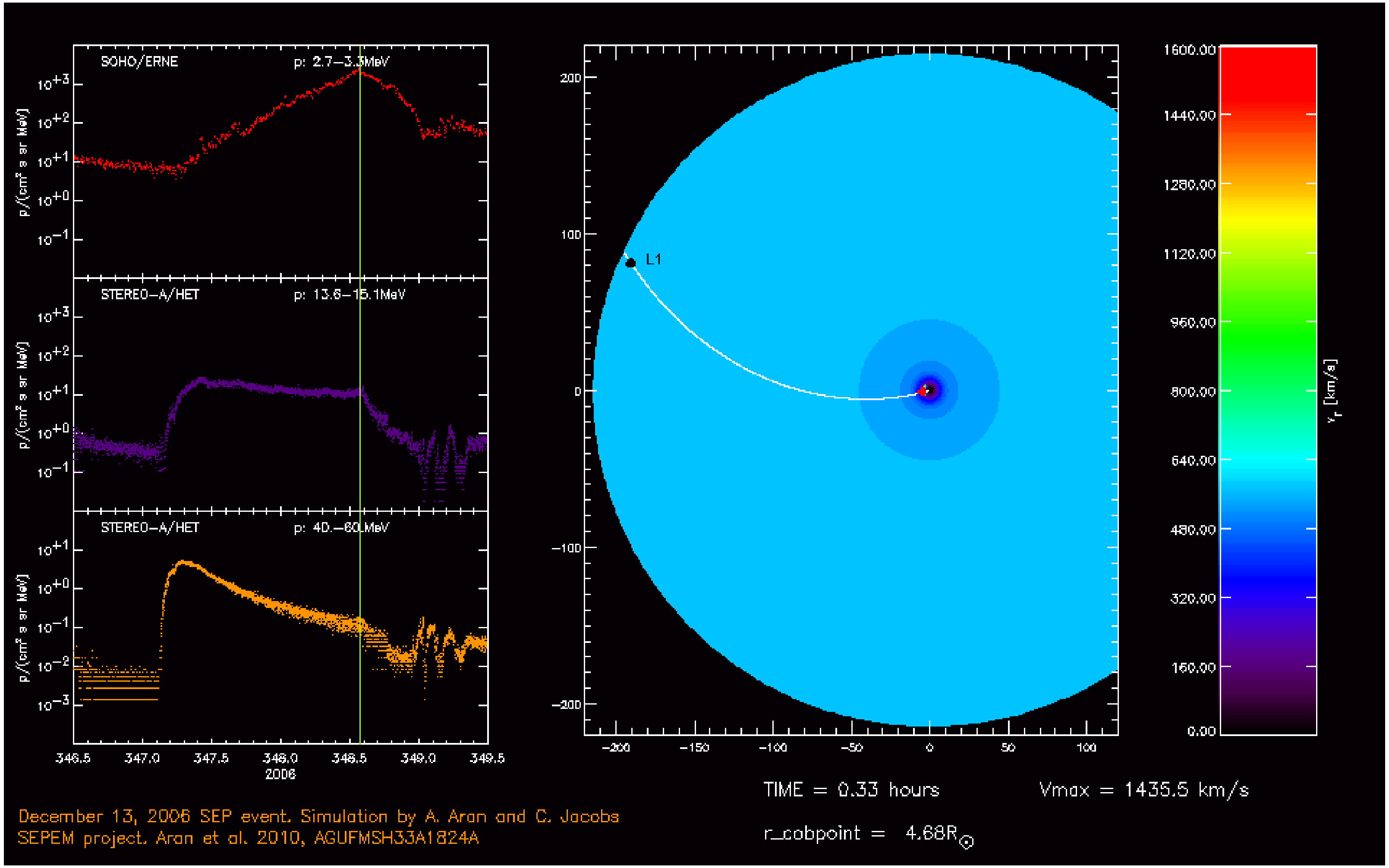
Simulation of an SEP event



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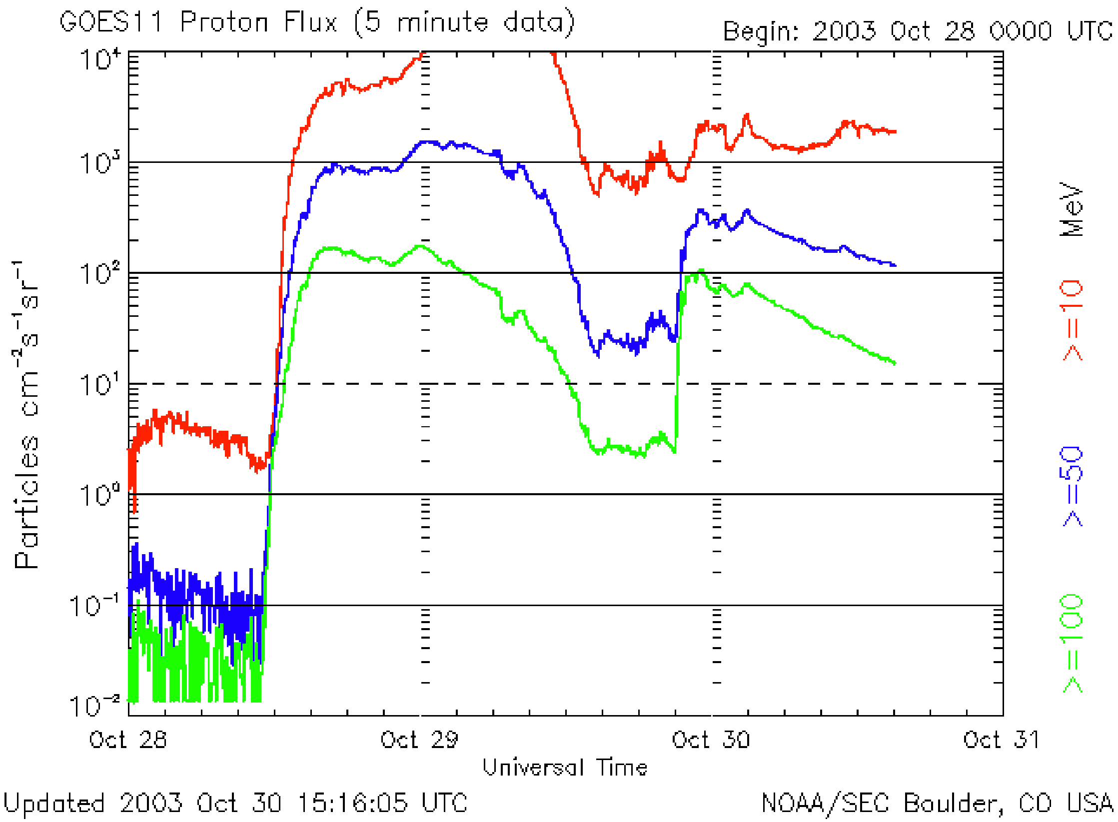
Solar Energetic Particle Events



- 2003 event
- Cause single event upsets in electronics
