# Charged Particle Environments in Earth's Magnetosphere and their Effects on Space Systems

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# Introduction

"Space weather" refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological system and can endanger human life or health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socioeconomic losses.

*National Space Weather Plan, Strategic Plan*, 1995

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**Overview**

- Space radiation environments important to magnetospheric missions
  - Trapped radiation
  - Solar particle events
  - Cosmic Rays
  - Solar wind
- Radiation effects on space systems
- Spacecraft charging

# Charged Particle Effects on Space Systems

- Spacecraft operate in a harsh space environment
  - Sensitive electrical, optical components, materials are continually subjected to energy and charge depositing interactions

- Devices in space are believed to have failed because of:
  - Electrostatic discharge
  - Receiving a total dose (energy/mass) exceeding acceptable limits
  - Random cosmic ray strike at a sensitive location
  - Displacement damage caused by particle non-ionizing energy loss

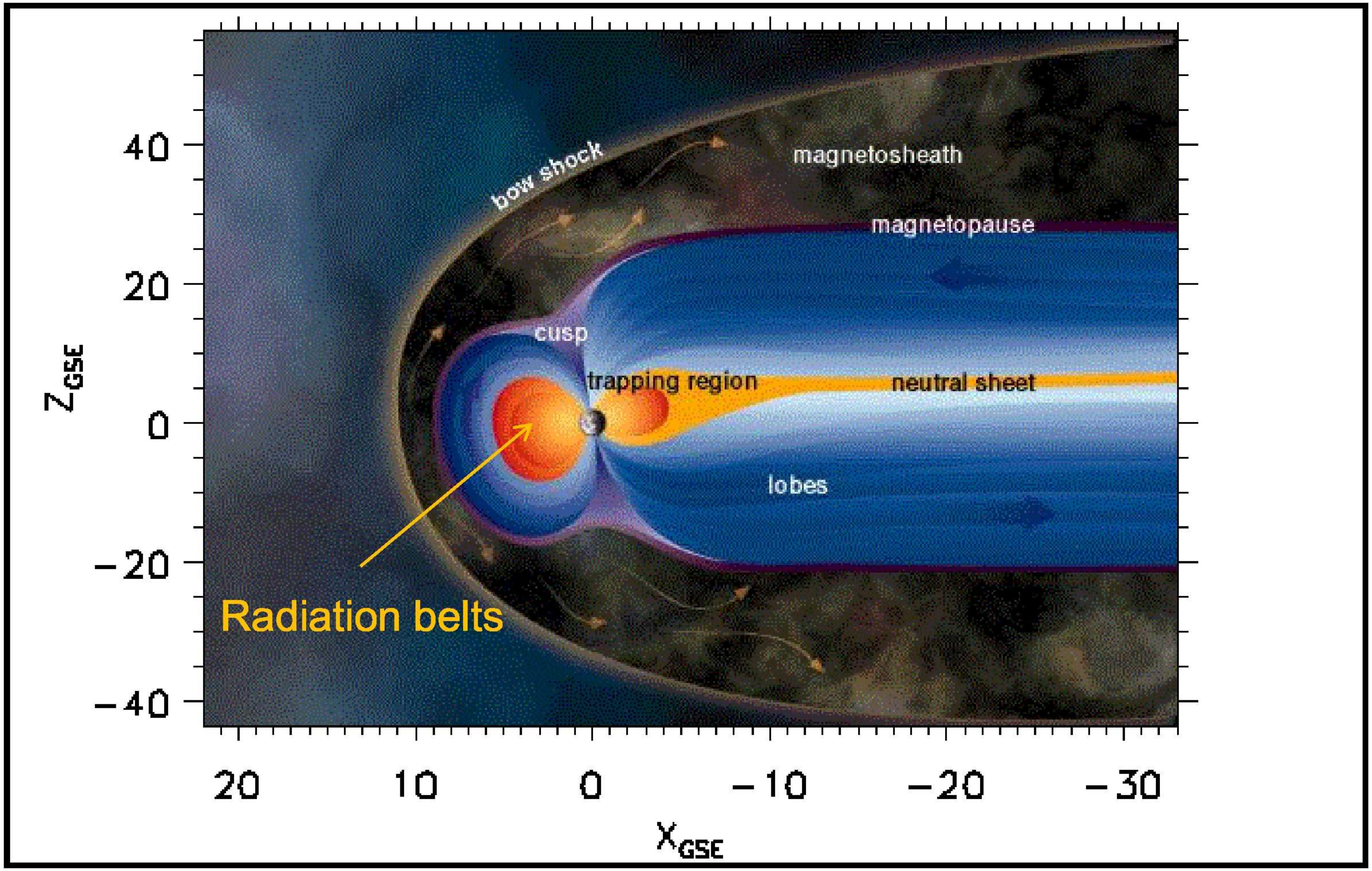
- Magnitude of radiation effects issues depend on mission specific exposure environments:
  - Particle flux
  - Particle fluence (exposure duration)
  - Spatial variations in environment
  - Temporal variations in environment

**Environments**

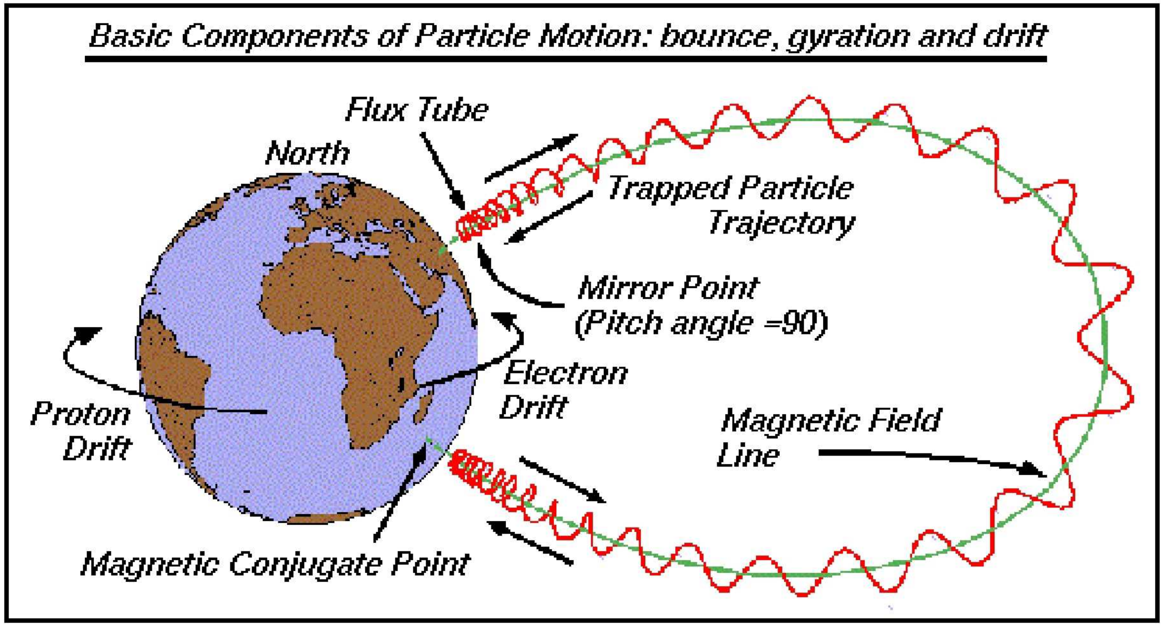
Radiation Effects

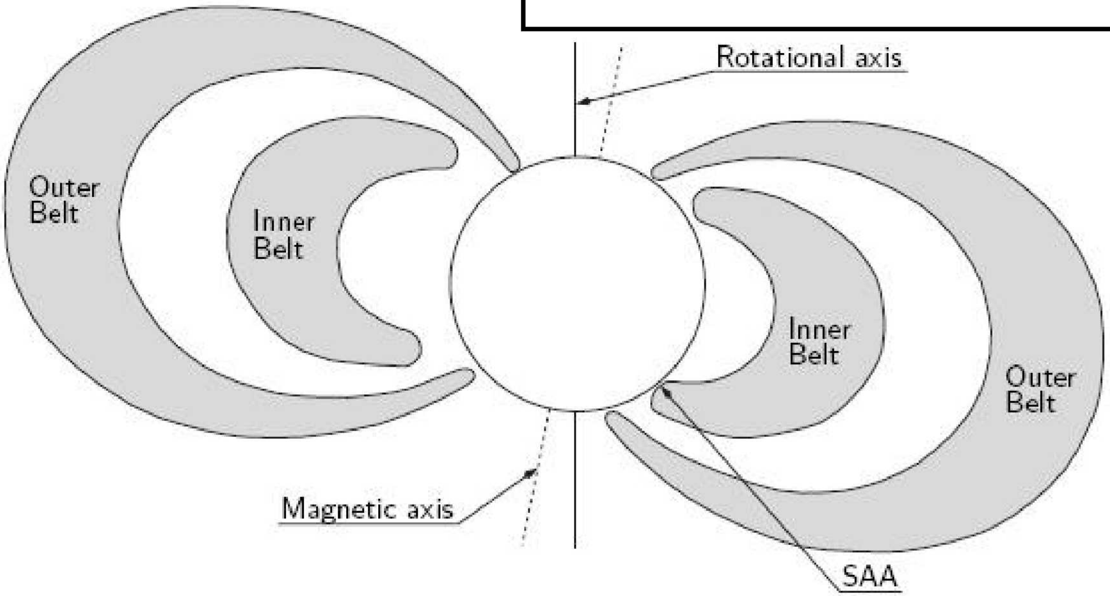
Spacecraft Charging

# Magnetosphere

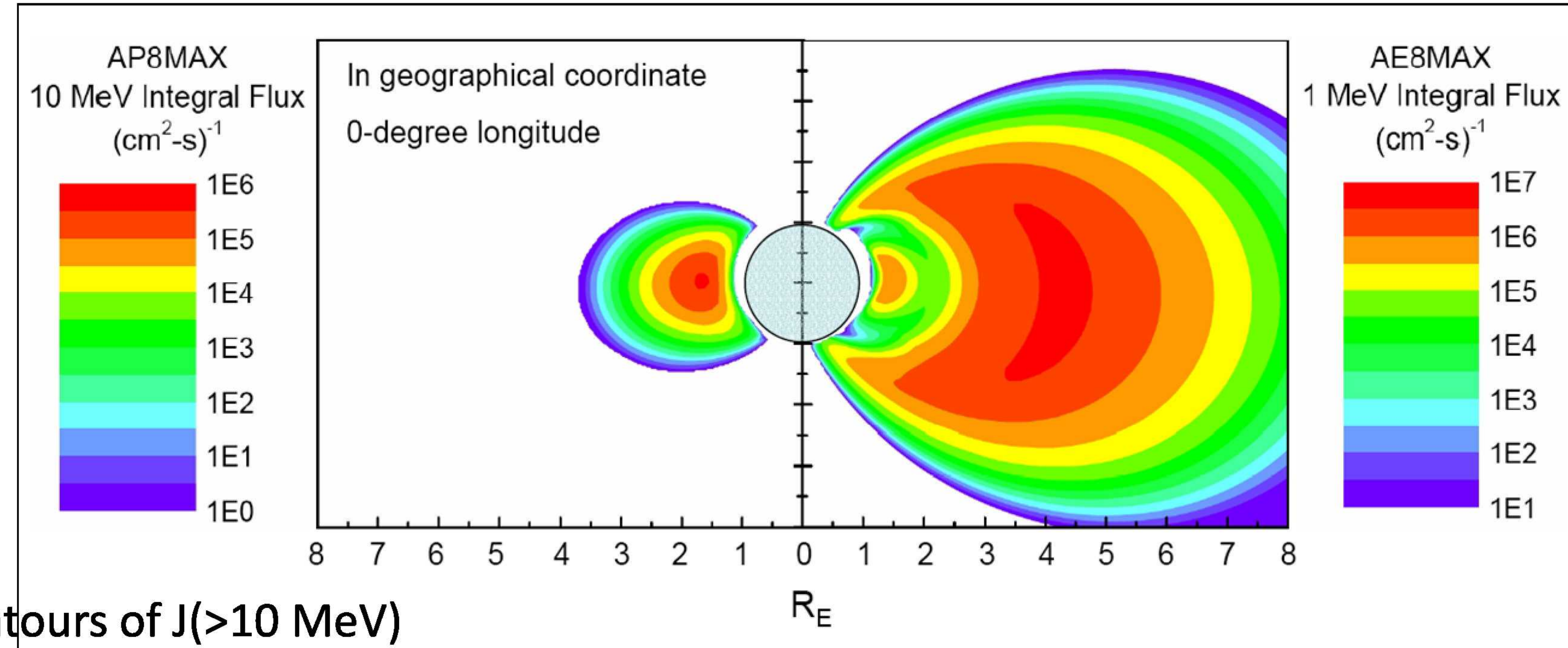


# Radiation Trapping in Magnetic Field



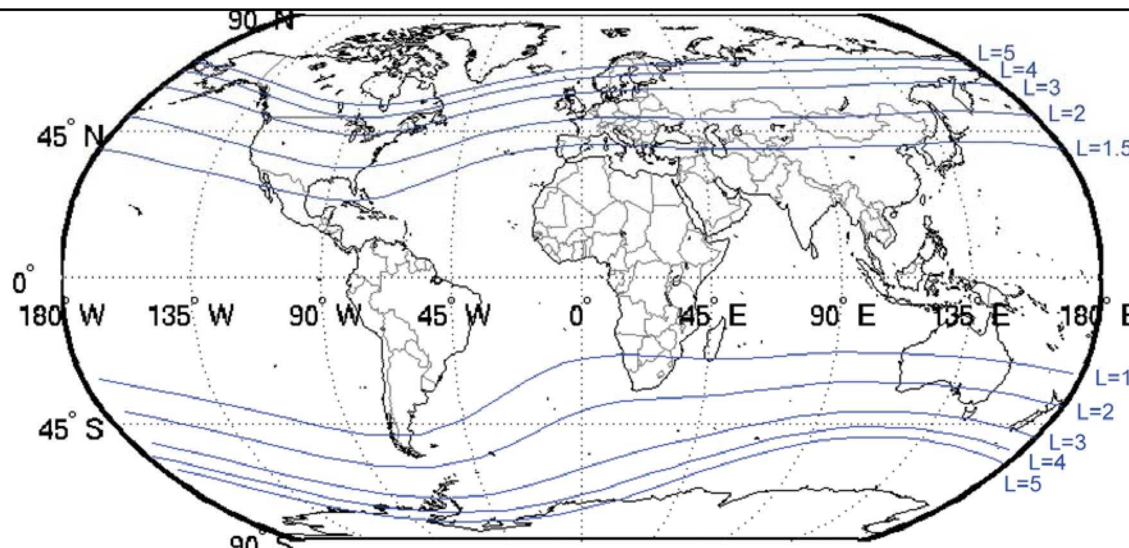



# AP-8/AE-8 Trapped Radiation Models



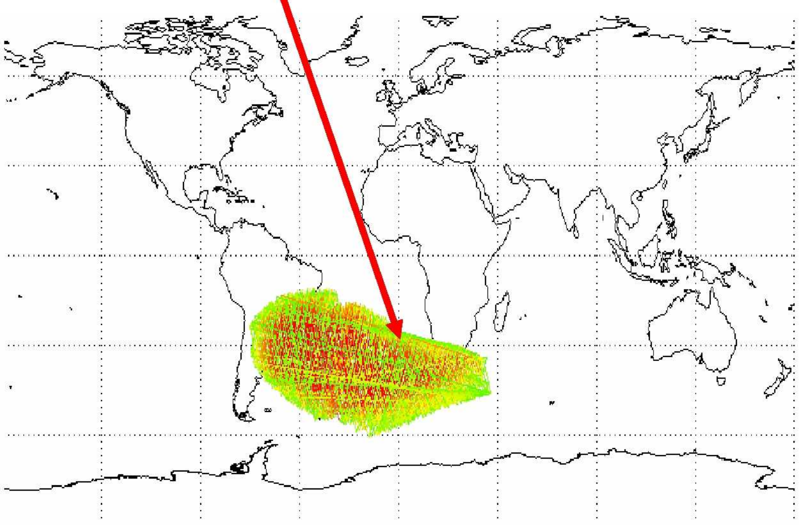

- Contours of J(>10 MeV) proton flux and J(>1 MeV) electron flux in 0° meridian plane

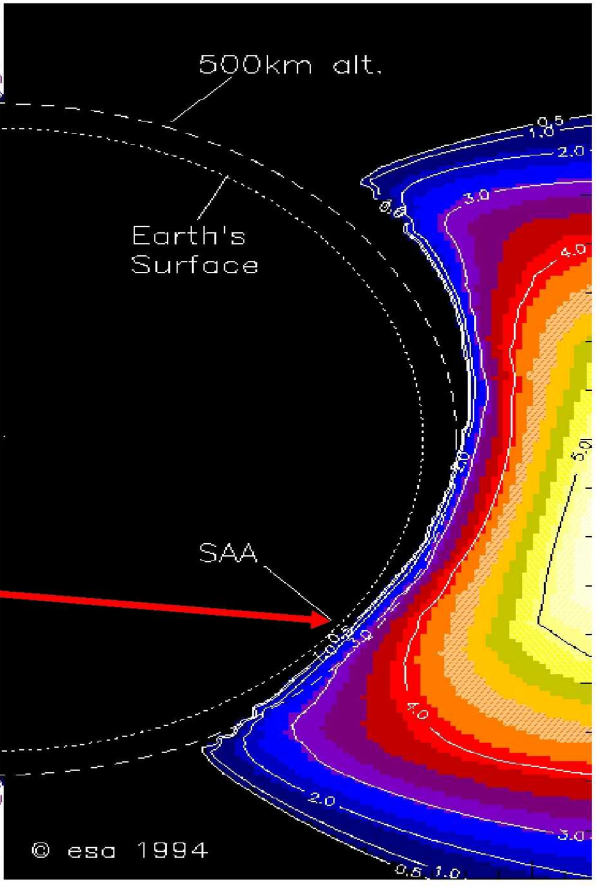
- L-shells mapped to Earth's surface



# South Atlantic Anomaly

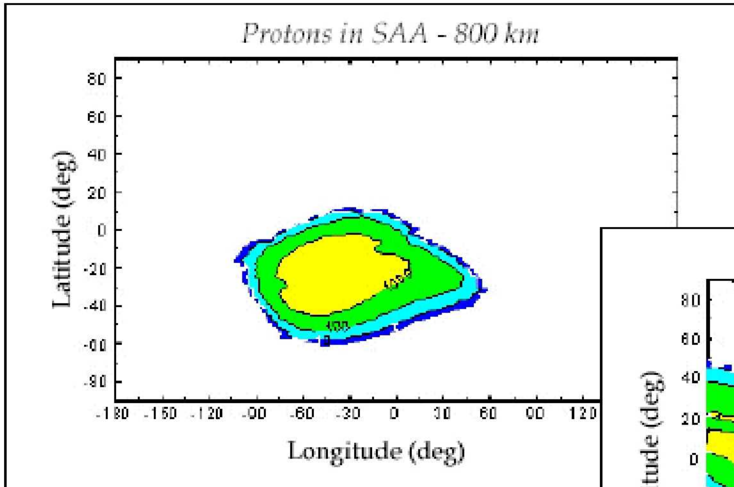
- Magnetic dipole field is
  - –tilted ~11° from Earth's rotation axis
  - –shifted by ~400 km from center of the Earth
- Combined effect of tilt and offset moves region of strong field towards Earth on one side of Earth and away on the other
- Weak field region is the South Atlantic Anomaly