- Cause loss of solar array power ~ 2% in modern solar cells (equivalent to ~1.5 years)
- Note the rapid increase in particle flux
- Event lasted for days

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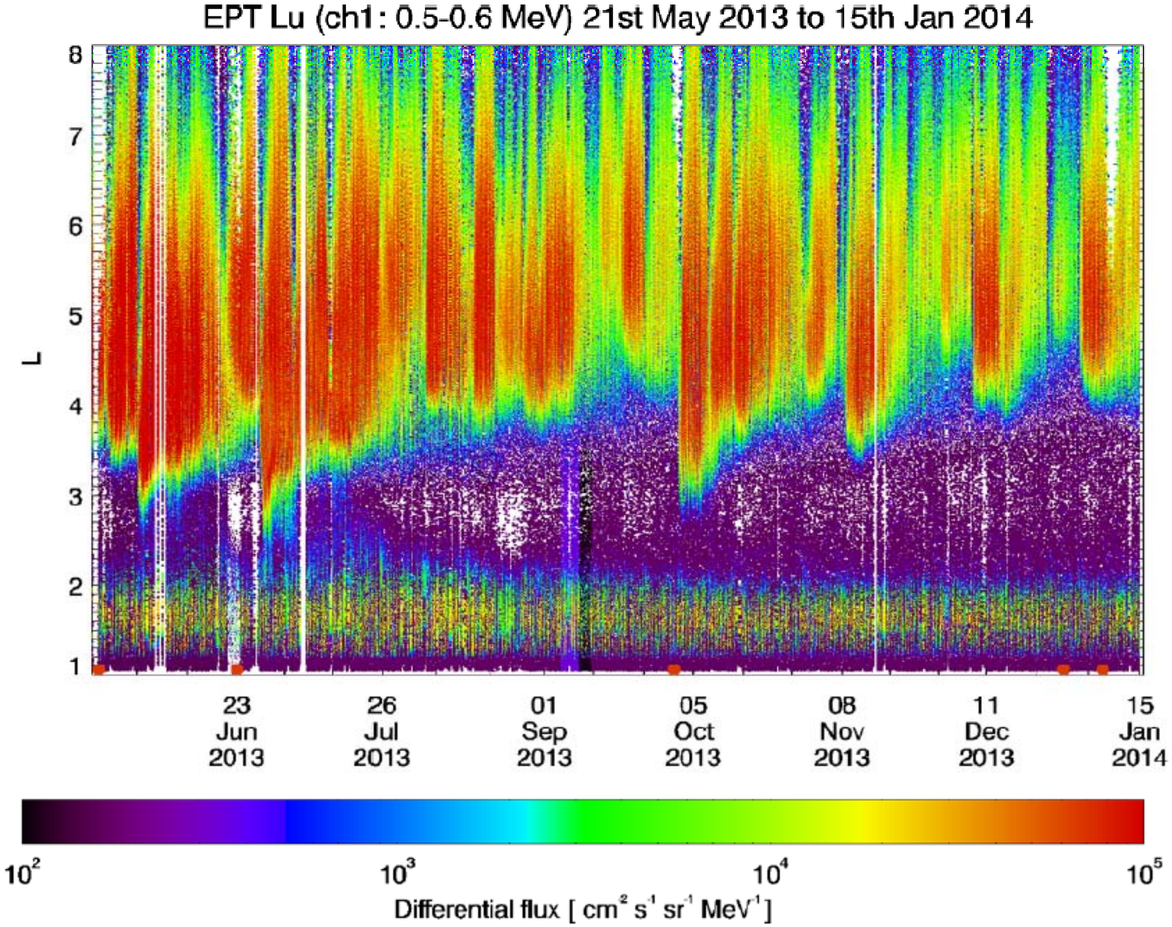
Electron flux variability