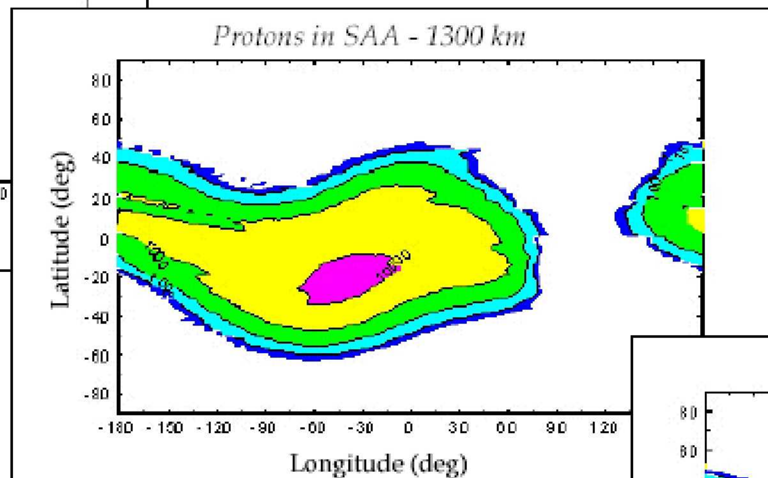


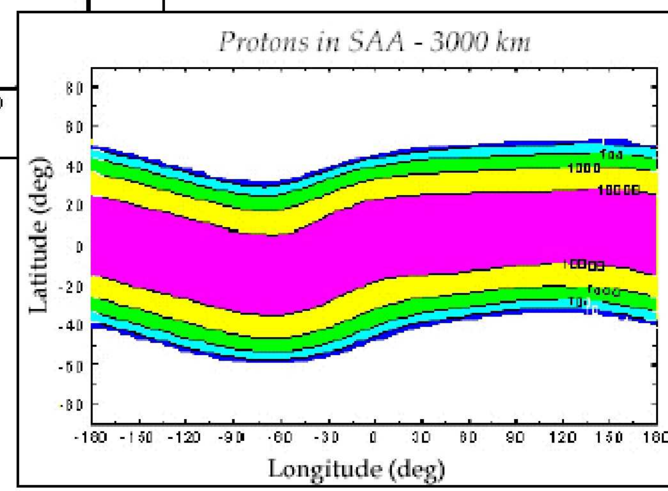

Low Earth orbit spacecraft exposed to enhanced flux in SAA

# South Atlantic Anomaly – Altitude Variation




Proton flux contours at 800 km define an oval SAA region

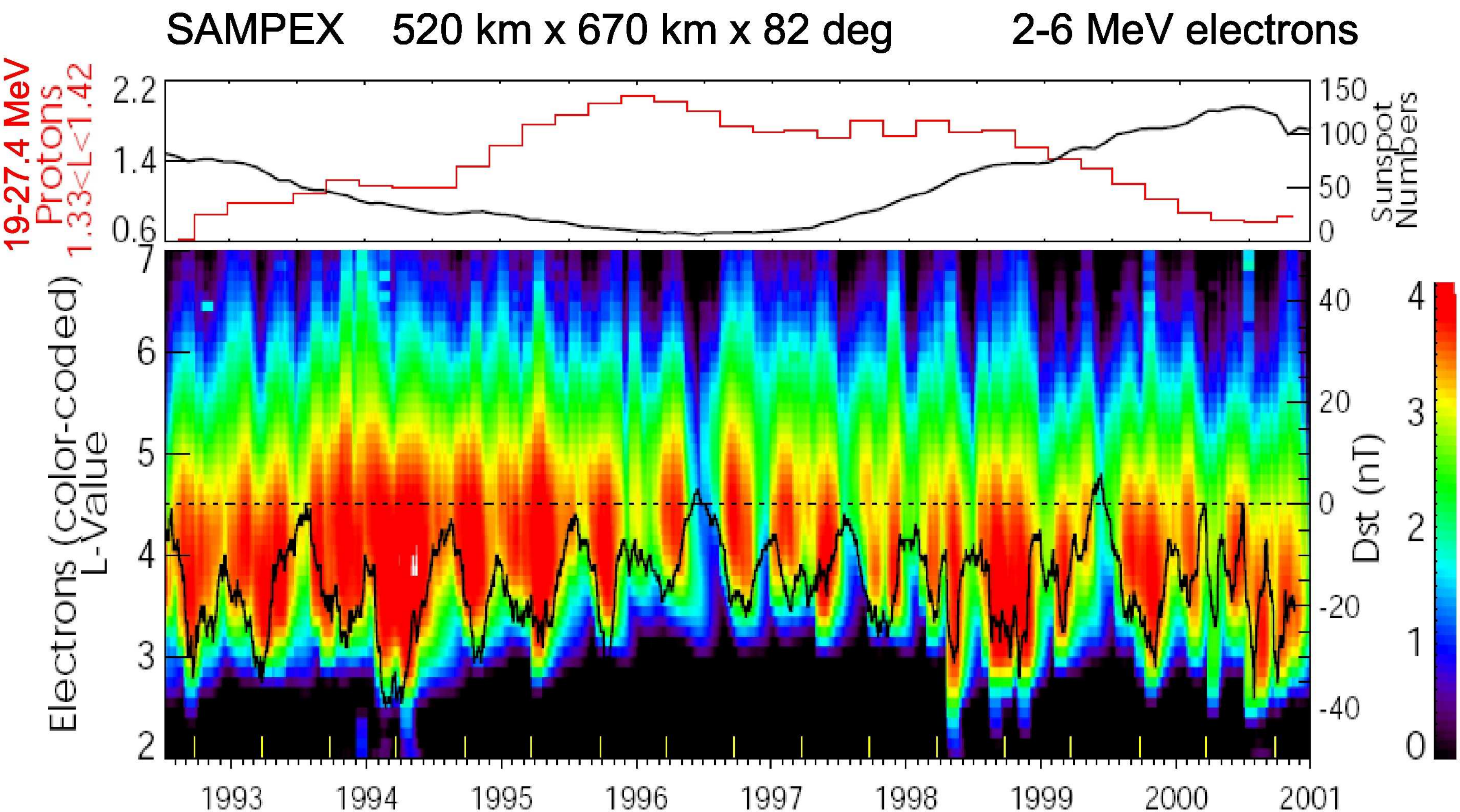



Proton flux contours at 3000 km exhibit the radiation belt structure

(adapted from Barth and Gorsky, 1999)

# Outer Electron Belt Solar Cycle Variation

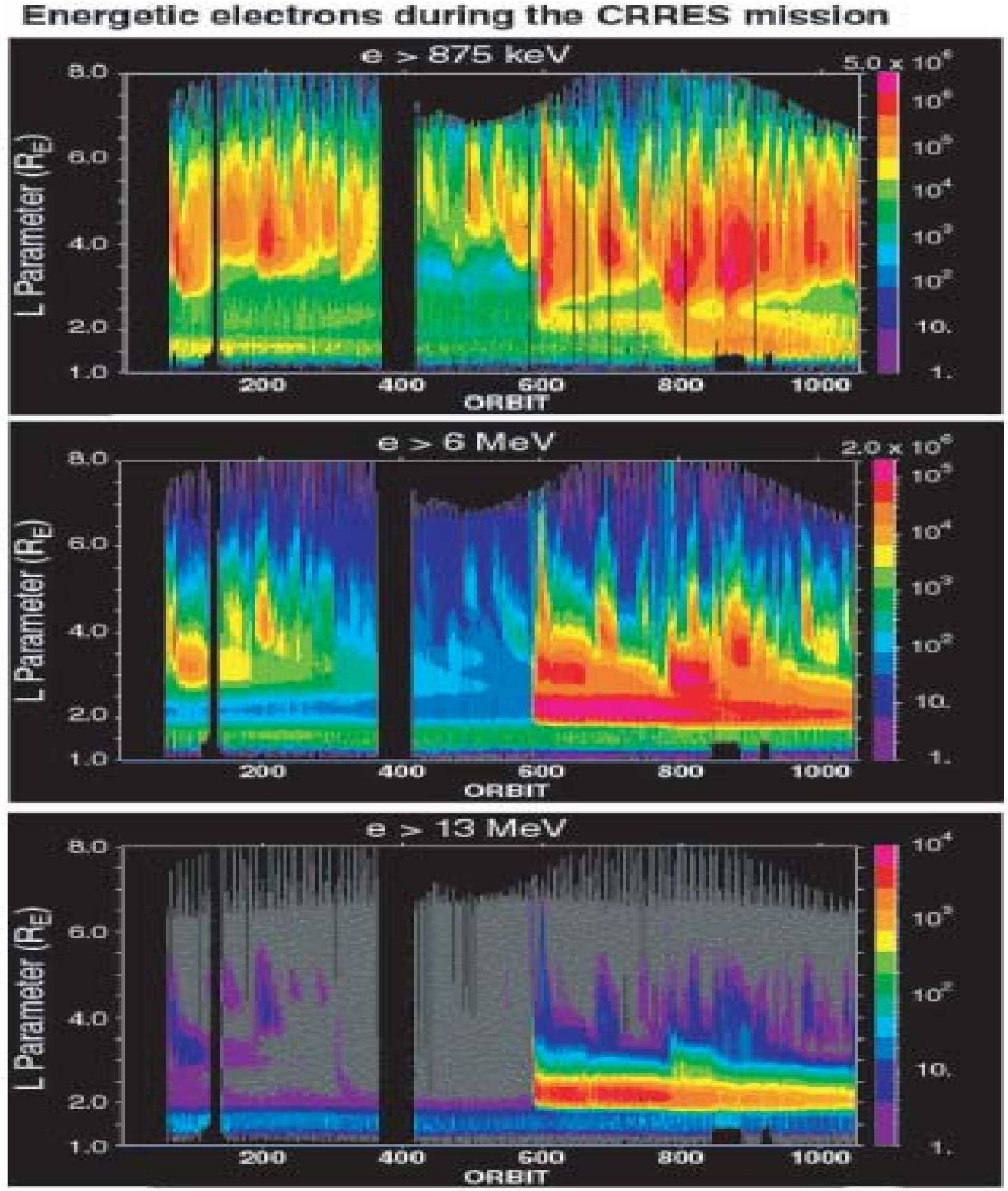



[adapted from Li et al., 2006]

# Electron Flux Variability

- Combined Radiation and Release Experiment Satellite (CRRES)
  - 350 km x 33584 km x 18.1°
  - July 1990 – Oct 1991

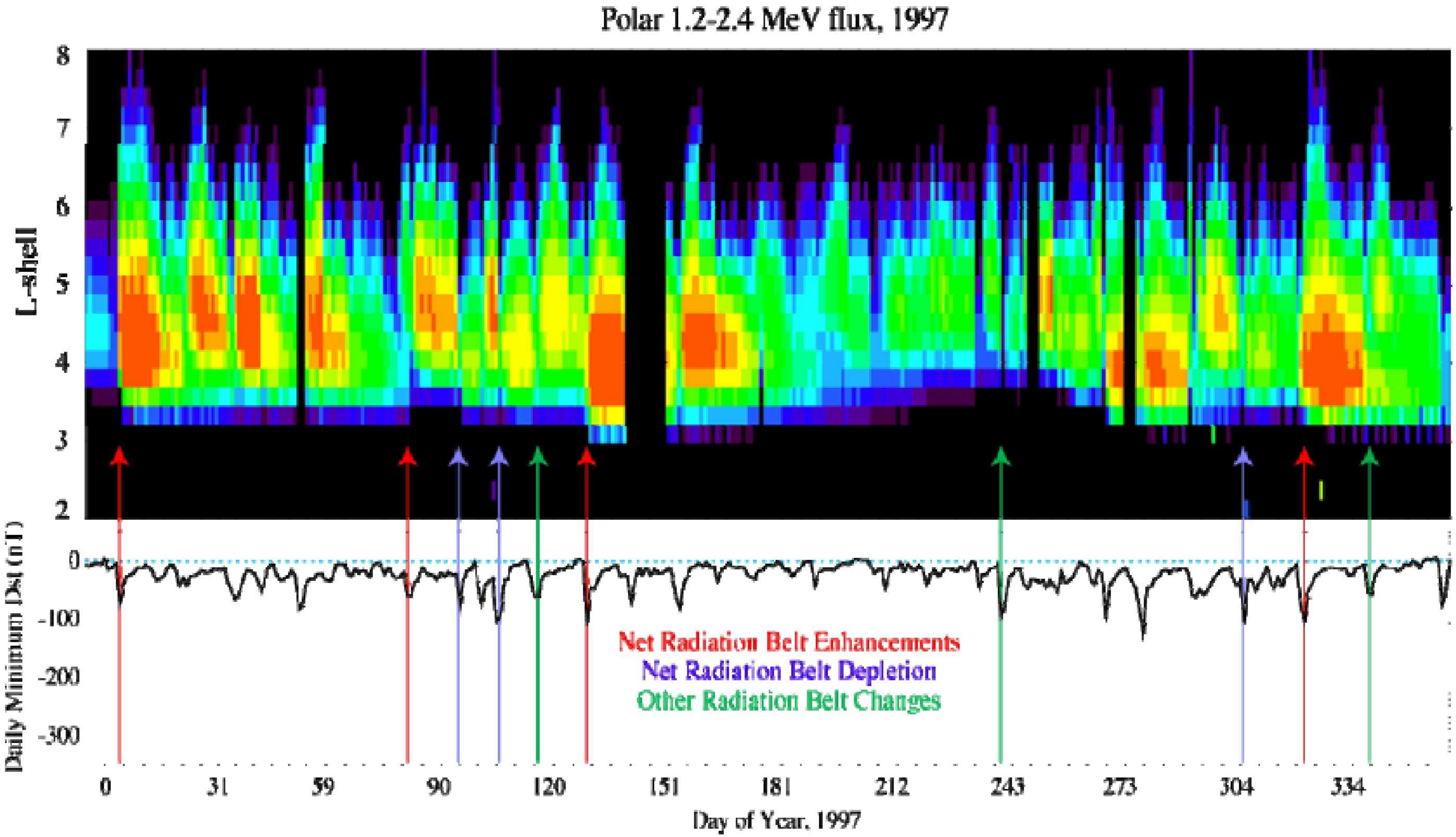
- Integrated integral electron flux mission summary
  - Electron flux most variable in outer radiation belts
  - Formation of an inner radiation belt following a geomagnetic storm in March,1991.




http://project.fdam.ca:7000/fdam/Wiki.jsp?page=MandateRadiationBelts

# Radiation Belt Enhancements, Depletions

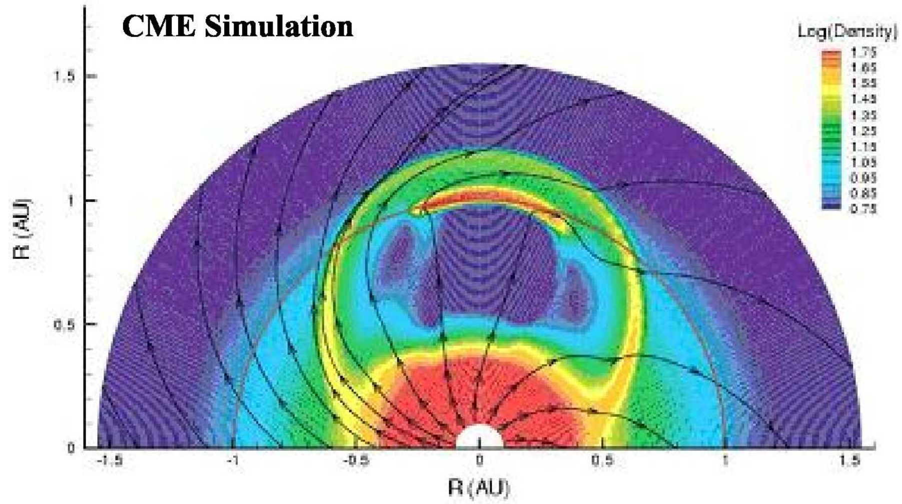
Polar 1.7 Re x 9 Re x 90°

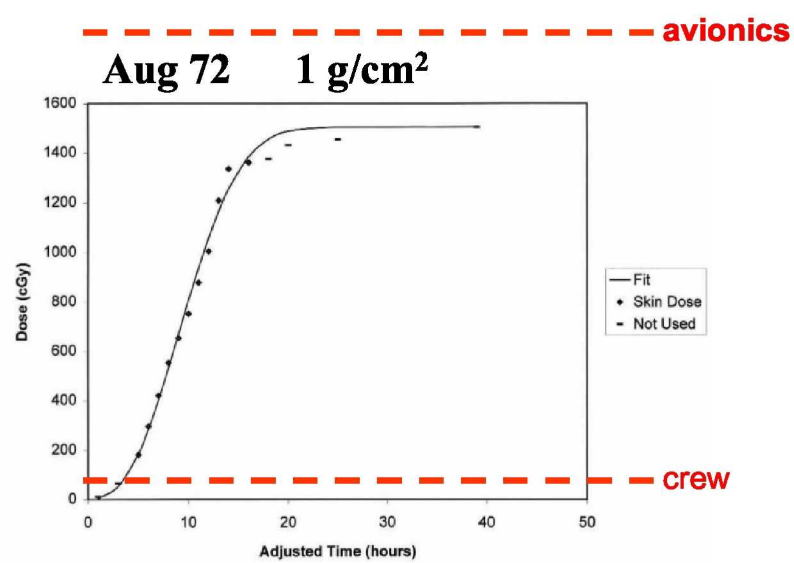


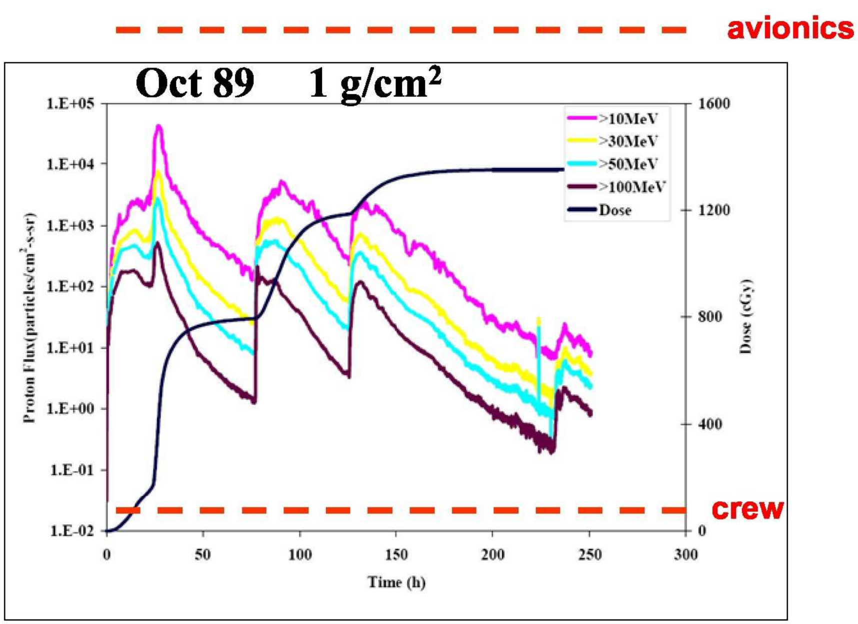

[Reeves, 2007]