- Proba V EPT data



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- Pierrard et al. [2014]

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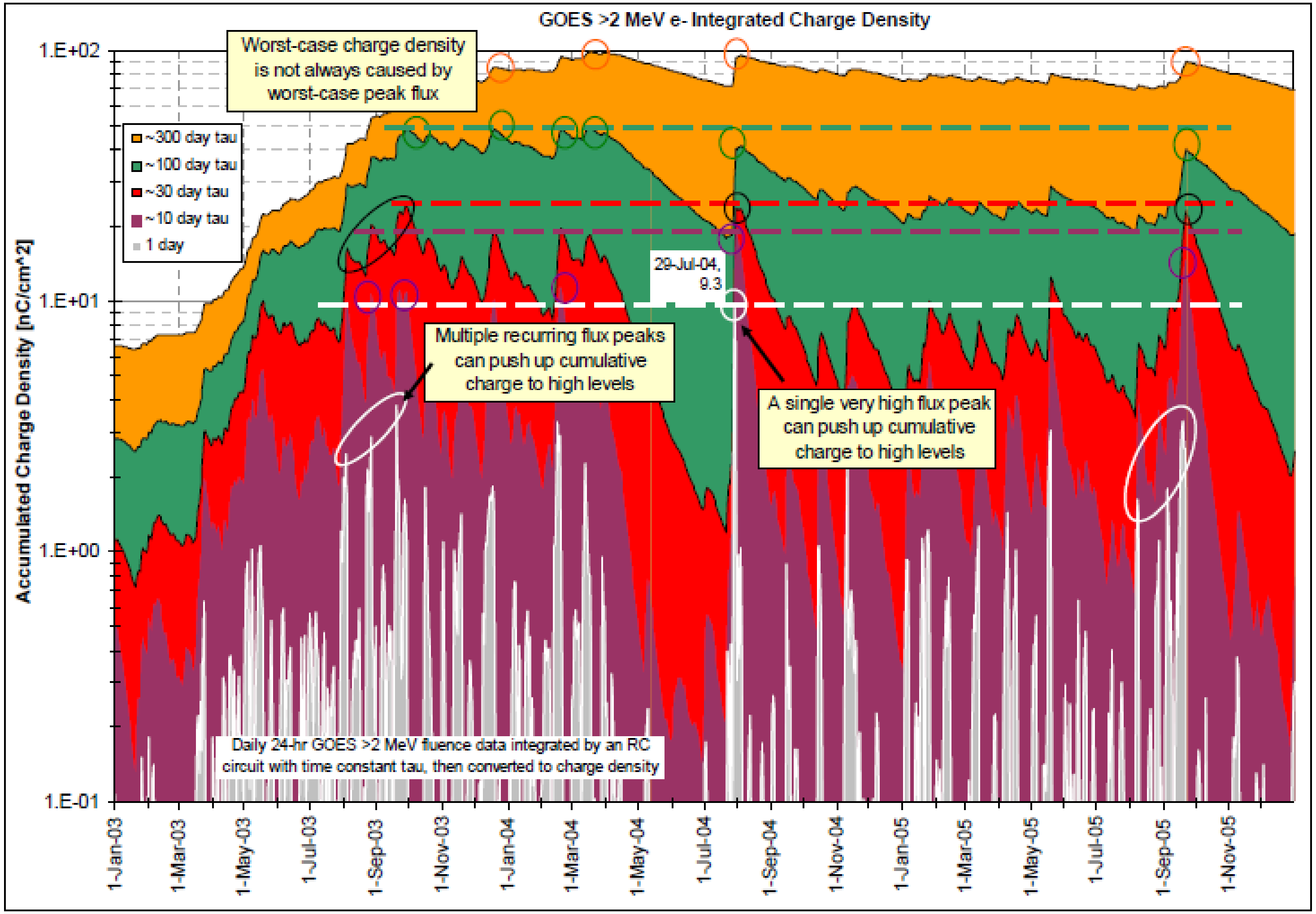
Time constant for satellite charging

Figure 8. Long time constants increase charge accumulated from recurring storms



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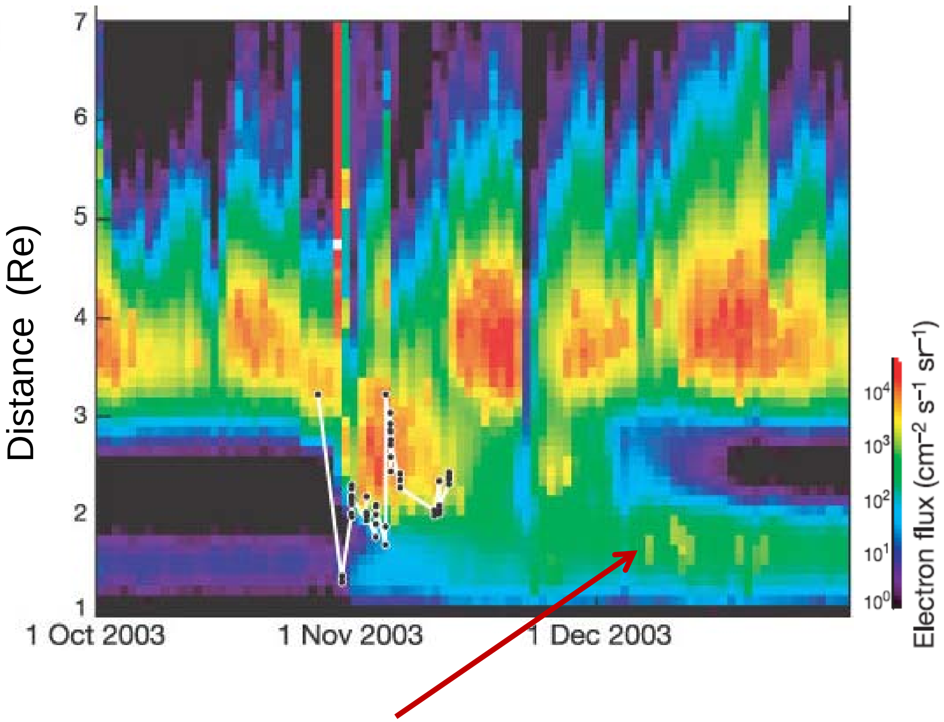
Similarities: Space Weather -

> 2 MeV electron flux



- Particles ‘injected’ during a magnetic storm – last for years

1960s high altitude nuclear detonations

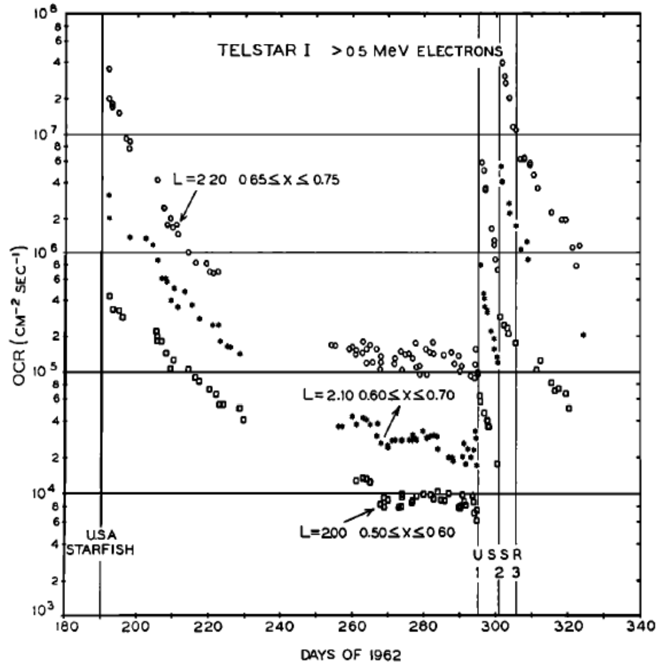


Fig. 8. Decay of >500-kev electrons following the high-altitude nuclear explosions of 1962. The data points for $L = 2.10$ and 2.00 have been displaced downward by one and two decades, respectively. On each L shell, the data are for a range of the coordinate $x = (1 - B_0/B)^{1/2}$.

- High altitude nuclear detonations also inject electrons into the radiation belts and last for years

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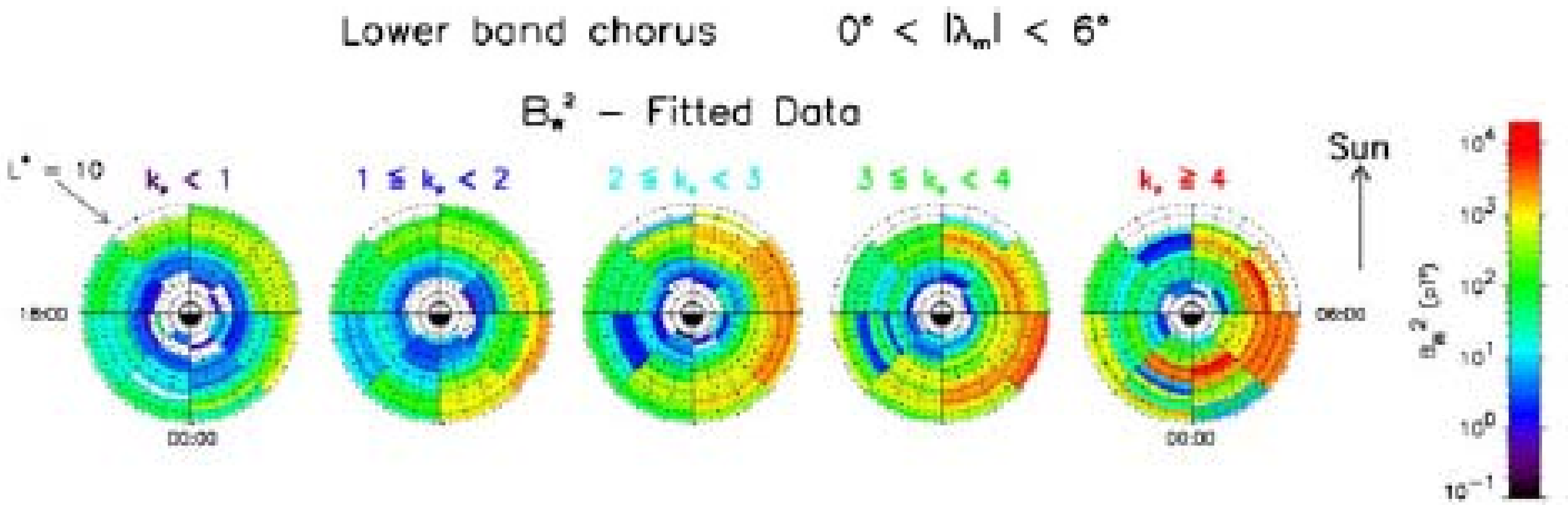
Whistler Mode Chorus Waves