# Flares, CME's

- Impulsive events
  - Minutes to hours
  - Electron rich
  - ~1000/yr at solar max
- Gradual events
  - Days
  - Proton rich
  - ~100/year

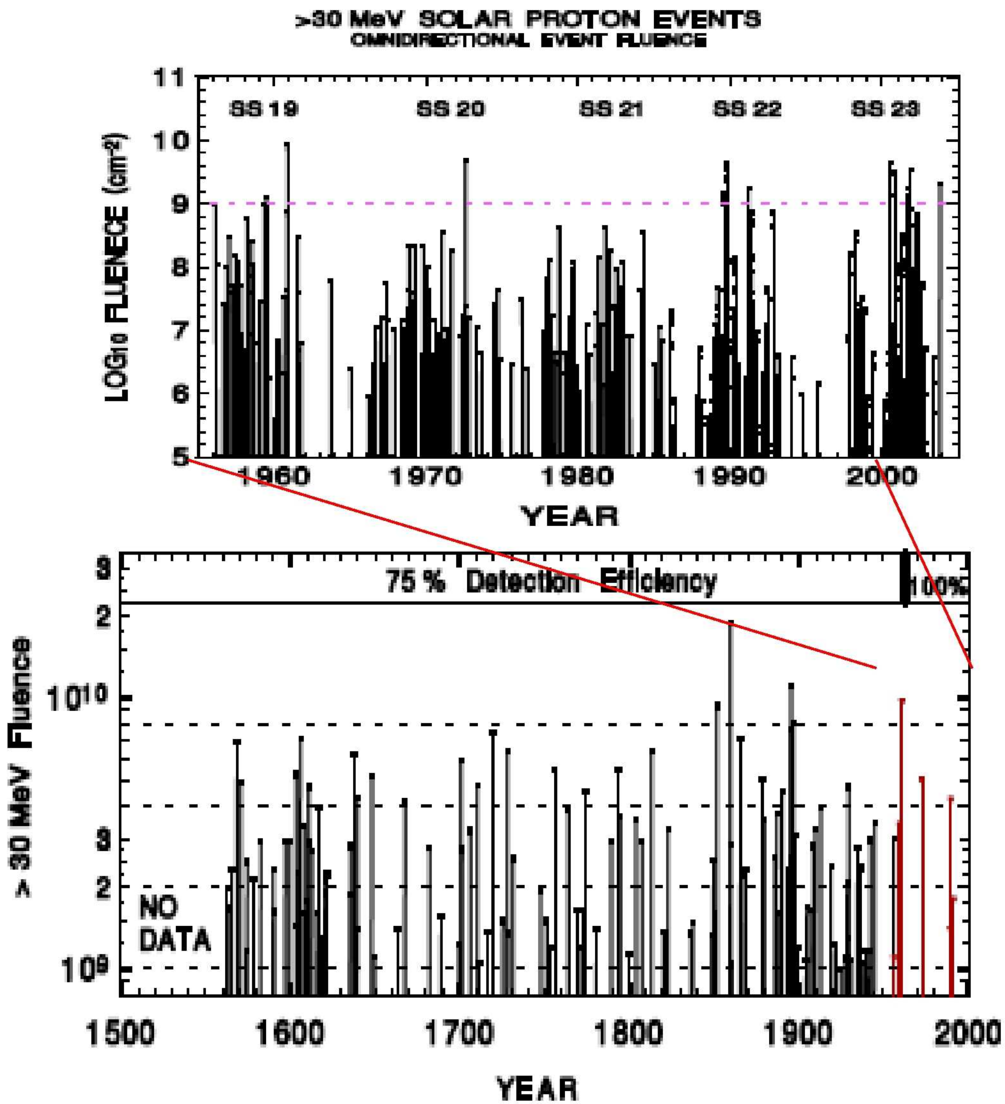


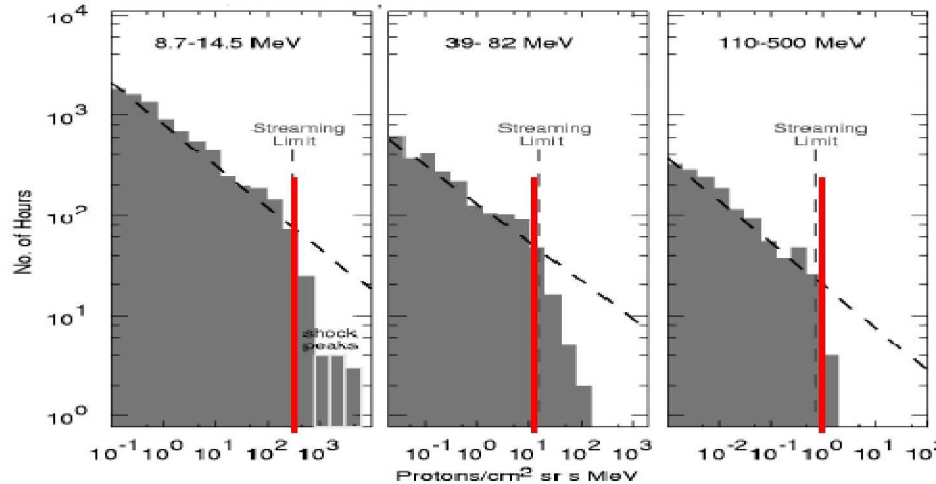
# How Large do Solar Particle Events Get?

- SPE events with >30 MeV fluence exceeding $10^9$ p/cm2 are major hazards and occur a few times per solar cycle
- NOx proxy for >30 MeV proton fluence provides extreme event history over multiple solar cycles for period ~400 years
- Ice core data shows 1859 Carrington event to be the largest in ~400 years
  - 4x October 1989 event
  - Carrington event is also consistent with Emission of Solar Proton (ESP) model worst case event
- Long time series of historical records and ice core proxy have been important in establishing extreme levels for solar proton events



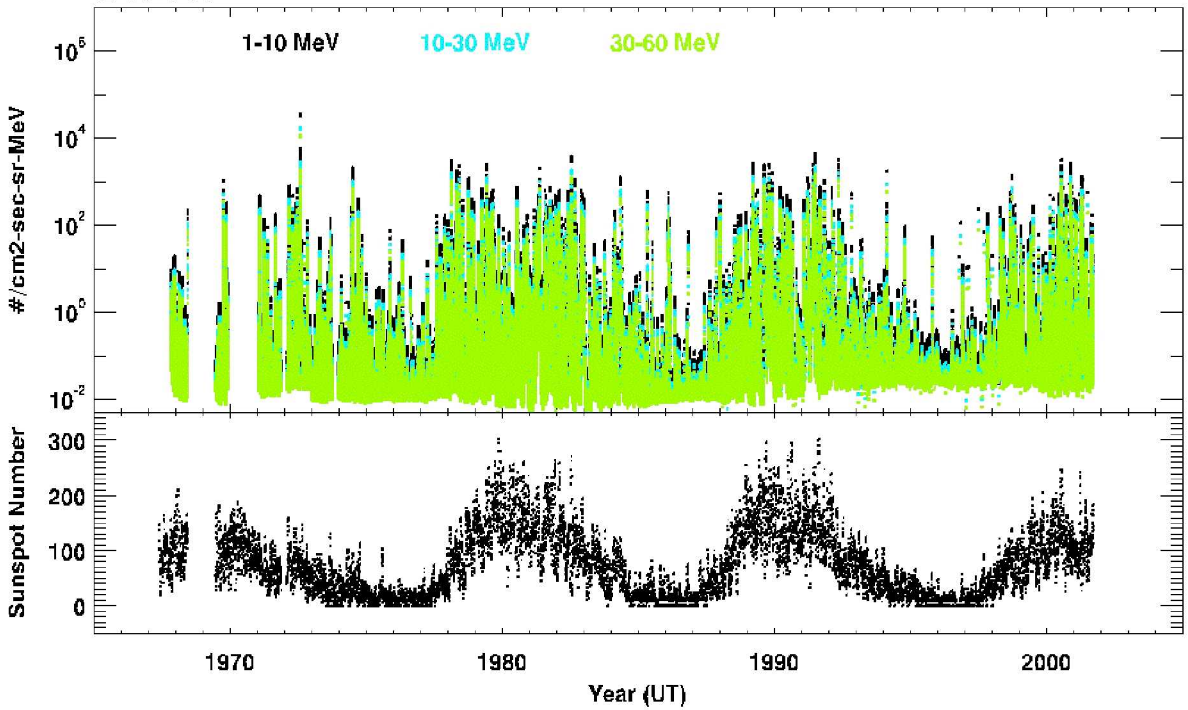
# Streaming Limits

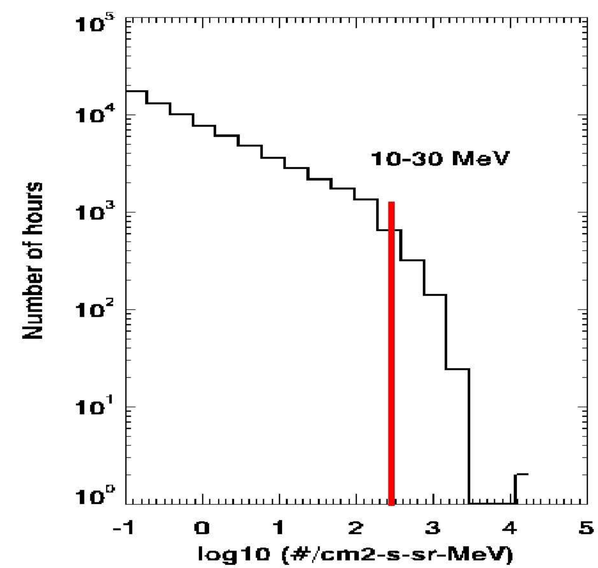
- Streaming limits appear to hold for single or multiple solar cycles
- Provides confidence in sufficiently conservative design limits without over design




~ 1 solar cycle

OMNI




~ 3 solar cycles

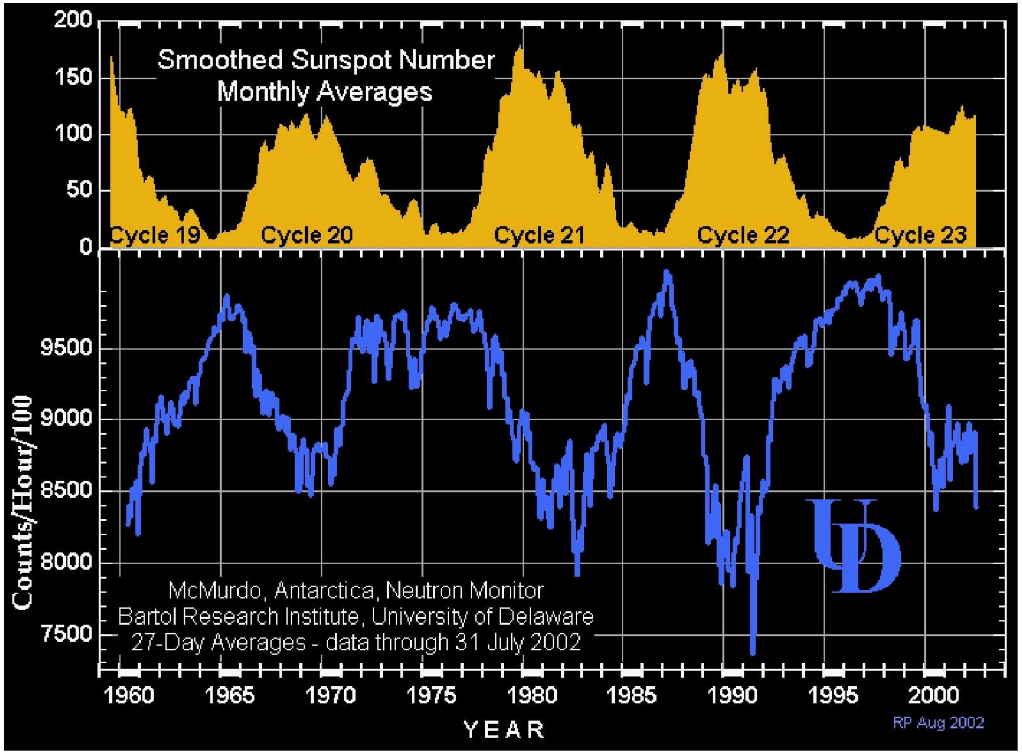
# Galactic Cosmic Rays

- Charged particles ejected in supernovae explosions
  - Accelerated in galactic magnetic fields to very high energies
- Protons, heavy ions, electrons

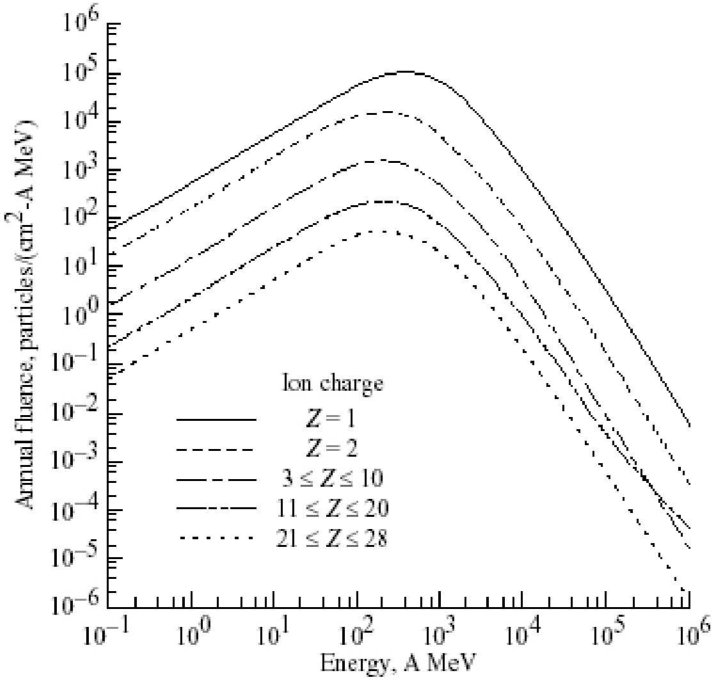
- Solar maximum indicated by peaks in sunspot number

- Neutrons produced by cosmic ray interactions indicated cosmic ray flux

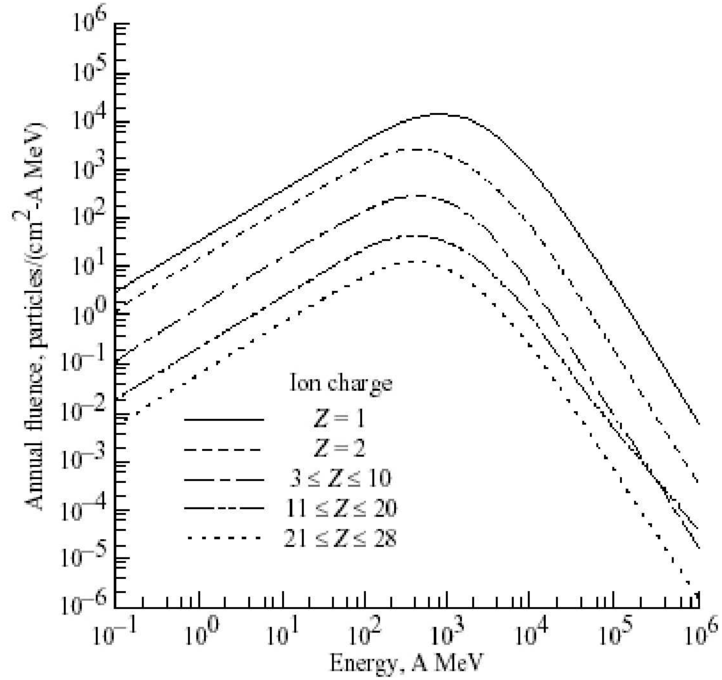
- Anti-correlated with solar cycle



# Galactic Cosmic Ray Spectra




(a) GCR ion fluence for 1977 solar minimum.




(b) GCR ion fluence for 1981 solar maximum.

Z = 1 hydrogon (protons)

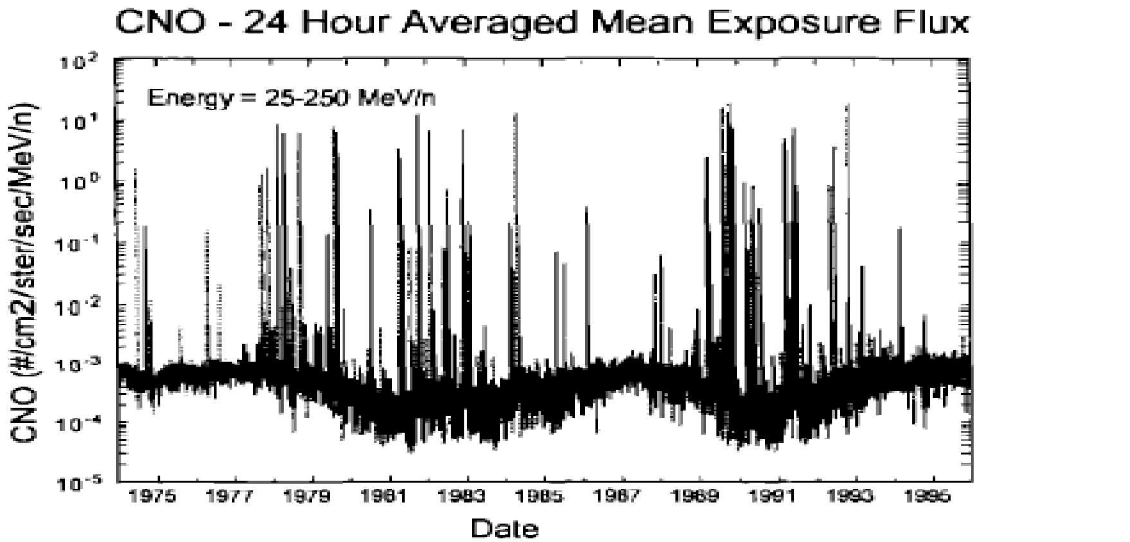
Z = 2 helium ($\alpha$ particle)

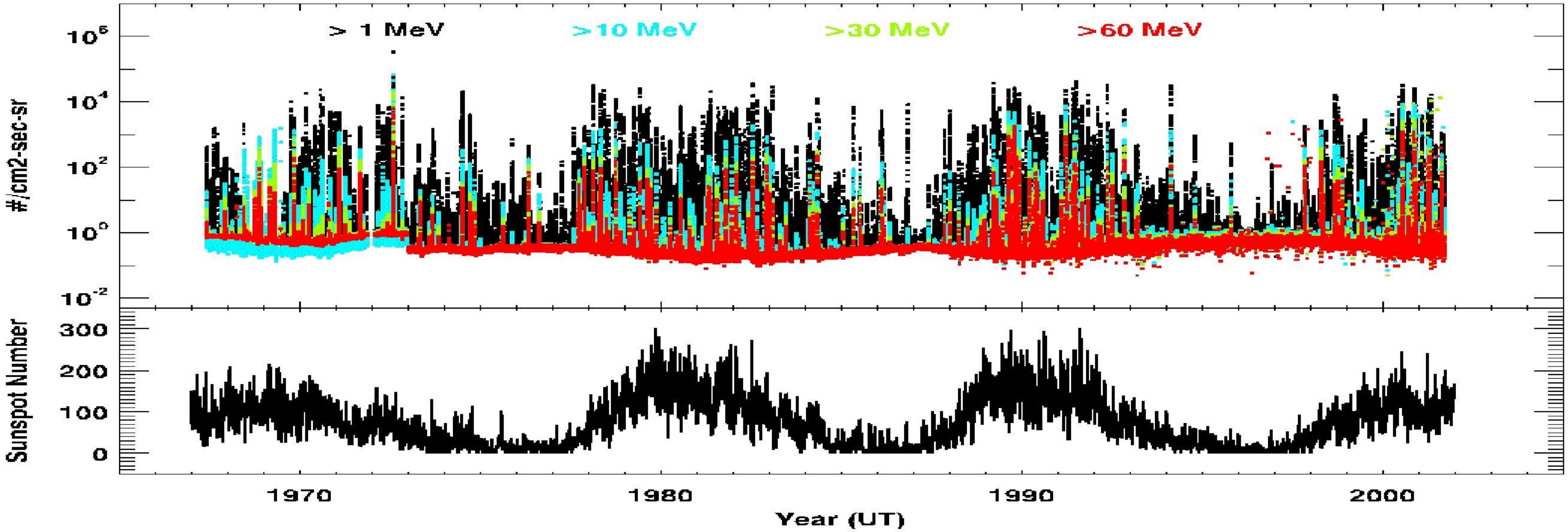
3≤ Z ≤ 10 includes "CNO", Z=6,7,8

(Wilson et al., 1997)

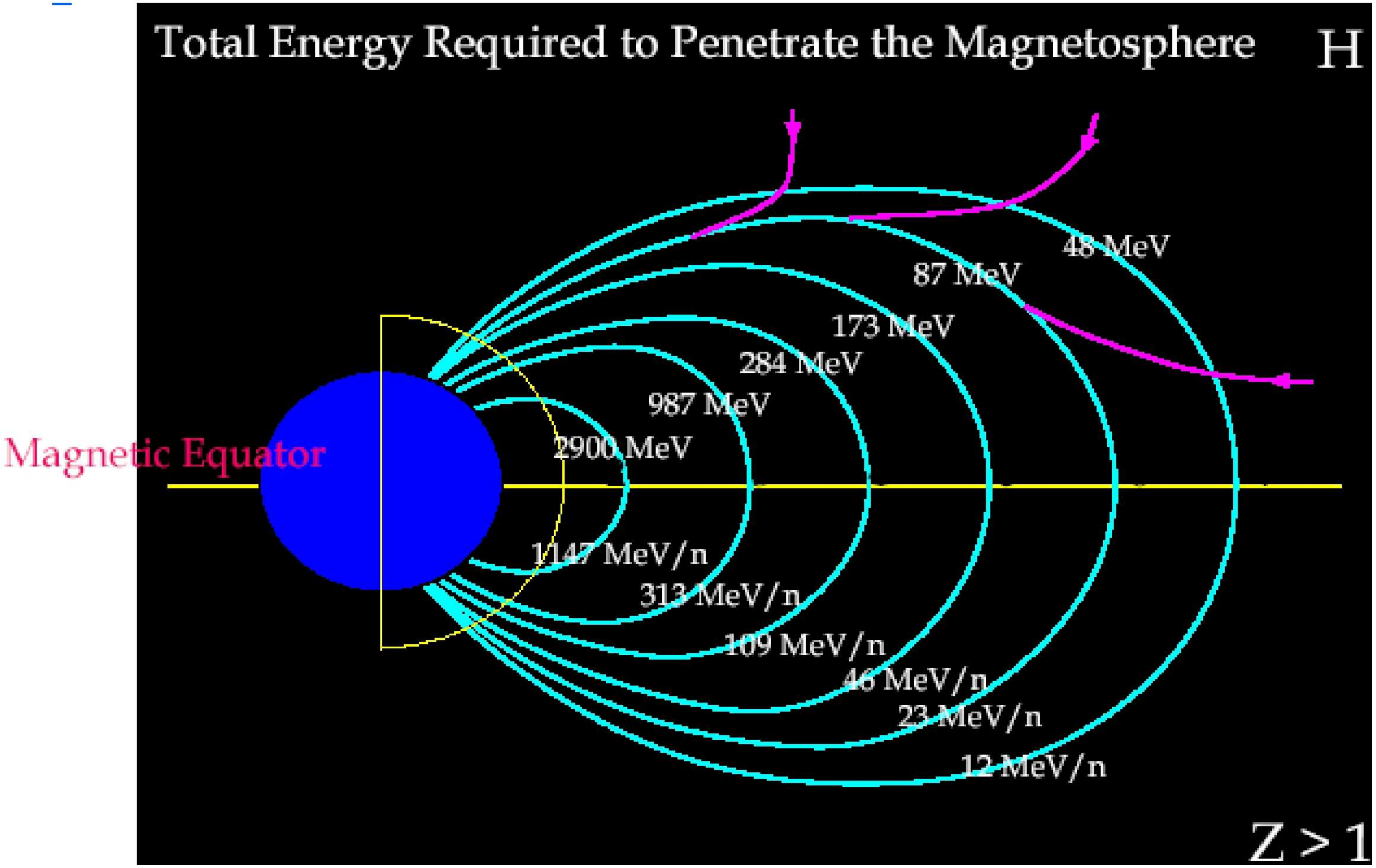
# GCR, SEP Solar Cycle Variation

- GCR
  - Anti-correlated with solar cycle
  - Small variation
- SEP
  - Correlated with solar cycle
  - Large variation



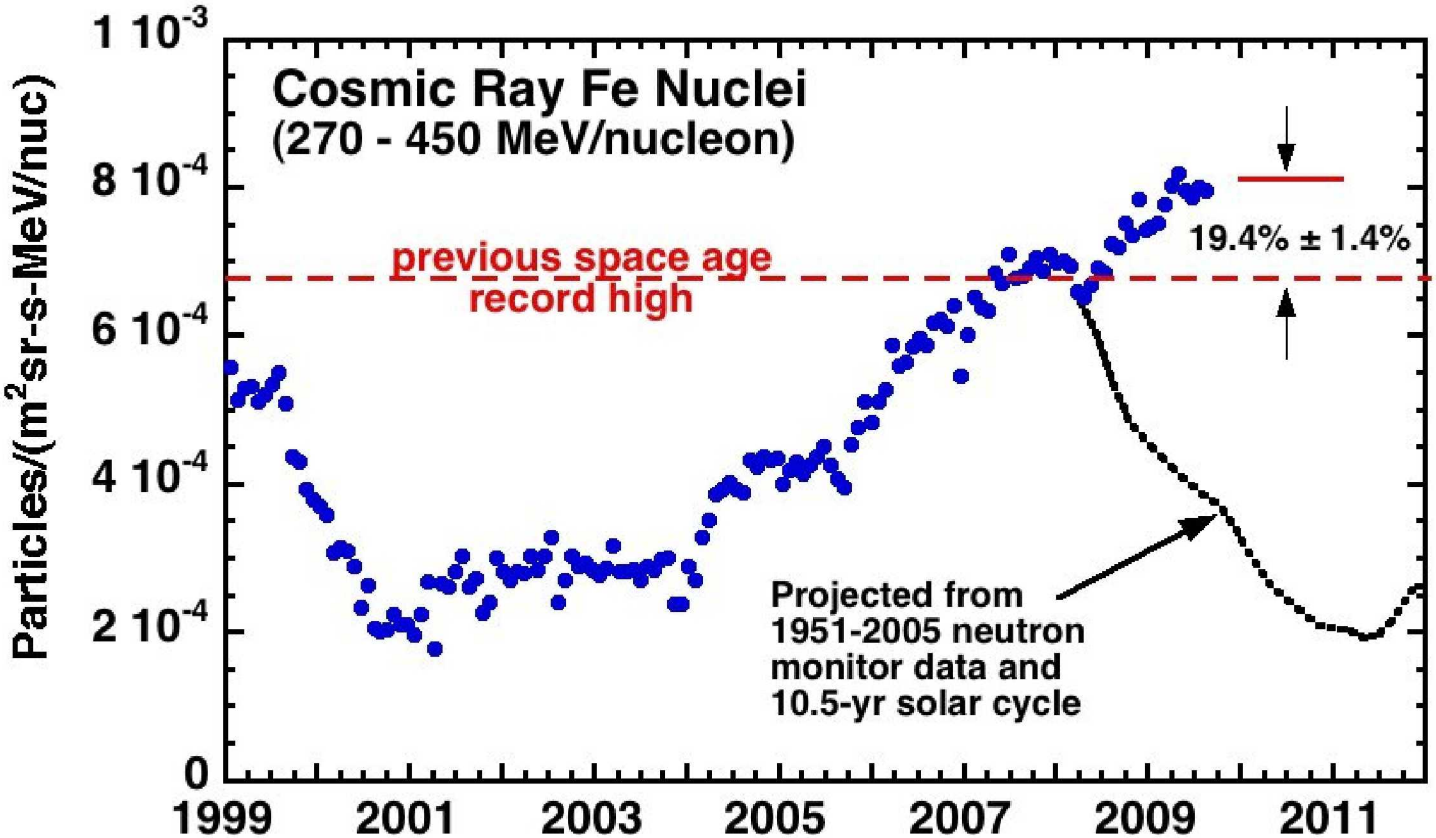



# Ion Penetration of Magnetosphere




Earth's magnetic field provides shielding from SPE, GCR particles

# Current Cosmic Ray Flux




http://science.nasa.gov/headlines/y2009/29sep_cosmicrays.htm

Environments

**Radiation Effects**

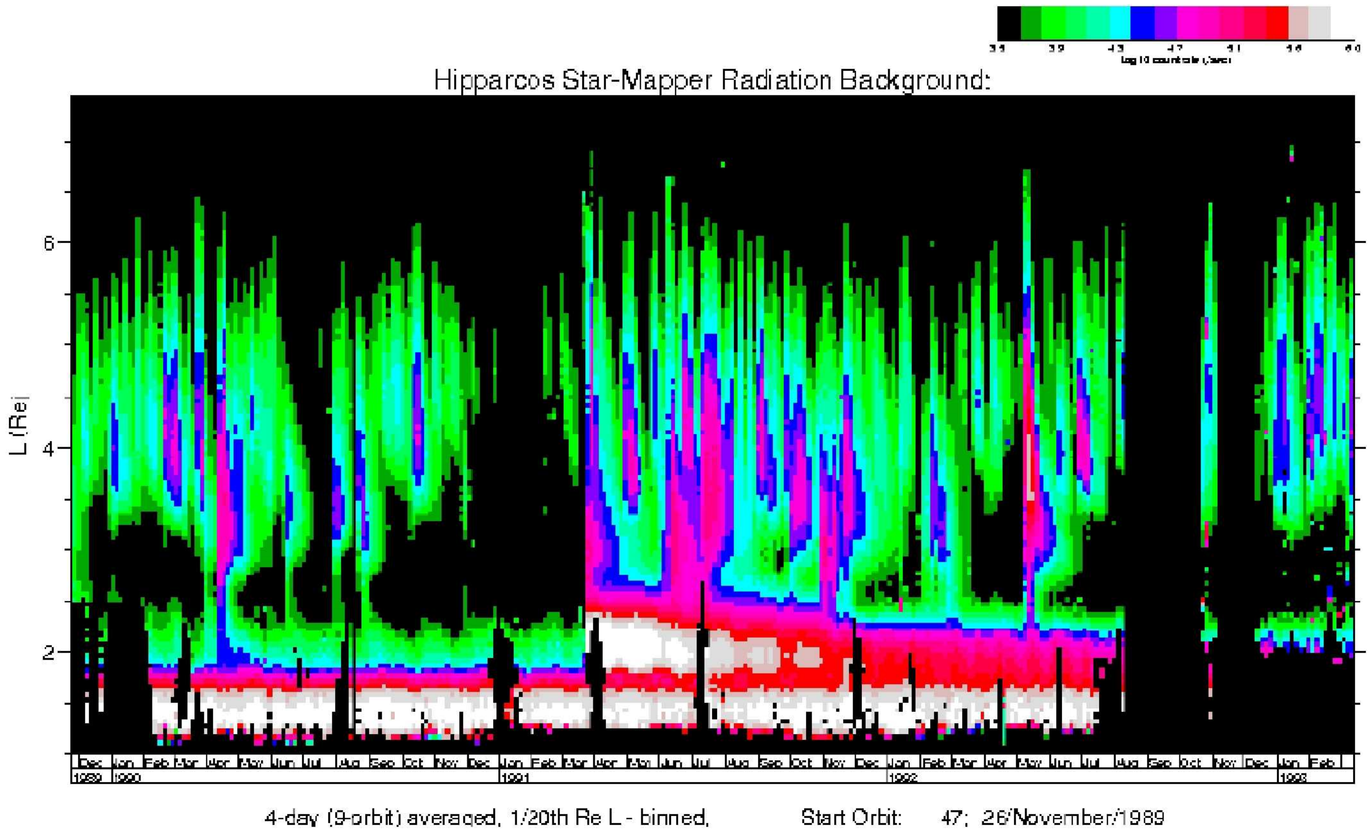
Spacecraft Charging

# Radiation Effects

- Total Ionizing Dose (TID) and Displacement Damage Dose (DDD)
  - Performance degradation of electronics, materials due to the cumulative exposure to ionizing radiation
  - Observed effects range from increased power consumption to parametric failure to complete failure of components to successfully function