- Wave-particle interactions cause electron acceleration and precipitation (loss)
- Plasma wave intensity varies with location - increases with geomagnetic activity (Kp)
- To calculate net change in electron flux – need wave properties
- Timescale – milliseconds – but need on timescale of days

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BAS Radiation Belt Model

- Fokker-Planck Equation

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

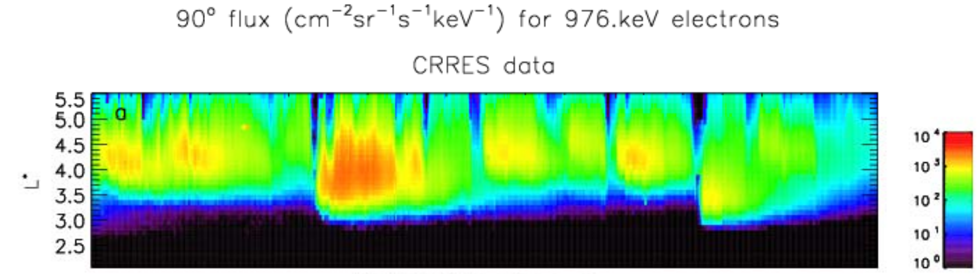
Radial transport | Pitch angle diffusion | Energy diffusion | Losses

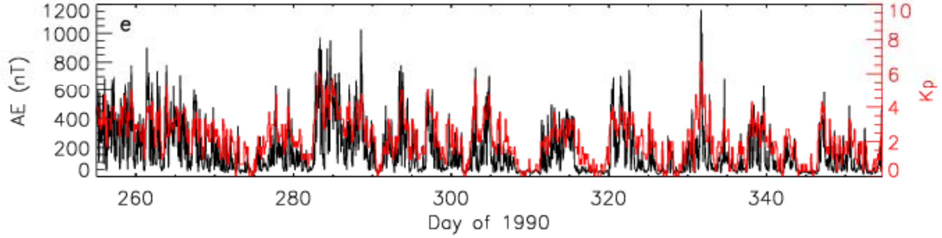
- Drift & bounce averaged diffusion coefficients D_{LL}, $D_{\alpha\alpha}$, D_{EE} are activity, location and energy dependent

- Details in: Glauert et al. [2014]