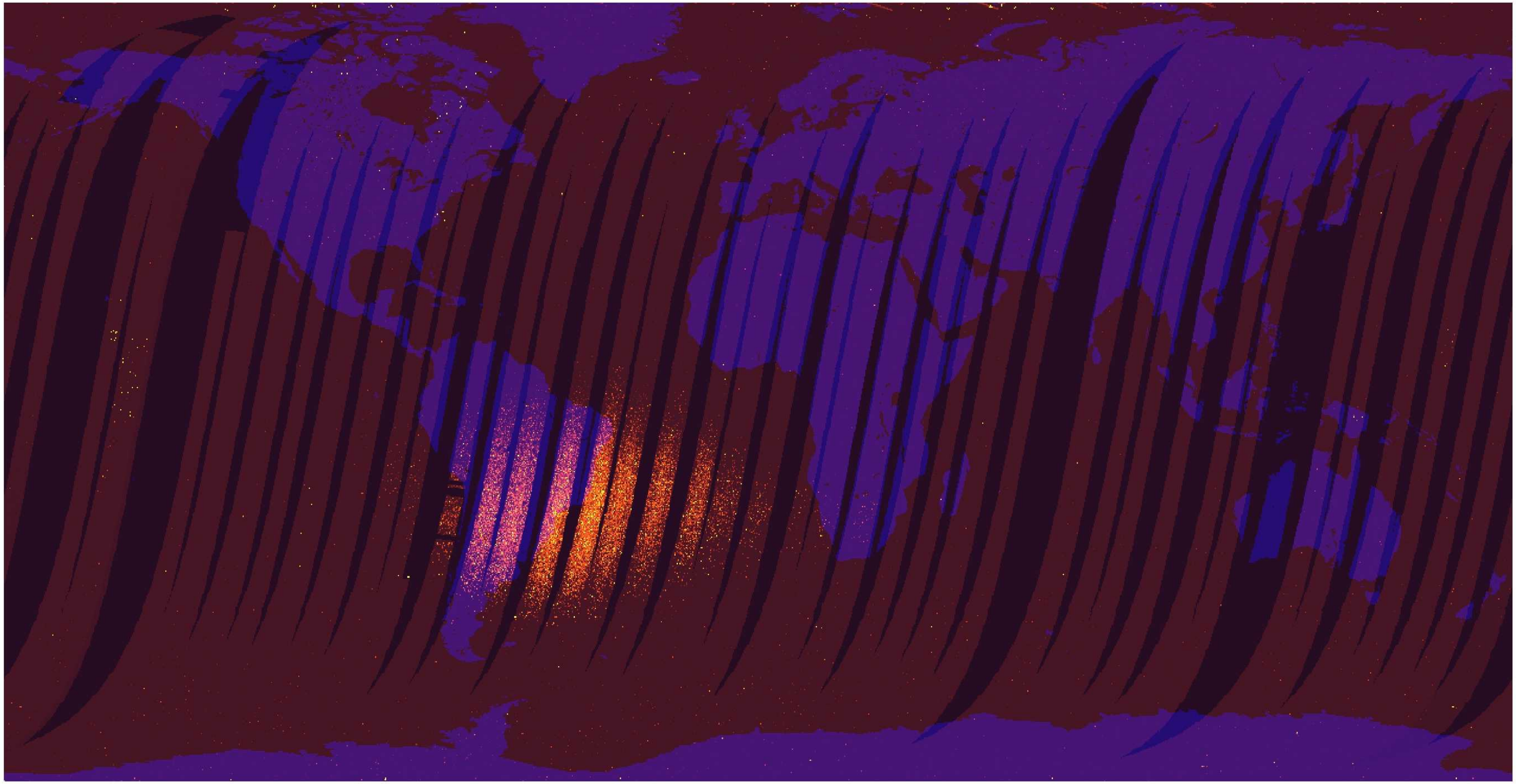
- Single Event Effects (SEE)
  - Effect generated by charge deposition during passage of a single particle through a sensitive region of an electronic device
    - Effects range from transient currents which simply change state in bipolar devices and change of state in dynamic memory to catastrophic failure of components due to high currents
  - The types of effects are almost as numerous are there are device types
  - They range from Upsets (SEU) to Transients (SET, both analog and digital) to Functional Interrupts (SEFI) for non-destructive effects
  - They range from Latchup (SEL) to Burnout (SEB) to Gate Rupture (SEGR) for destructive effects
  - Transient noise in CCD imagers

# Star-Mapper Radiation Background



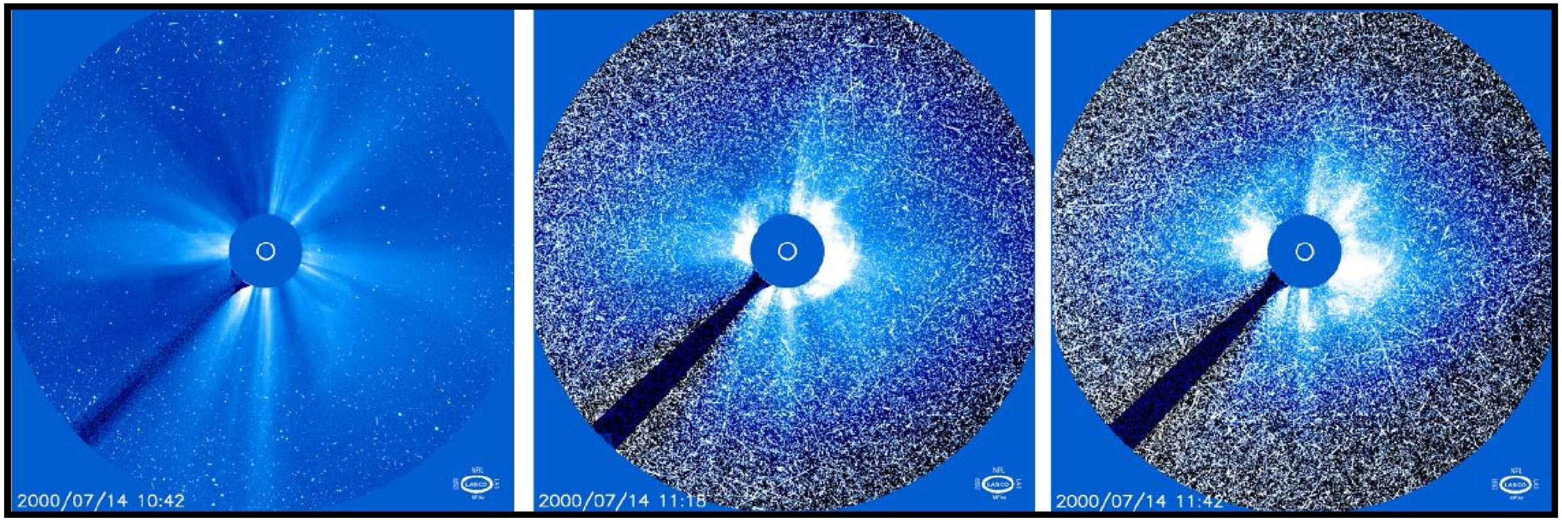
# CCD Radiation Response

- **MISR instrument CCD response from the EOS - Terra spacecraft before cover was opened**



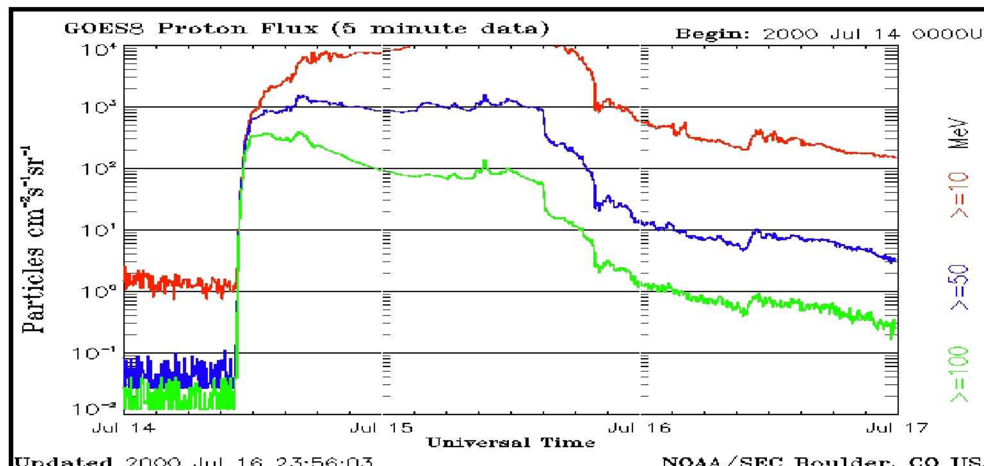
(Image courtesy MISR Science team
from http://eosweb.larc.nasa.gov/HPDOCS/misr/misr_html/darkmap.html)

# CCD Noise

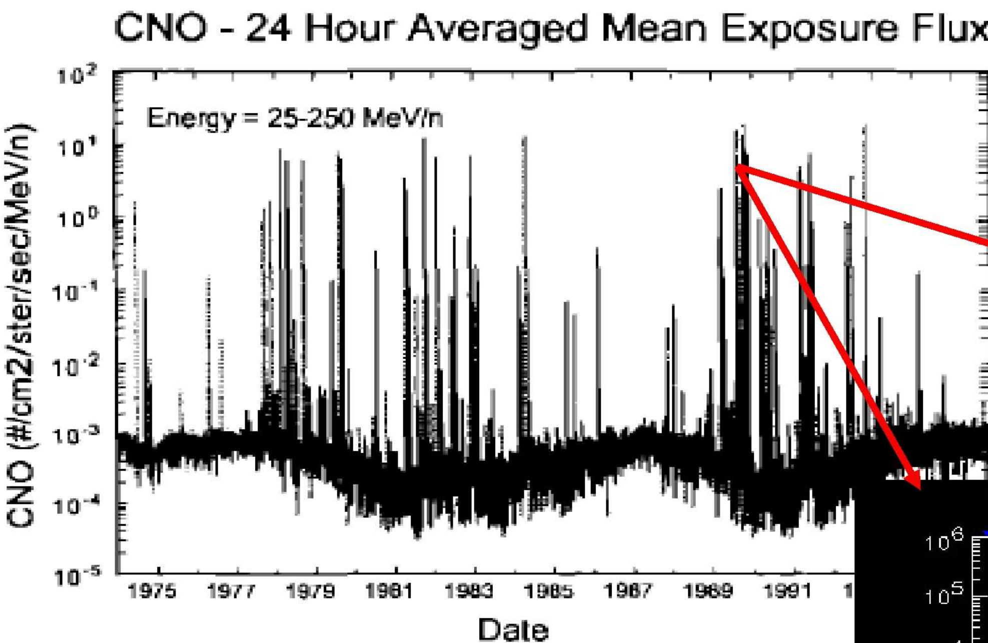



**10:42 UT** **11:16 UT** **11:42 UT**

**14 July 2000 "Bastille Day Event"**

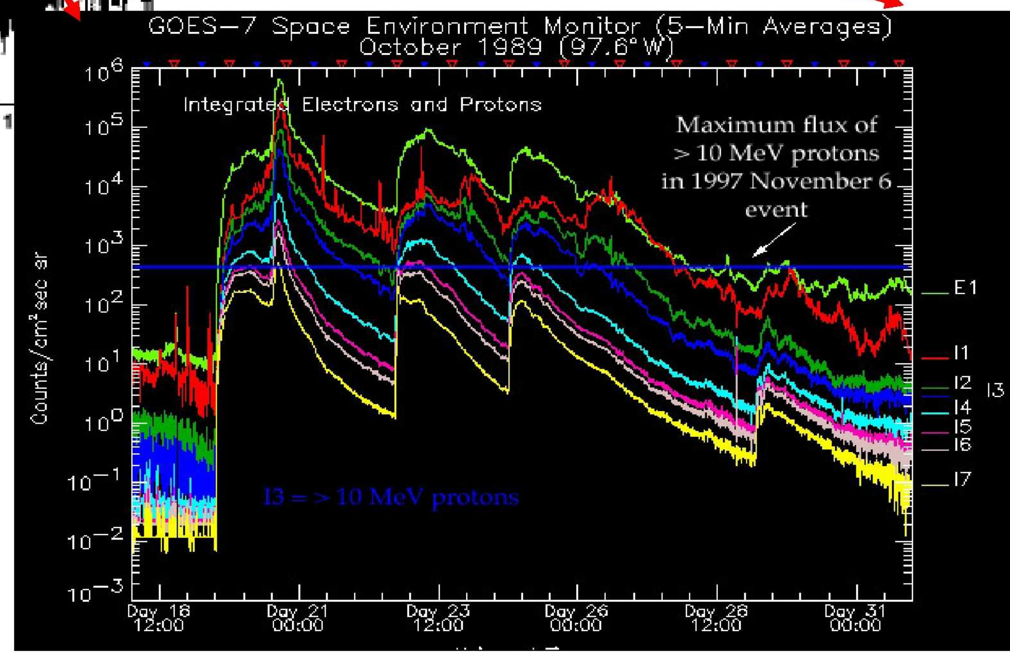


# Solar Particle Event ("Flare") Environments



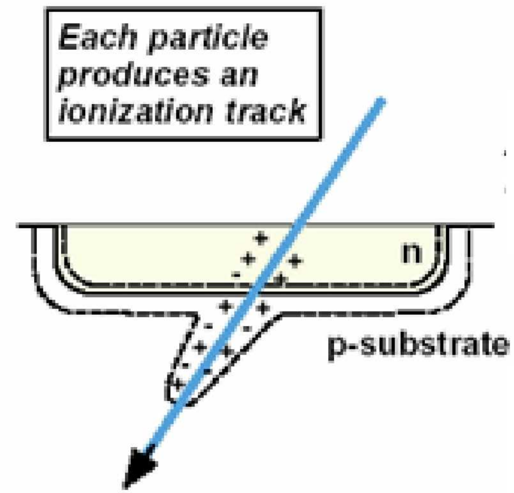

Example flux and duration of large proton solar particle event in October 1989

*IMP-8 interplanetary ions from the C-N-O group Episodic high flux solar particle events are superimposed on the slowly varying galactic cosmic ray background flux*



# Single Event Effects (SEE)

Single event effects (SEE) occur when charge deposited by an ion passing through the sensitive volume of a biased electronic device is of sufficient magnitude to change the operating state of the device.




Example SEE types include:

- **Single event voltage transient (SET):** self correcting but could cause system malfunction if propagated as a signal
- **Single event upset (SEU):** operating state change (e.g. memory bit upset)-errors in data and executable output if uncorrected
- **Single event latchup (SEL):** operation ceases-effect may be correctible by power cycling or part may be destroyed
- **Single event burnout (SEB):** part is destroyed by over-current

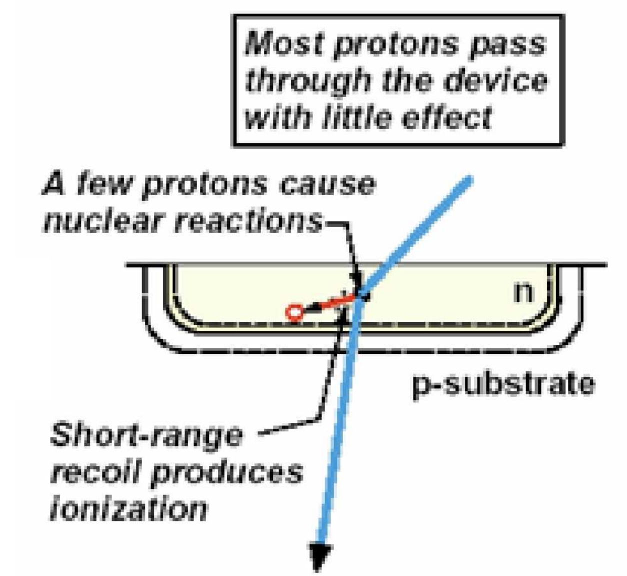
Single Event Effects Caused by Heavy Ions (Z=2-92)

- High linear energy transfer (LET) rate of heavy ions produces ionization along track as ion slows down
- Dense ionization track over a short range produces sufficient charge in sensitive volume to cause SEE
  --SEE is caused directly by ionization produced by incident heavy ion particles
    - Small contribution to SEE rates from secondary particles produced in inelastic collisions (small cross section for nuclear interactions and small flux of incident energetic particles)

# Proton Induced SEE Events

• Protons cause SEE through secondary particles produced in inelastic collisions with nuclei of atoms (usually silicon) inside electronics. Energy is transferred to a target atom fragment or recoil ion with high linear energy transfer (LET) and charge deposited by recoil ion(s) is the direct cause of SEE.

• LET spectra of recoil ions is a function of proton energy. Maximum LET from 200 MeV protons is ~12 MeV-cm2/mg. A small fraction of protons are converted to such secondary particles (1 in $10^4$ to 1in $10^5$).




Protons also lose energy through multiple <u>elastic collisions</u> with atoms encountered during passage through material:

• A very diffuse track of ionized atoms is produced. The low charge density in a device sensitive volume is unlikely to affect operation. LET of protons is far less than 1 MeV-cm$^2$/mg.

• Charge density deposited by protons within the sensitive volume of most electronic devices is too small to influence the device operating state and induce SEE

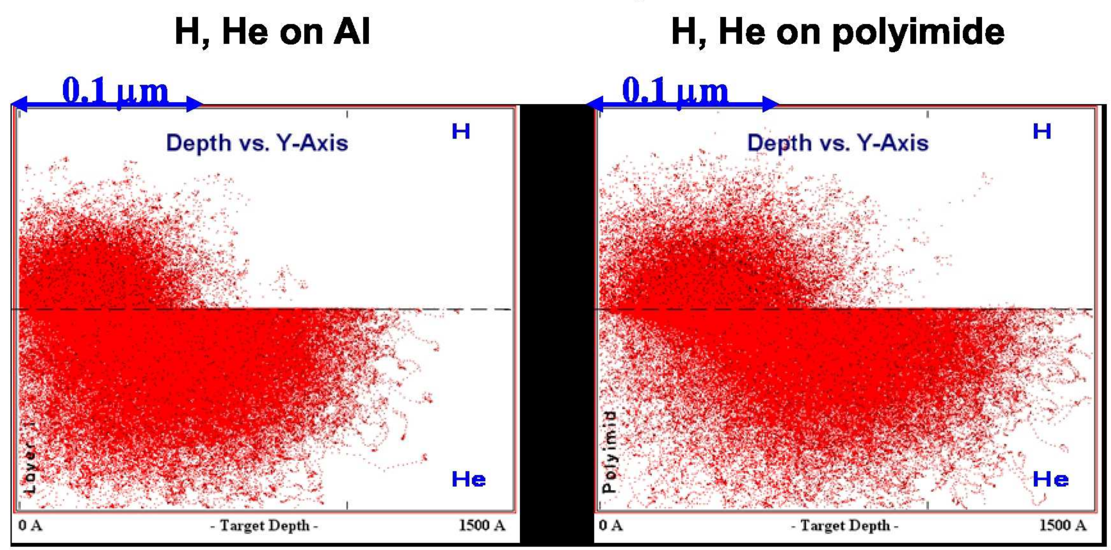
• As devices move to lower operating voltages and smaller feature sizes (some now have gate lengths of ~0.1micron) less electrical charge is required to cause a SEE:

-- Direct SEE from protons is possible in very sensitive (soft) parts and has been observed in some high speed optocouplers and Charge Coupled Devices (CCDs)

# Solar Wind as Radiation Environment

- Solar wind is generally considered a benign radiation environment
  - Solar wind velocity ~400 km/sec to 800 km/sec, mean ~450 km/sec
    - Kinetic energy of $H^+$ ~ 0.21 keV to 3.3 keV, mean 1.1 keV
    - Kinetic energy of $He^{++}$ ~ 0.84 keV to 13 keV, mean 4.2 keV
  - $H^+$ flux ~ NV ~ (7 $H^+/cm^3$)(450 x$10^3$ m/s) ~ 3.2x$10^8$ $H^+/cm^2$-sec
  - $He^{++}/H^+$ ~ 0.038  $He^{++}$ flux ~ 0.12x$10^8$ $H^+/cm^2$-sec
  - Fluence
    - $H^+$ ~ 9.9x$10^{15}$ $H^+/cm^2$-year
    - $He^{++}$ ~ 3.8x$10^{14}$ $H^+/cm^2$-year
- Solar wind penetration depths are only fractions of a micron
  - Bulk materials impacted only on "surfaces"
  - 1000 Å (0.1 μm) coating is impacted throughout the material
  - ~$10^2$ MGy/yr dose rates within the thin 0.1 μm coating
  - Important for optical (and therefore thermal) properties of materials

**TRIM Analyses**




[*Minow et al.*, 2007]

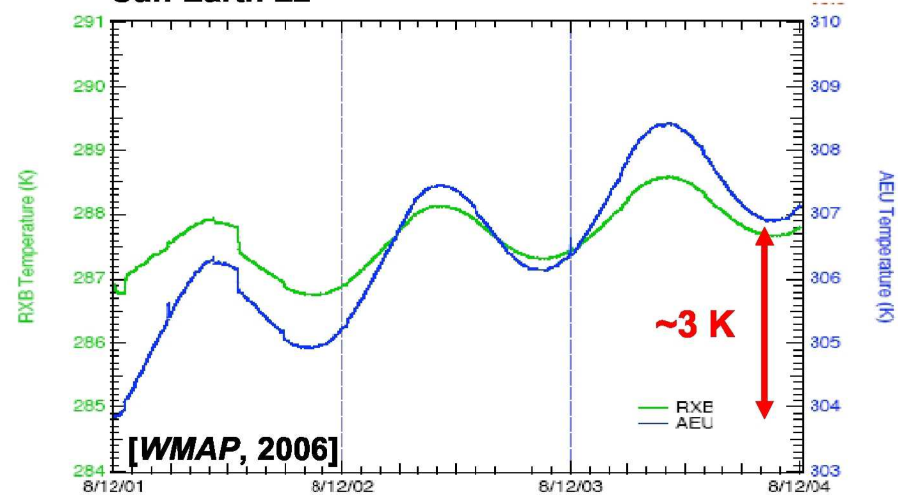
**10,000 1.22 keV $H^+$**
**10,000 5.27 keV $He^{++}$**

# Material Surfaces Modified by Space Environment

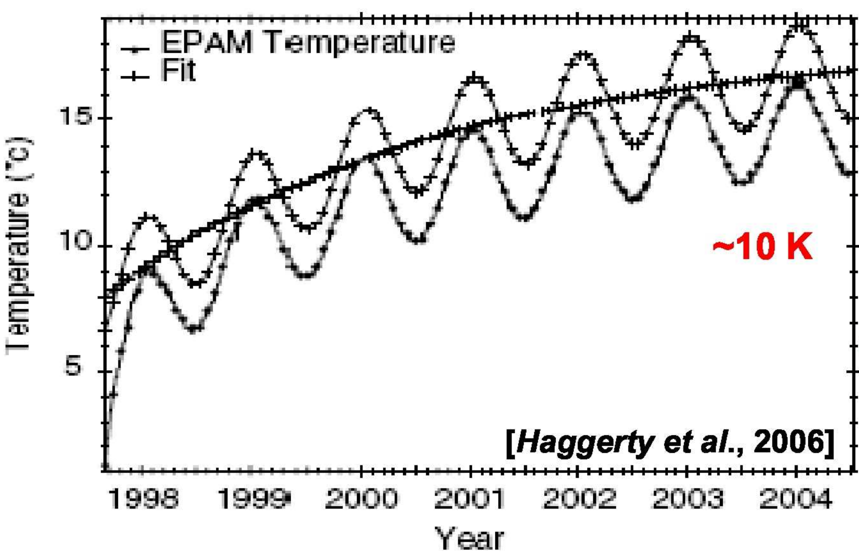
- Surface properties of materials degrade
  - Changes in optical properties are import
    to solar wind for long periods
  - Not just charged particles…UV, out gassi

Temp(t) ~ $\sin(2\pi t + \varphi)\exp(-t/\tau)$

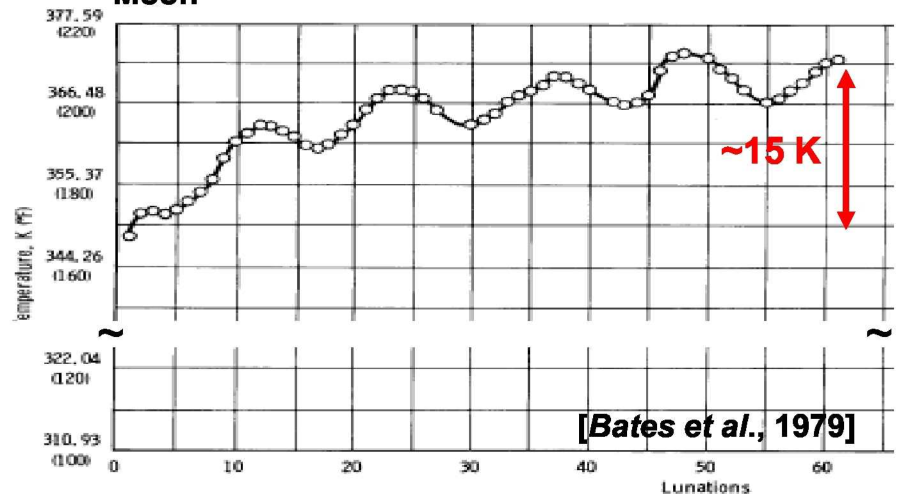
**Wilkerson Microwave Anisotropy Probe (WMAP)**
**Sun-Earth L2**




**Advanced Composition Explorer (ACE)**
**Sun-Earth L1**




**Apollo Lunar Surface Experiment Package (ALSEP)**
**Moon**




**Temperature profile for Apollo 14 ALSEP central station (normalized to 90° Sun angle)**

Environments

Radiation Effects

**Spacecraft Charging**

# Surface Charging

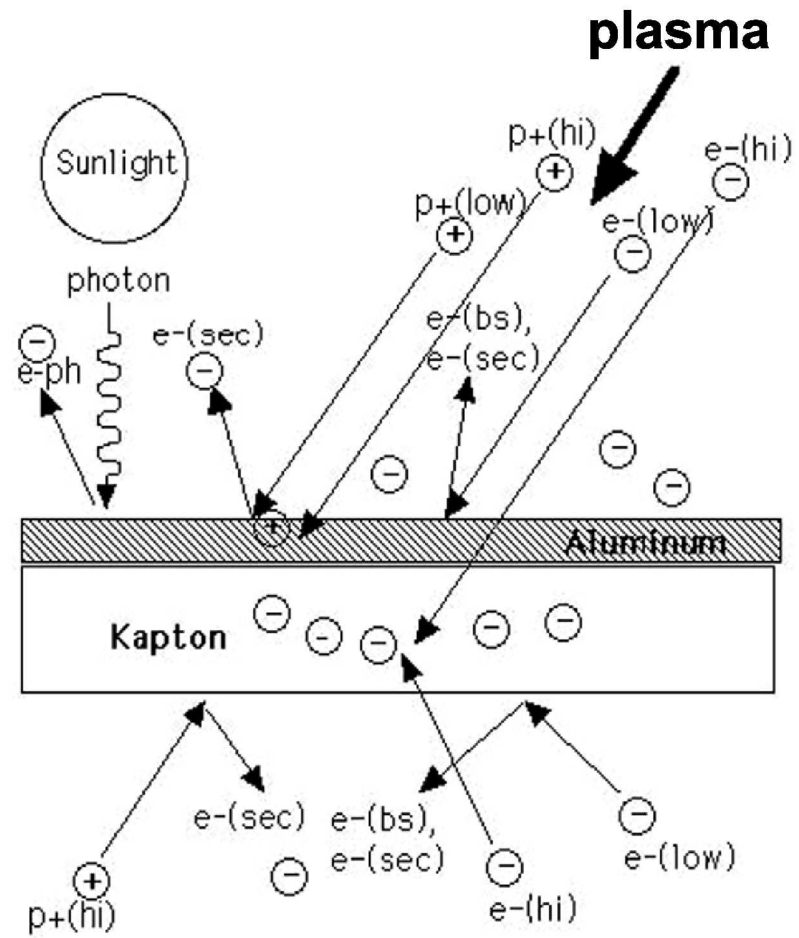
Time dependent current balance on surfaces

$$\frac{dQ}{dt} = C\frac{dV}{dt} = \sum_k I_k \quad (\sim 0 \text{ at equilibrium})$$

$$\sum_k I_k =$$

| | |
|---|---|
| $+ I_i(V)$ | incident ions |
| $- I_e(V)$ | incident electrons |
| $+ I_{bs,e}(V)$ | backscattered electrons |
| $+ I_{se}(V)$ | secondary electrons due to $I_e$ |
| $+ I_{si}(V)$ | secondary electrons due to $I_i$ |
| $+ I_{ph,e}(V)$ | photoelectrons |
| $+ I_C(V)$ | conduction currents |
| $+ I_B(V)$ | active current sources (beams, electric thrusters, etc.) |

$$C\frac{dV}{dt} = \sum_{k'} I_{k'} + \sigma V$$




(Garrett and Minow, 2004)

# Bulk (Deep Dielectric) Charging

Radiation charging of insulators, isolated conductors

$$\nabla \bullet D = \rho$$

$$D = \varepsilon E$$

$$\varepsilon = \kappa \varepsilon_0$$

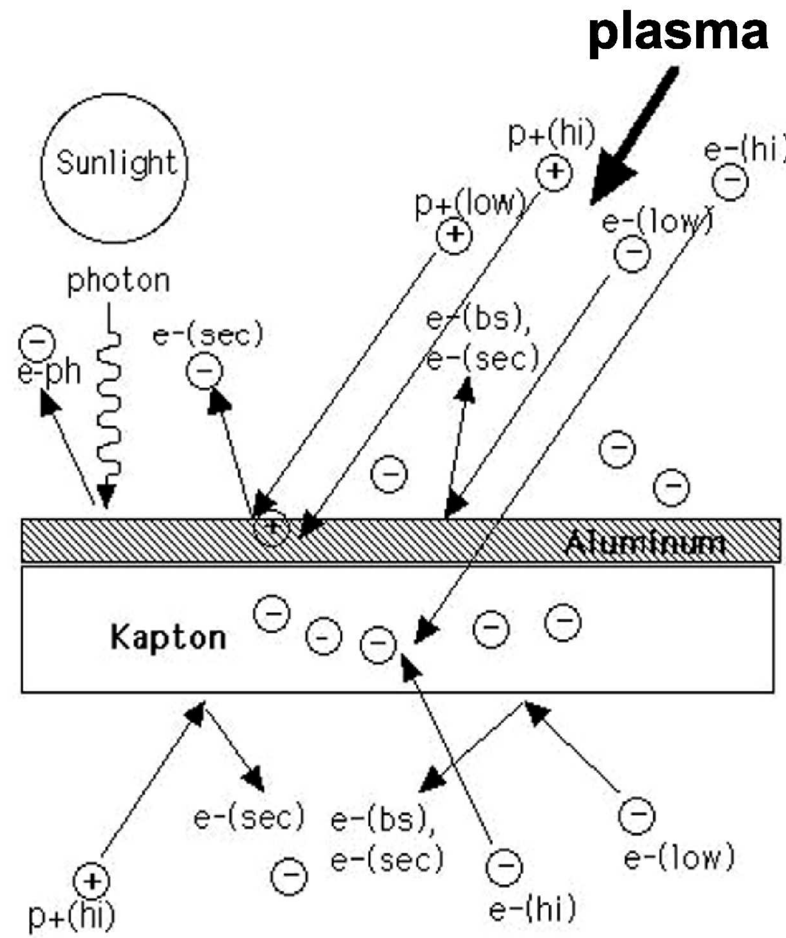
$$\frac{\partial \rho}{\partial t} = -\nabla \bullet J$$

$$J = J_0 + J_C$$

$$J = \sigma E$$

$$= \left(\sigma_{dark} + \sigma_{radiation}\right) E$$

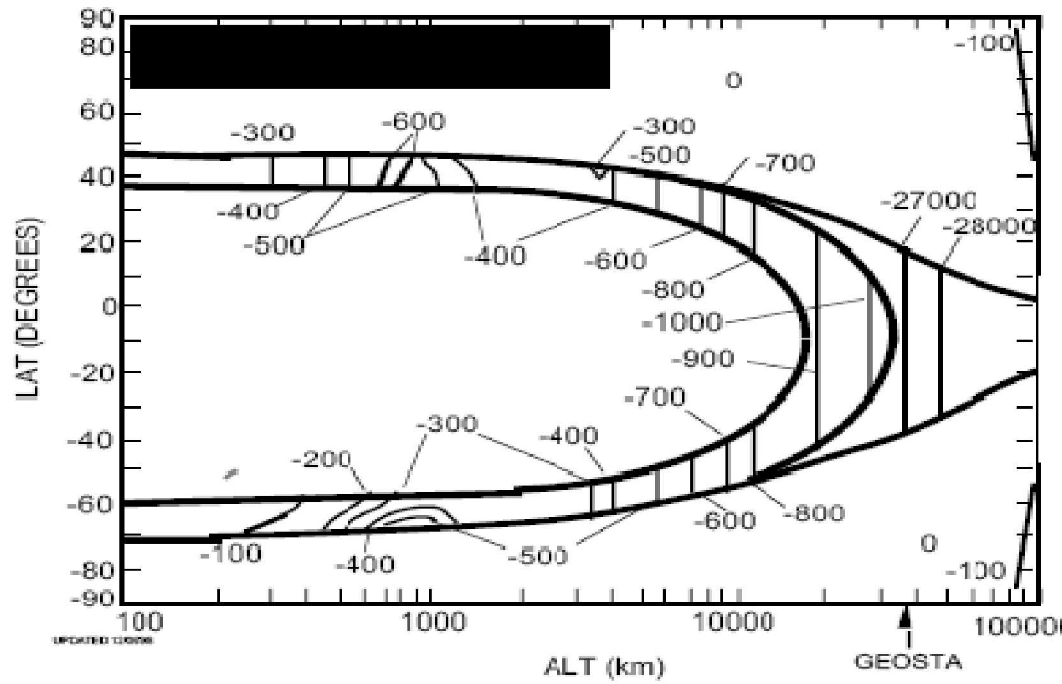
$$\sigma_{radiation} = k \left( \frac{d\gamma}{dt} \right)^{\alpha} \quad 0.5 < \alpha < 1.0$$




(Garrett and Minow, 2004)

# Spacecraft Charging Effects

- Differential charging of dielectrics, ungrounded conducting materials in space plasma and radiation environments generates electric fields
- Fields exceeding material breakdowr strength result in electrostatic discharge
- Risks include:
  - ESD generated radio noise exceeding EMC/EMI requirements
  - Current pulses couple into sensitive electronics generating phantom commands, upsets, or destruction of critical components
  - Material degradation




| Environment | Spacecraft Potential |
|---|---|
| LEO | - 0.1 to 0.5 V |
| GEO | - 0.1 to -10’s kV |
| Auroral zone | - 0.1 to -1 kV |
| Magnetotail at lunar orbit | |
| --eclipse | - 0.1 to -0.5 kV |
| --sunlight | +10’s V |
| Solar wind | +10’s V |

# Low Earth Orbit (<1000 km)

- Current collection on surfaces in ionosphere charge vehicle few volts negative relative to plasma
- LEO charging dominated by solar array current collection
  - Potentials relative to plasma depend on solar array design
  - Bare interconnects with vehicle grounded on negative end of array can drive vehicle potential to voltages as much as ~90% of array bias
- Potential difference across vehicle generated by motion in geomagnetic field:

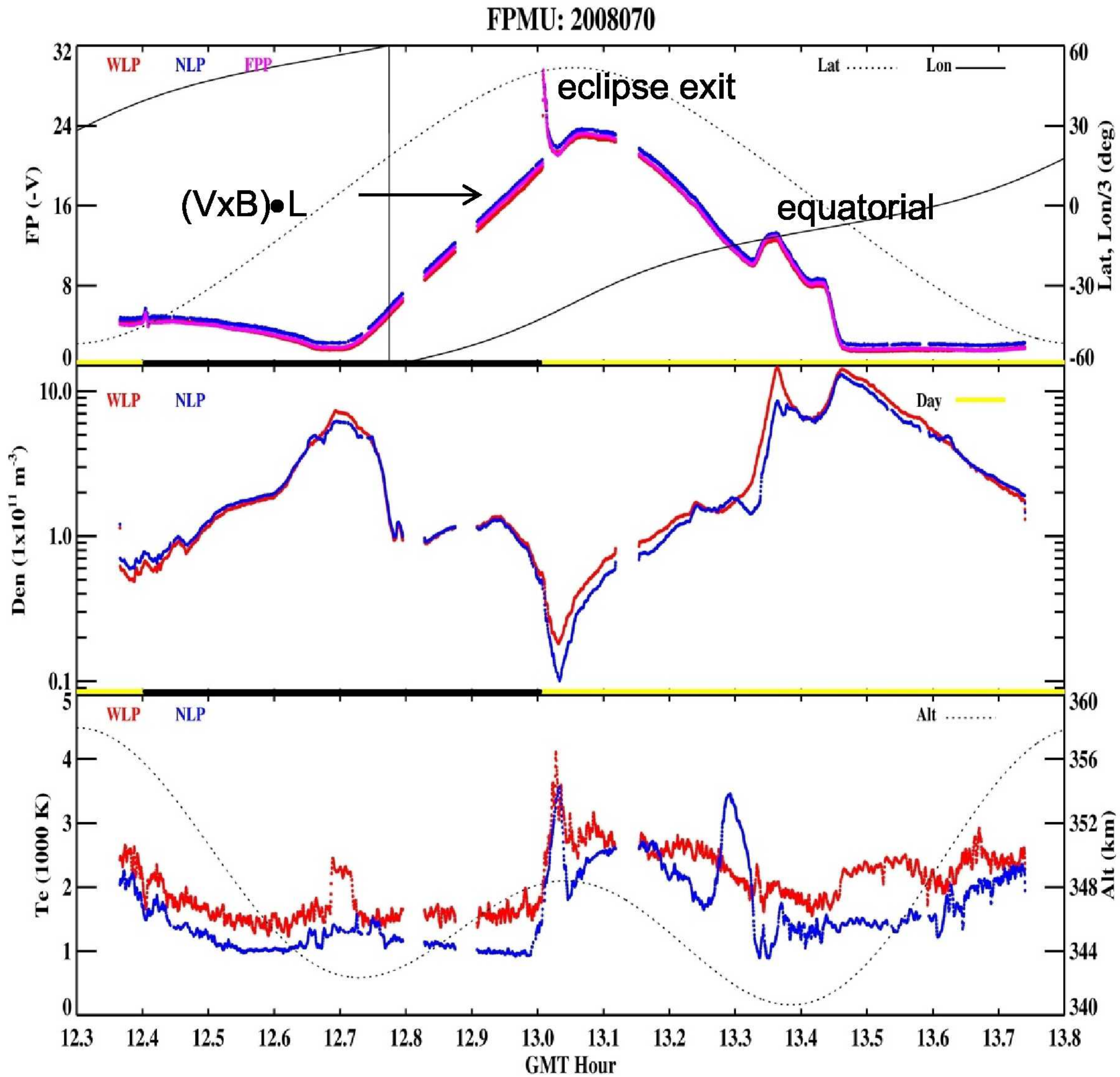
$\Delta\Phi \sim (V \times B) \bullet L \sim 0.37$ V/m in LEO