Importance of Wave-Particle Interactions

Satellite data - Electrons





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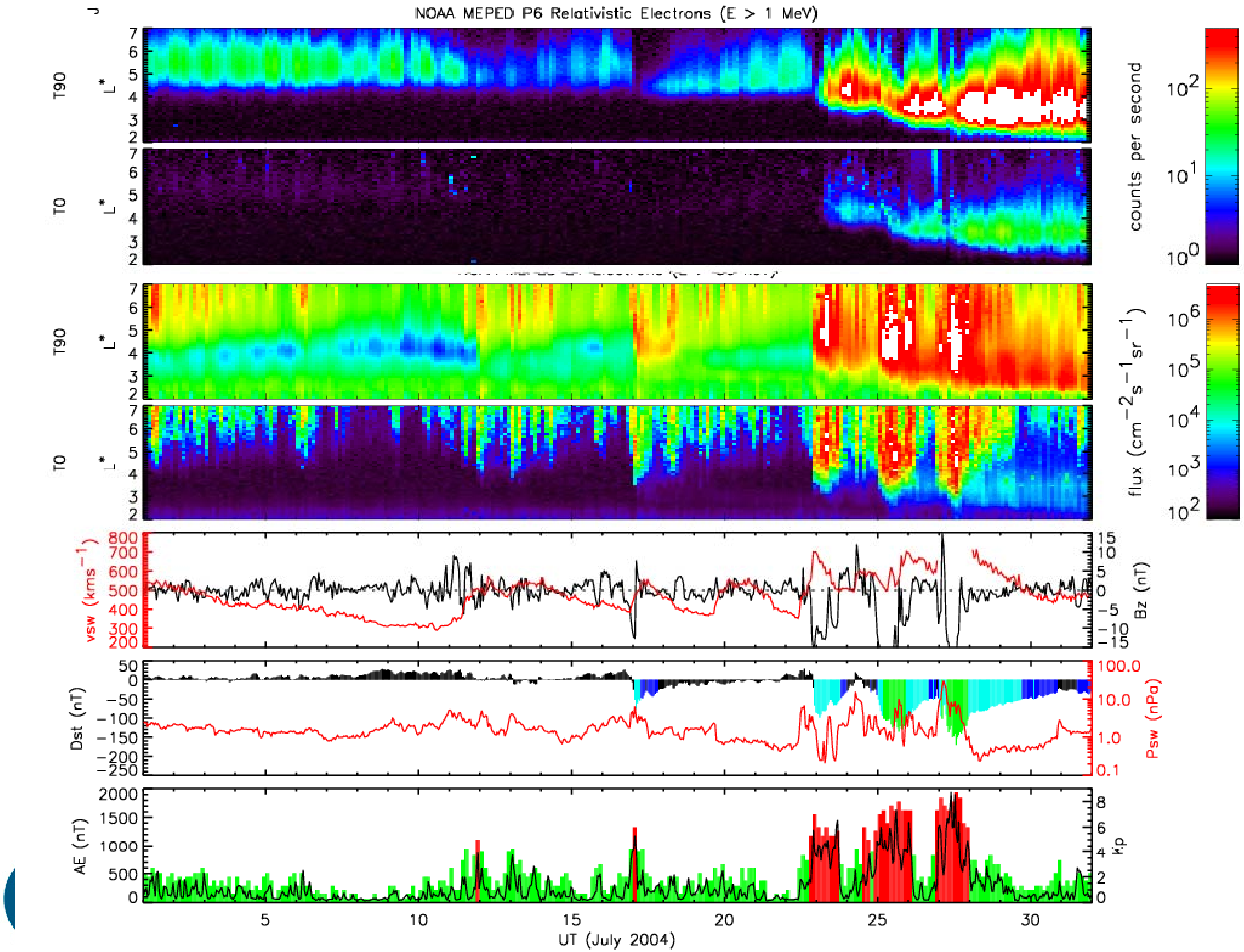
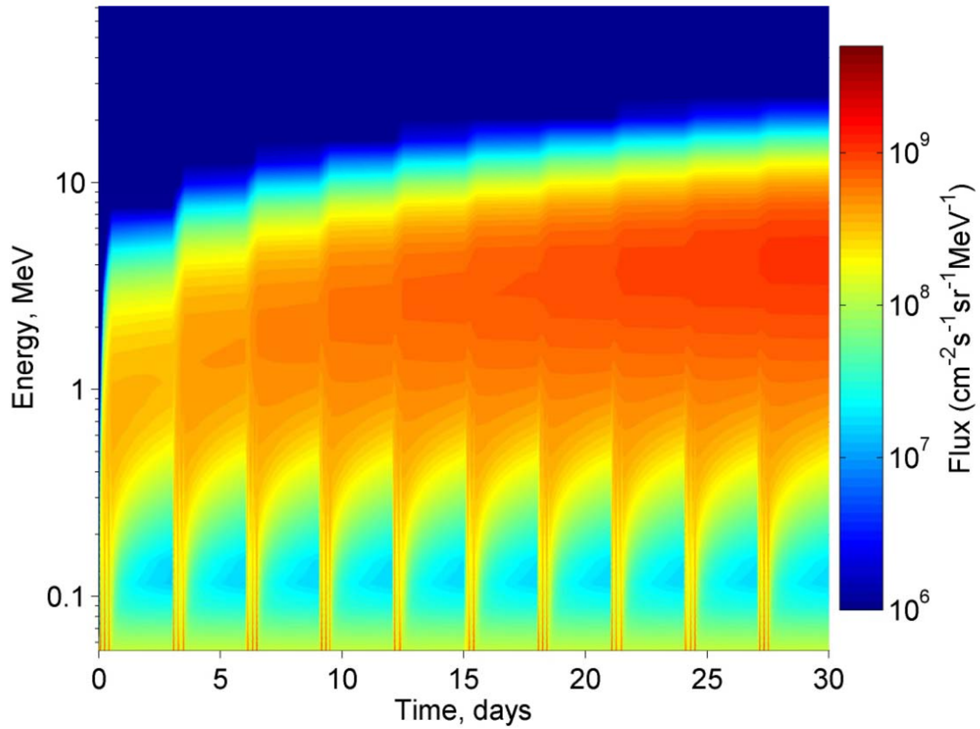


NOAA MEPED P6 Relativistic Electrons (E > 1 MeV)
T90
T0
L*
counts per second
flux (cm−2s−1sr−1)
vsw (kms−1)
Bz (nT)
Dst (nT)
Psw (nPa)
AE (nT)
Kp
UT (July 2004)

Low energy plasma injections - Jupiter



- Woodfield et al. [2014]

- Vary flux at minimum energy boundary
- 12 hr bursts of hour long injections every 3 days (based on Mauk et al., 1999)
- Flux increases at higher energies are cumulative
- Need better analysis of injections for Earth's radiation belts – POES data