For example, consider ISS

$\Delta\Phi \sim (7.7\text{km/sec} * 46{,}200 \text{ nT}) (108 \text{ m})$

$\sim 40$ volts

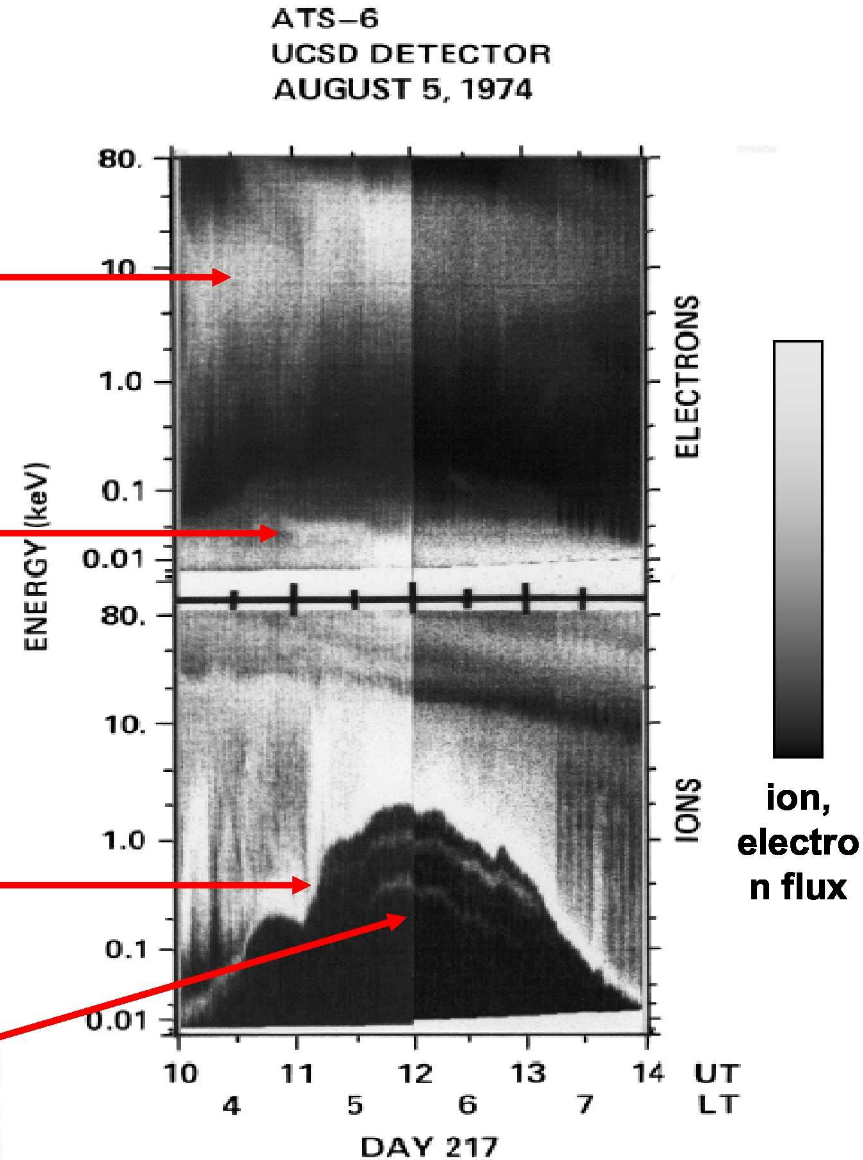
51.6 N, 240 E, 348 km




[Craven et al., 2009]

# "Ion Line" Charging Signature

- ATS-6, geostationary orbit
  - Spacecraft charged to potential $\Phi < 0$
- Primary electrons, $E' = E_0 - q\Phi$
  - Only electrons with energy $E_0 > |-e\Phi|$ can impact spacecraft surface
- Photoelectrons, locally generated secondary electrons returned to spacecraft by electrostatic barrier generated by differential charging of insulators near the particle detector
- Ions attracted to $\Phi < 0$ spacecraft and impact with energy $E = E_0 + e\Phi$
  - $E_0 = 0$ ions impact with minimum energy $E = e\Phi$
- Secondary, locally generated ions



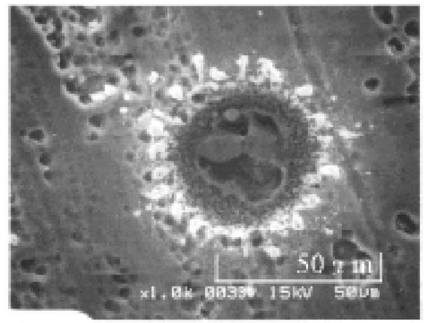
# Spacecraft Charging Impacts Space Systems

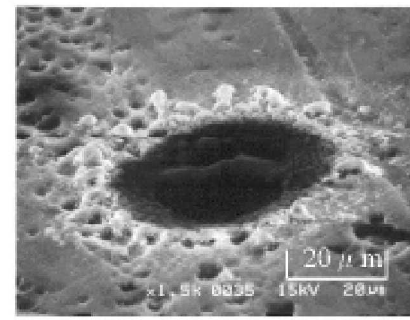
**Space Environment Impacts on Space Systems (Koons et al., 2000)**

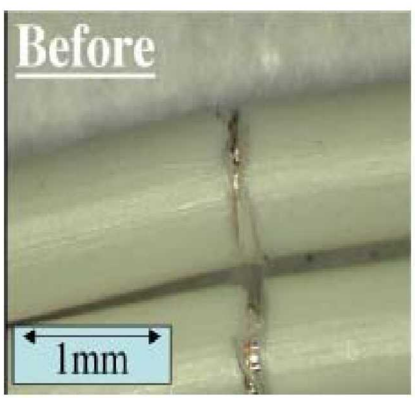
| Anomaly Diagnosis | Number | % |
|---|---|---|
| ESD-Internal, Surface and uncatergorized | 162 | 54.1 |
| SEU (GCR, SPE, SAA, etc.) | 85 | 28.4 |
| Radiation Dose | 16 | 5.4 |
| Micrometeoroids, orbital debris | 10 | 3.3 |
| Atomic oxygen | 1 | 0.3 |
| Atmospheric drag | 1 | 0.3 |
| Other | 24 | 8.0 |
| Total | 299 | 100.0% |

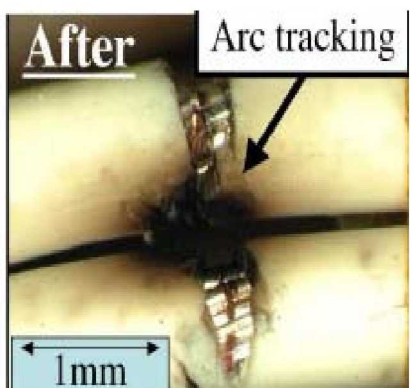
**Risks to Spacecraft**

- Phantom commands
- Discharge currents damage materials, electronics systems
- Damage to thermal control coatings, solar cells
- Trigger arcs on power systems lead to sustained arcing




Kawakita et al., 2005

Kawakita et al., 2005

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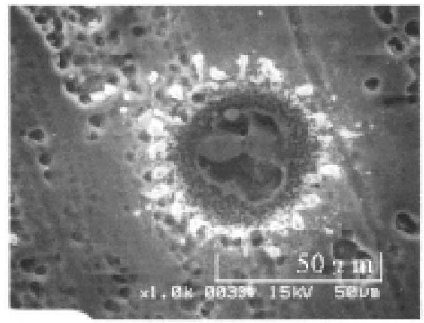


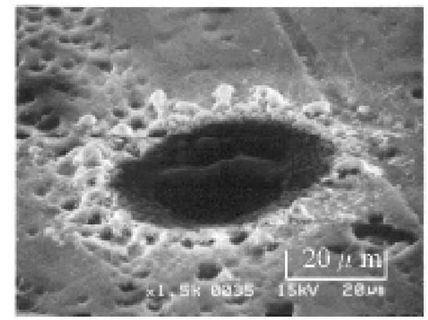


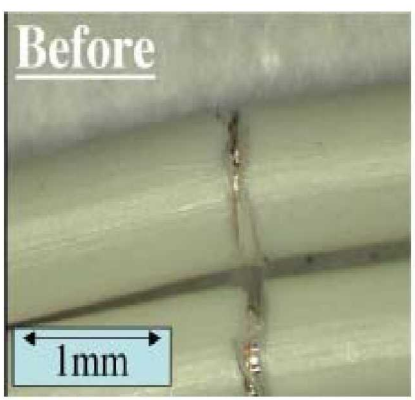


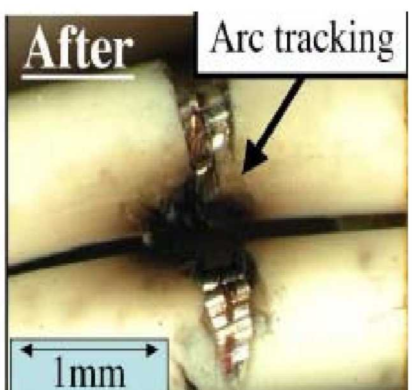


Kawakita et al., 2005


Kawakita et al., 2005

# Spacecraft Charging Impacts Space Systems

Space Environment Impacts on Space Systems (Koons et al., 2000)

Anomaly Diagnos

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ESD-Internal, Sur

and uncater

SEU (GCR, SPE, SA

Radiation Dose

Micrometeoroids

debris

Atomic oxygen

Atmospheric drag

Other

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Total

**Risks to Spacecraft**

Phantom commands

erials, electronics

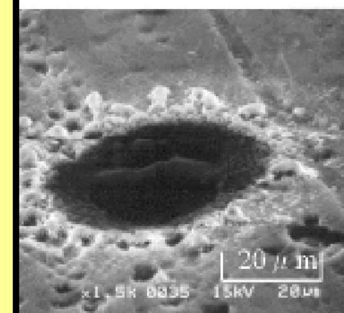
ngs, solar cells

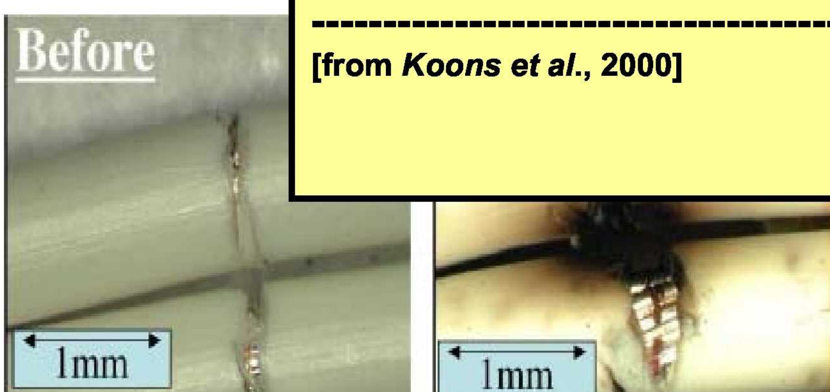
ead to sustained arcing

## Spacecraft Lost and Missions Terminated Due to Charging

| Spacecraft | Date | Cause |
|---|---|---|
| DSCS II | Jun 1973 | Surface ESD |
| GOES 4 | Nov 1982 | Surface ESD |
| Feng Yun 1 | Jun 1988 | ESD |
| MARECS A | Mar 1991 | Surface ESD |
| Anik E2 | Jan 1994 | ESD? |
| Telstar 401 | Jan 1997 | ESD? |
| INSAT 2D | Oct 1997 | Surface ESD |
| ADEOS-II | Oct 2003 | ESD |

[from *Koons et al.*, 2000]

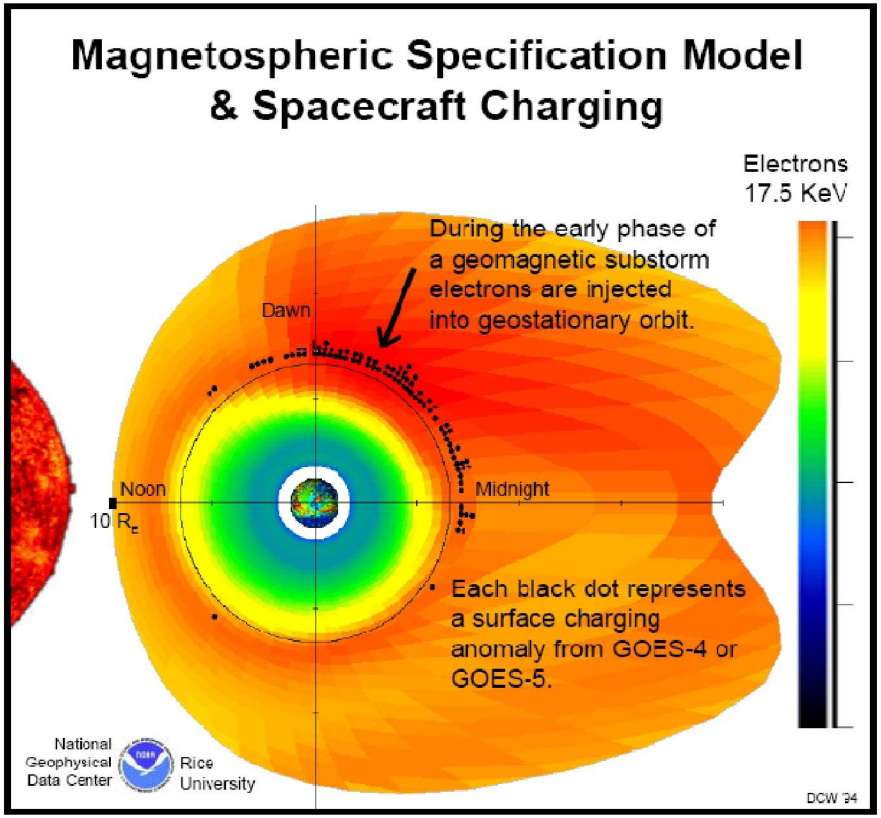


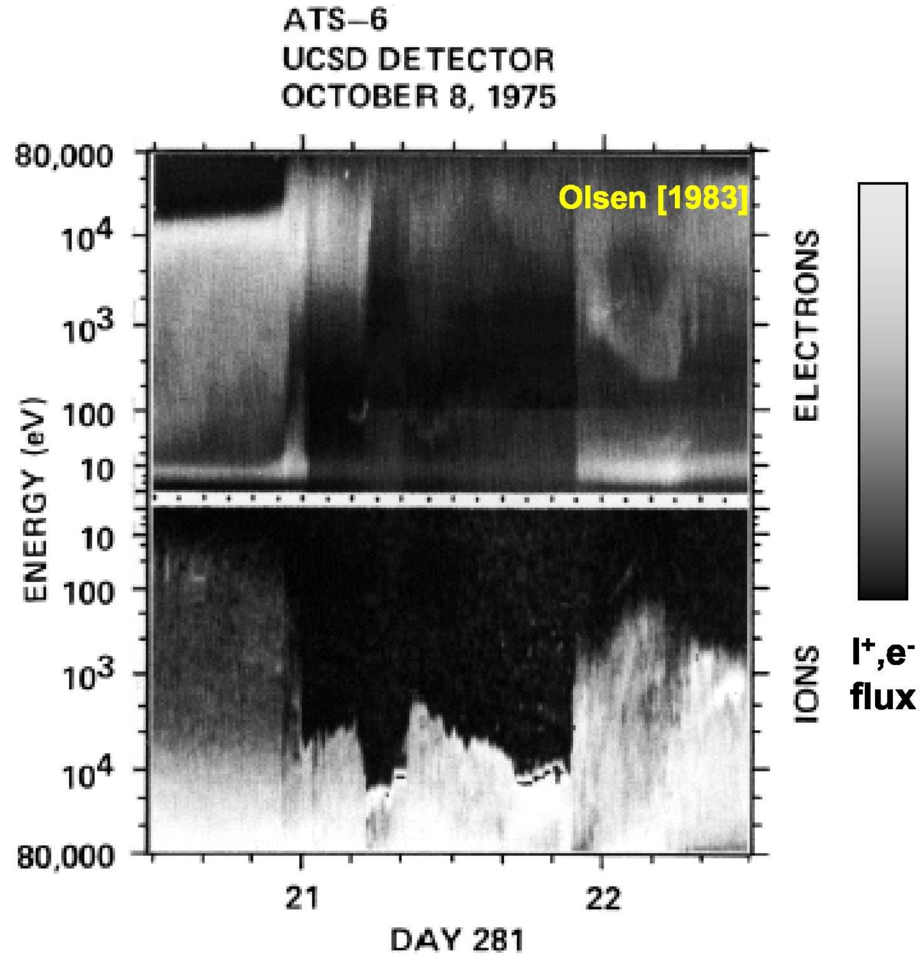

Kawakita et al., 2005


Kawakita et al., 2005

# GEO Surface Charging



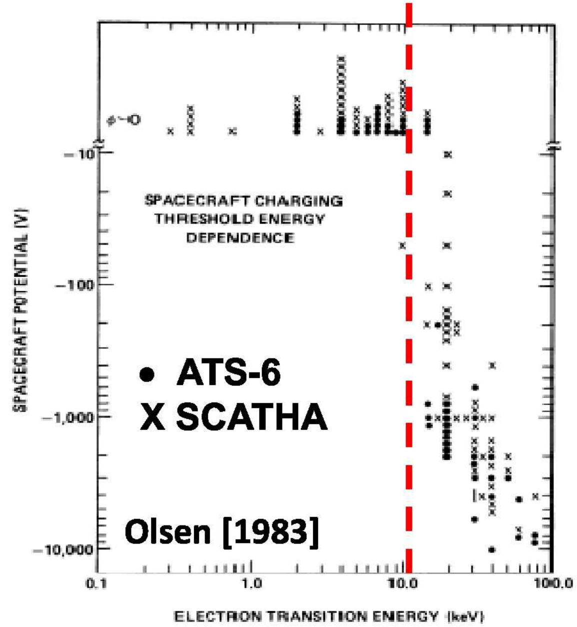

**Surface charging anomalies typically occur in midnight to dawn local time sector where hot electrons are injected during geomagnetic substorms**