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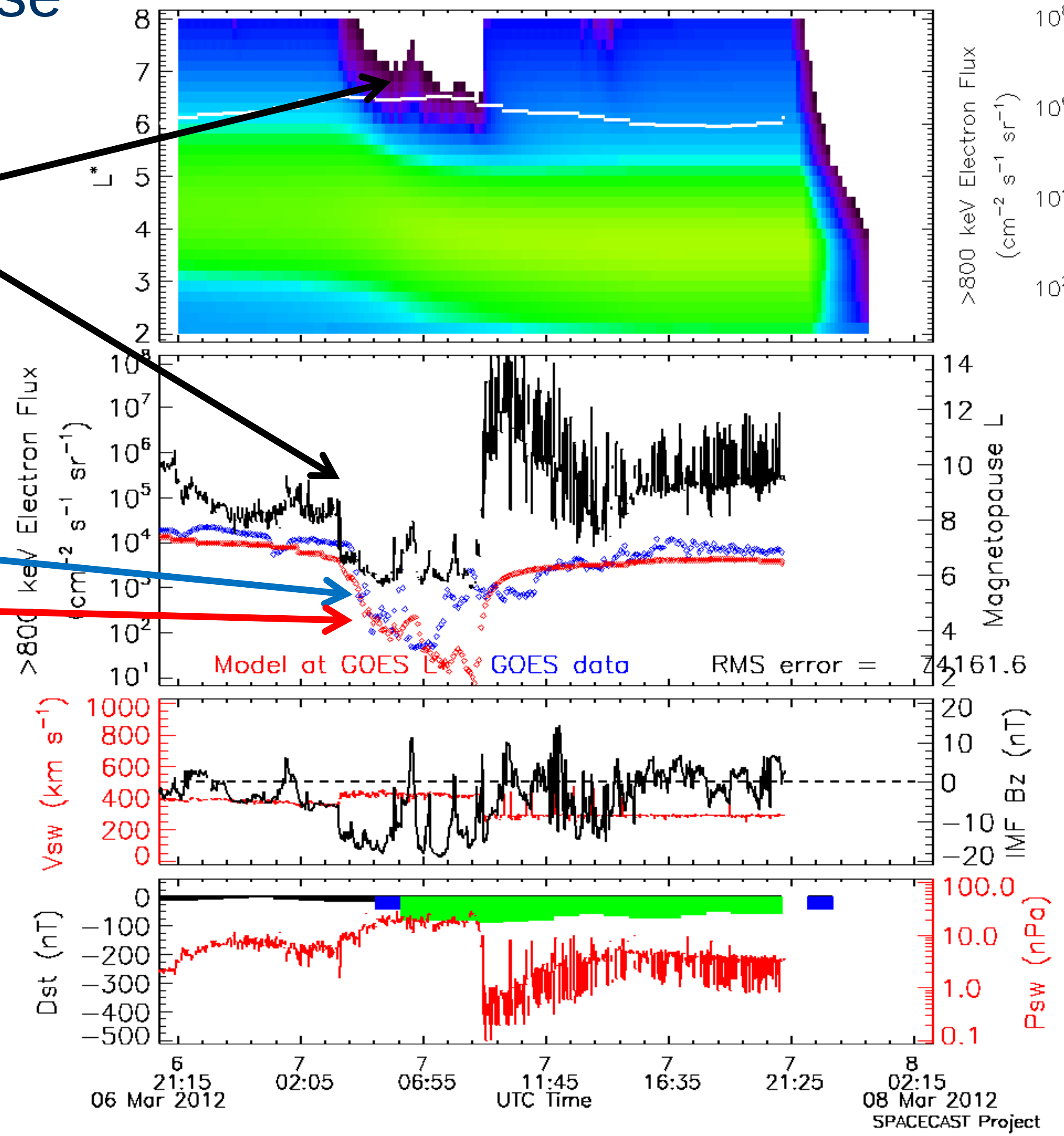
Magnetopause Losses

Magnetopause

Losses outside last closed drift shell

GOES data

BAS model



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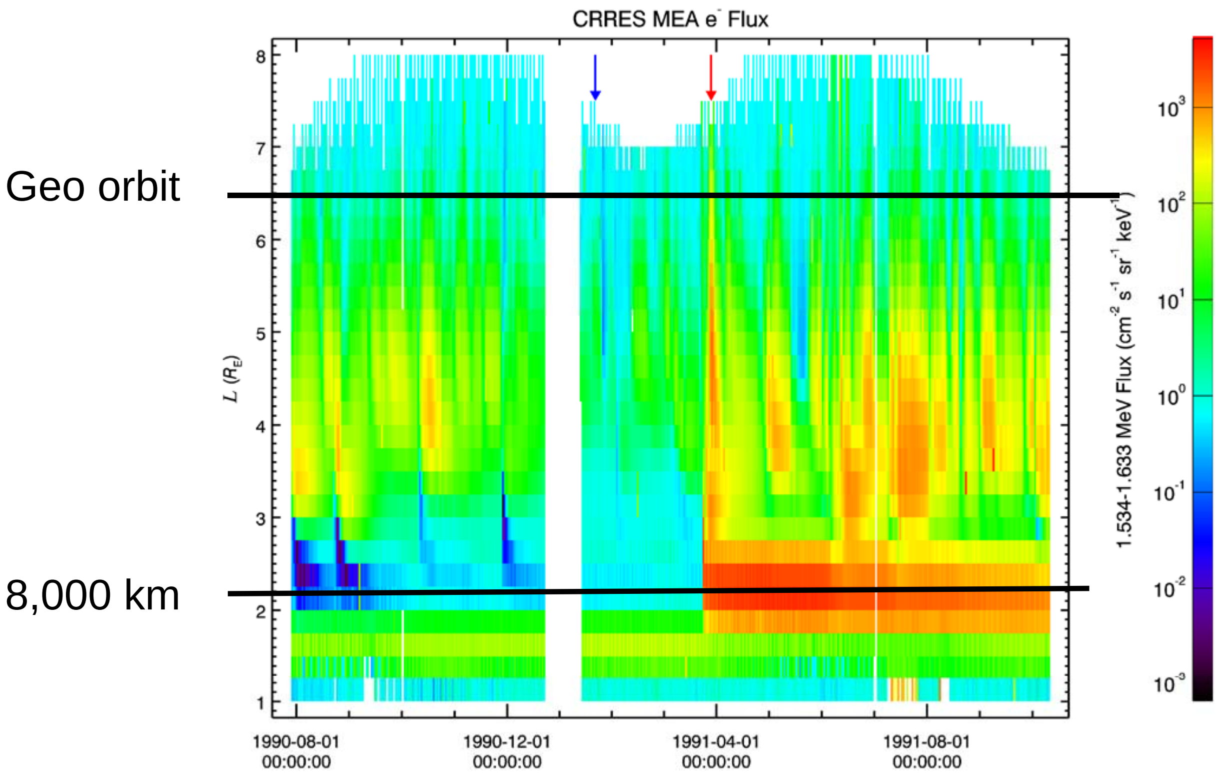
All Electric Propulsion Satellites