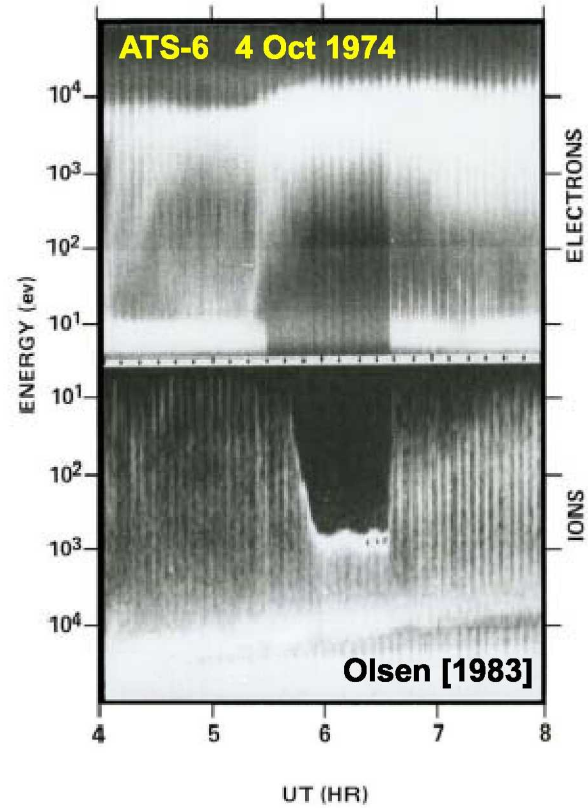


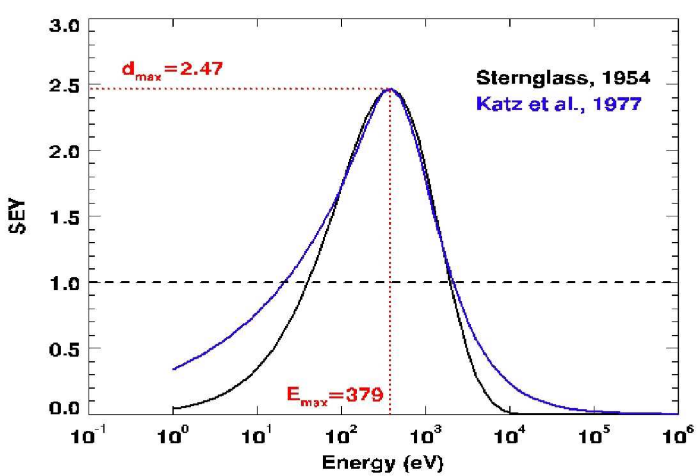

**Record ATS-6 charging event**
**$\Phi$ ~ -19 kV**

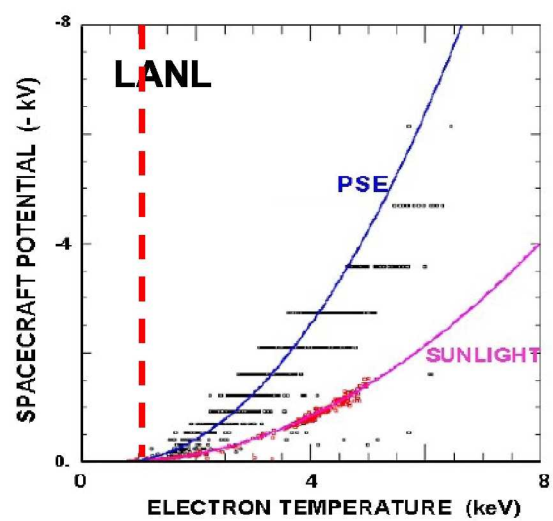
# Threshold for Charging Onset

Electron energy threshold for onset of charging is due to second crossover point of secondary electron yield curves (Olsen, 1983)



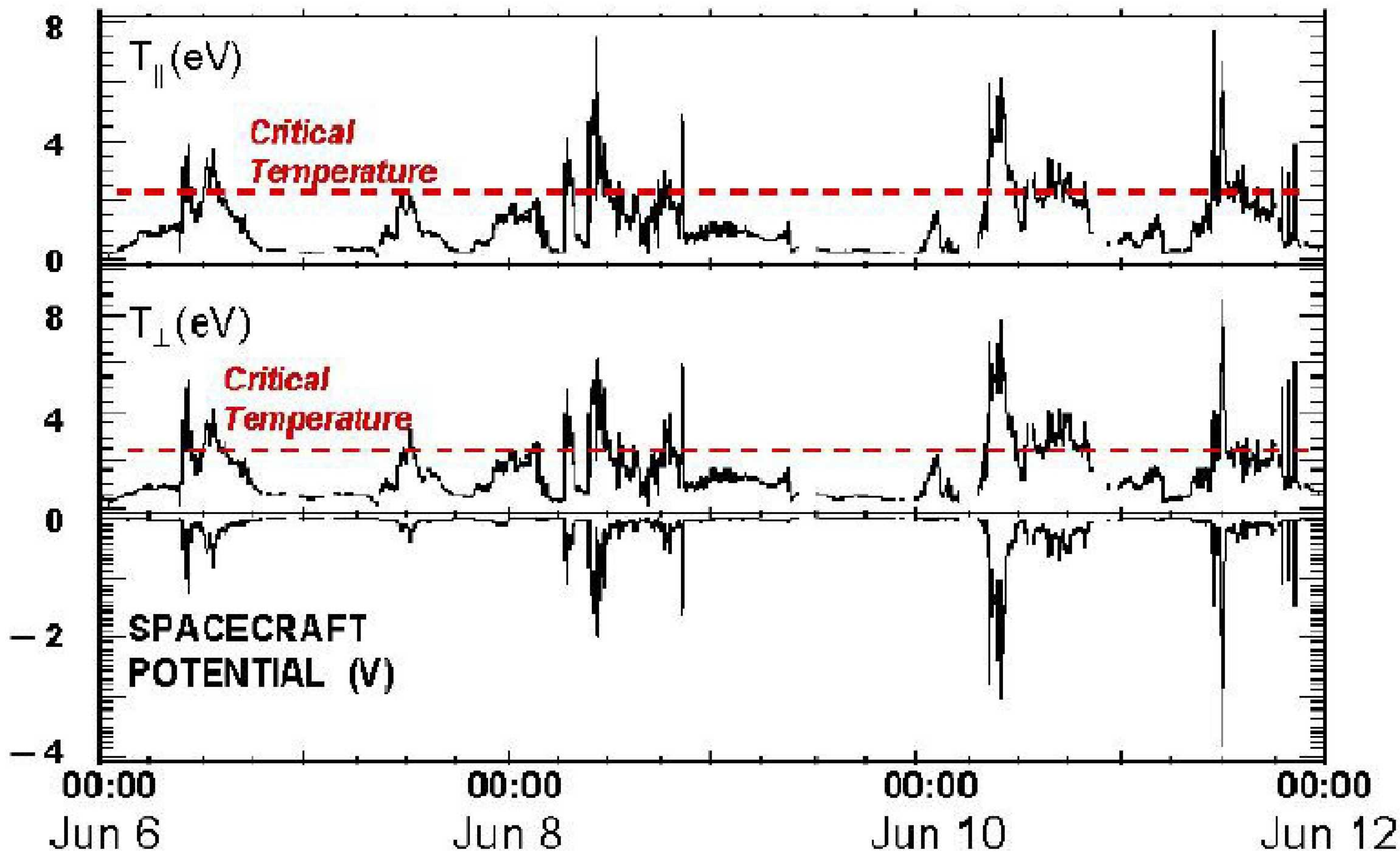




(Lai et al, 2003)

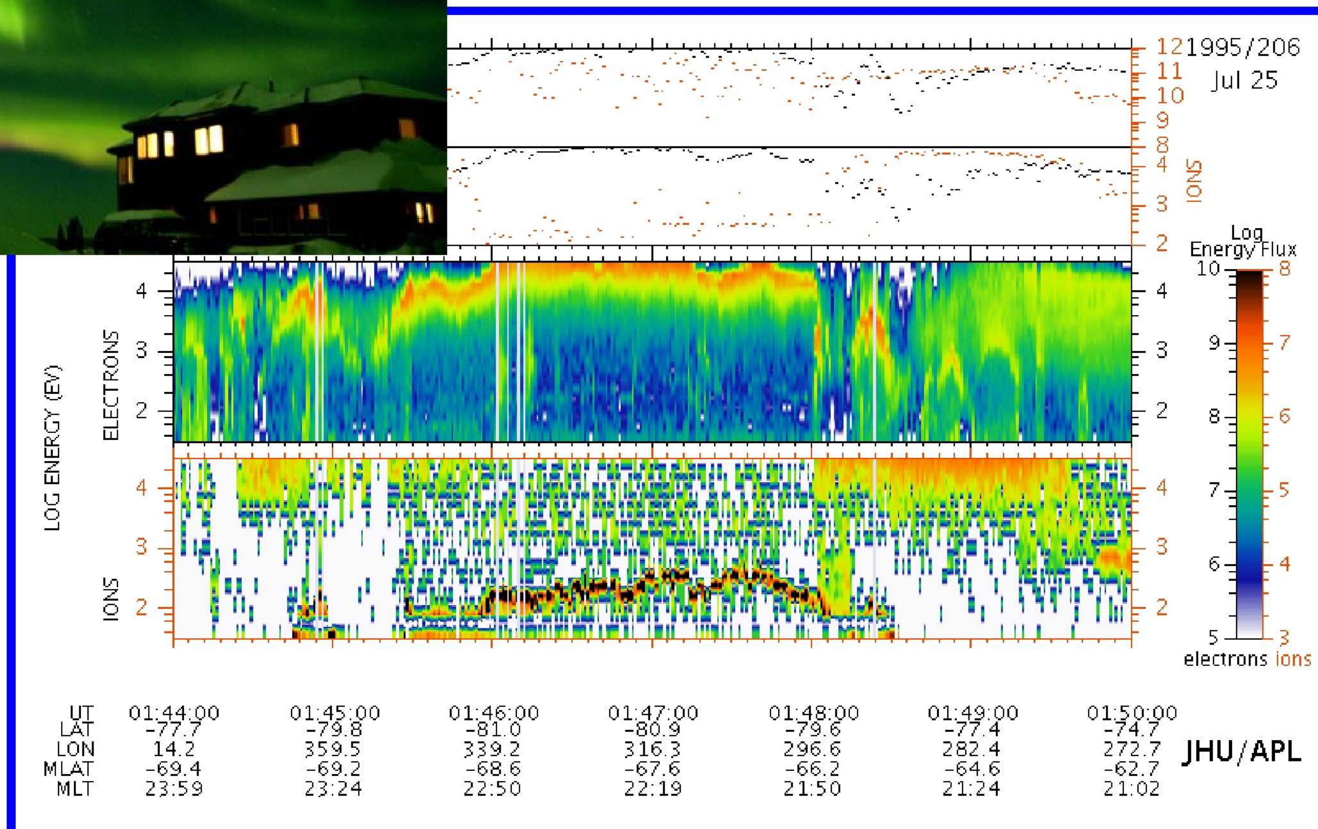
# Examples of $T_{crit}$ Onset




Examples for onset of charging at a critical temperature

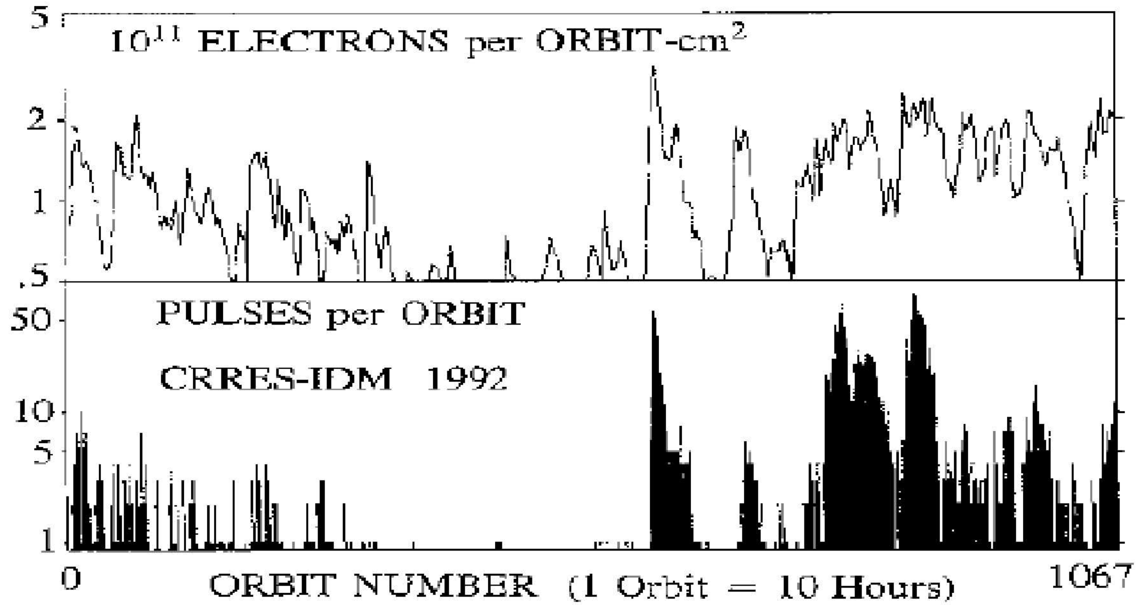
(Lai, 2003) 8th SCTC

# Auroral Charging

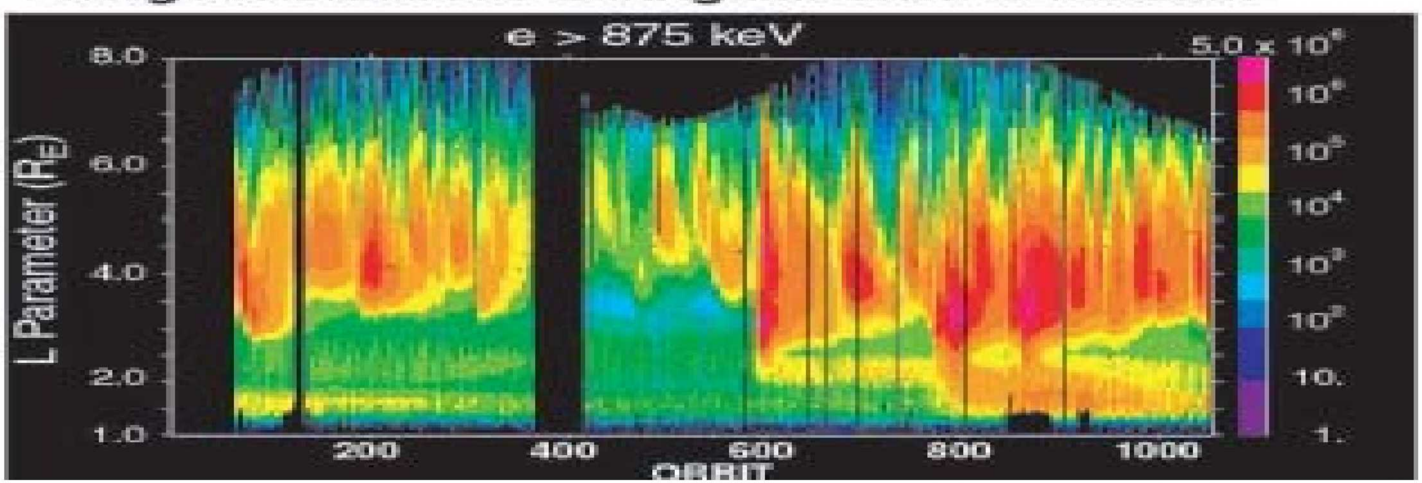


# CRRES Internal Discharge Monitor (IDM)

- ESD pulses are correlated with high energy electron flux
- Sum of pulses in all IDM samples




Energetic electrons during the CRRES mission




[*Frederickson and Brautigam*, 2004]

# Summary

- Geostationary transfer orbit (LEO to ~GEO) is a particularly challenging environment
- Careful attention to radiation and charging environments is required to design system to successfully operate long term in GTO environments
- Example GTO, near GTO missions:
  - Combined Radiation and Release Experiment Satellite 350 km x 33584 km x 18.1 deg
  - THEMIS suite of 5 satellites inclination 4.5 to 7 deg
    - Probe 1: 1.3 x 30 Re x
    - Probe 2: 1.2 x 20 Re
    - Probes 3 and 4: 1.5 x 12 Re
    - Probe 5: 1.5 x 10 Re
  - POLAR ~1.8 x 9 Re x 86 deg