- Launch to orbit ~ 100 – 180 days
- Needs full assessment of variable radiation environment
- SPACECSTORM will cover the whole outer belt – electron flux, fluence, charging



- 1.5 MeV electrons flux from CRRES
- Much higher charging environment after March 1991
- Charging depends on materials
- Note 8,000 km for O3b satellites

- Heynderickx [2014]

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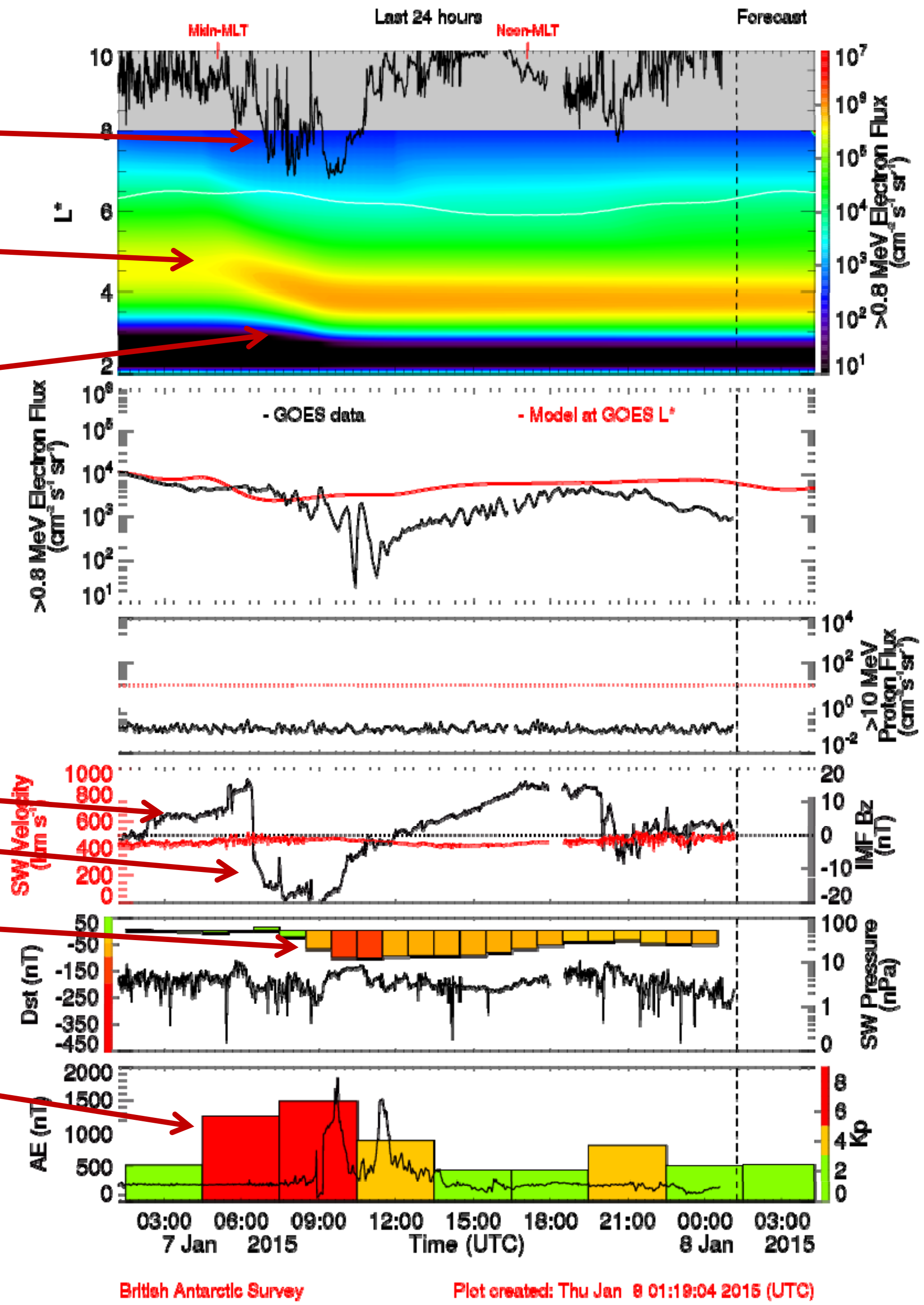
Forecasting

- Magnetopause compression
- Electrons accelerated to MeV energies by very low frequency waves (kHz)
- Transport towards the Earth by ultra-low frequency waves (mHz)

- IMF Bz ramps up
- IMF Bz turns southward
- Reconnection takes place
- Ring current develops – Dst < 0

- Magnetic activity increases – Kp index



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Summary

- Tremendous growth in satellites - doubled in 10 years to > 1000 operational
- In 2011 total revenue from the space industry was $289.8 bn (Satcom $177bn) [Satellite Industry Association, 2012]
- Several types of extreme events possible
  - CME driven storms, fast solar wind, Solar energetic particle events
- Impact of a severe event - is very uncertain
  - 10% of the fleet malfunctioning – all satellites will be aged - total loss?
- New risks associated with
  - All electric propulsion satellites
  - Growth of satellites in MEO and HEO for internet in space (>650 satellites)
- Need forecasting and situation awareness for all orbits - GEO, MEO, LEO, HEO