The Space Environment and its Assessment for Project Development

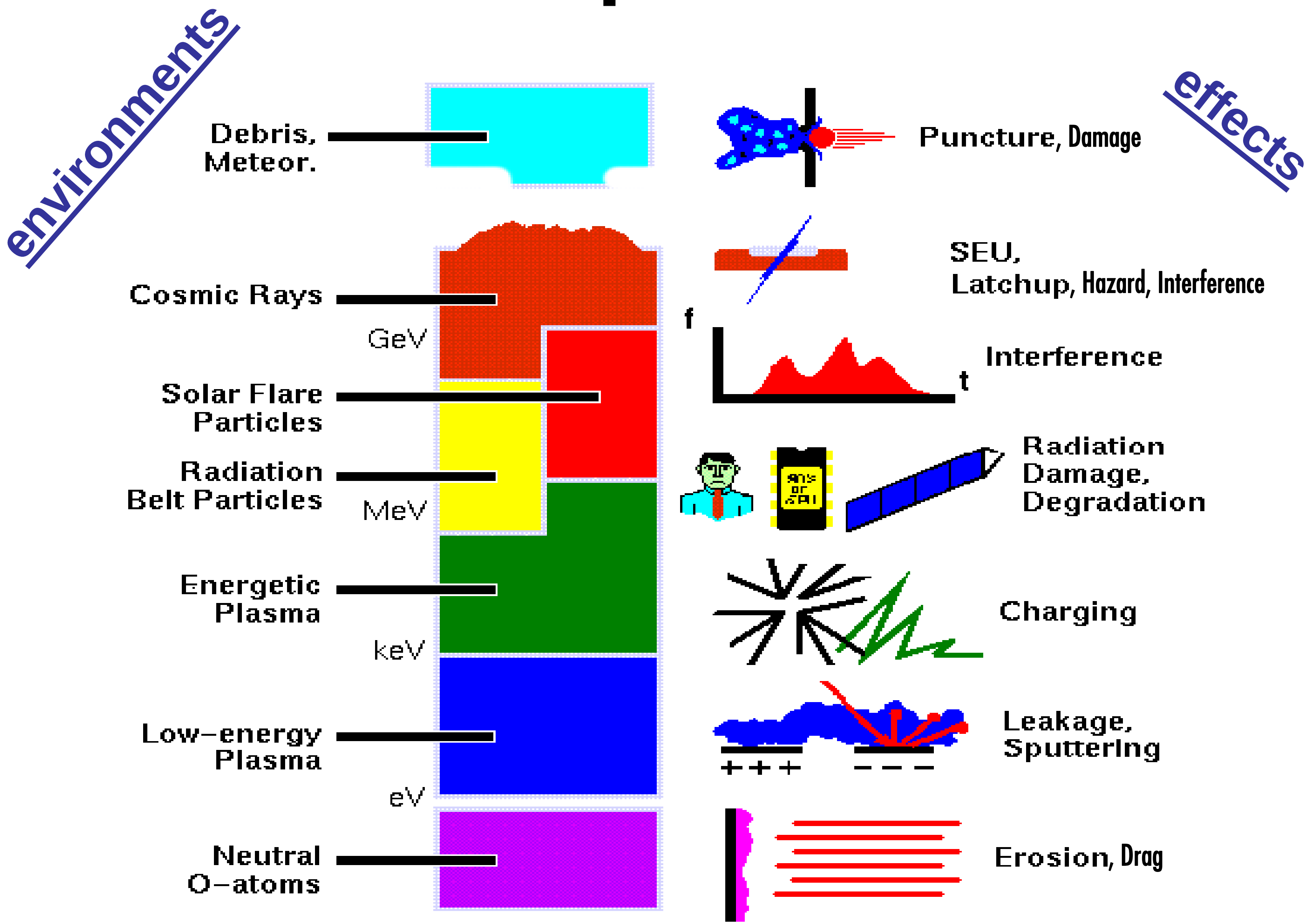
Eamonn Daly
Space Environments and Effects Section
ESTEC/TEC-EES
eamonn.daly@esa.int

Introduction

- The problem
  - The environment constituents
  - Problems from interactions with the environment
- The solution
  - Knowledge (models, measurements)
  - Simulation (prediction of effects)
  - Testing
- Learning lessons (feedback)
- The process
  - What the engineers do, & when
  - Standards, "tools"

The problem

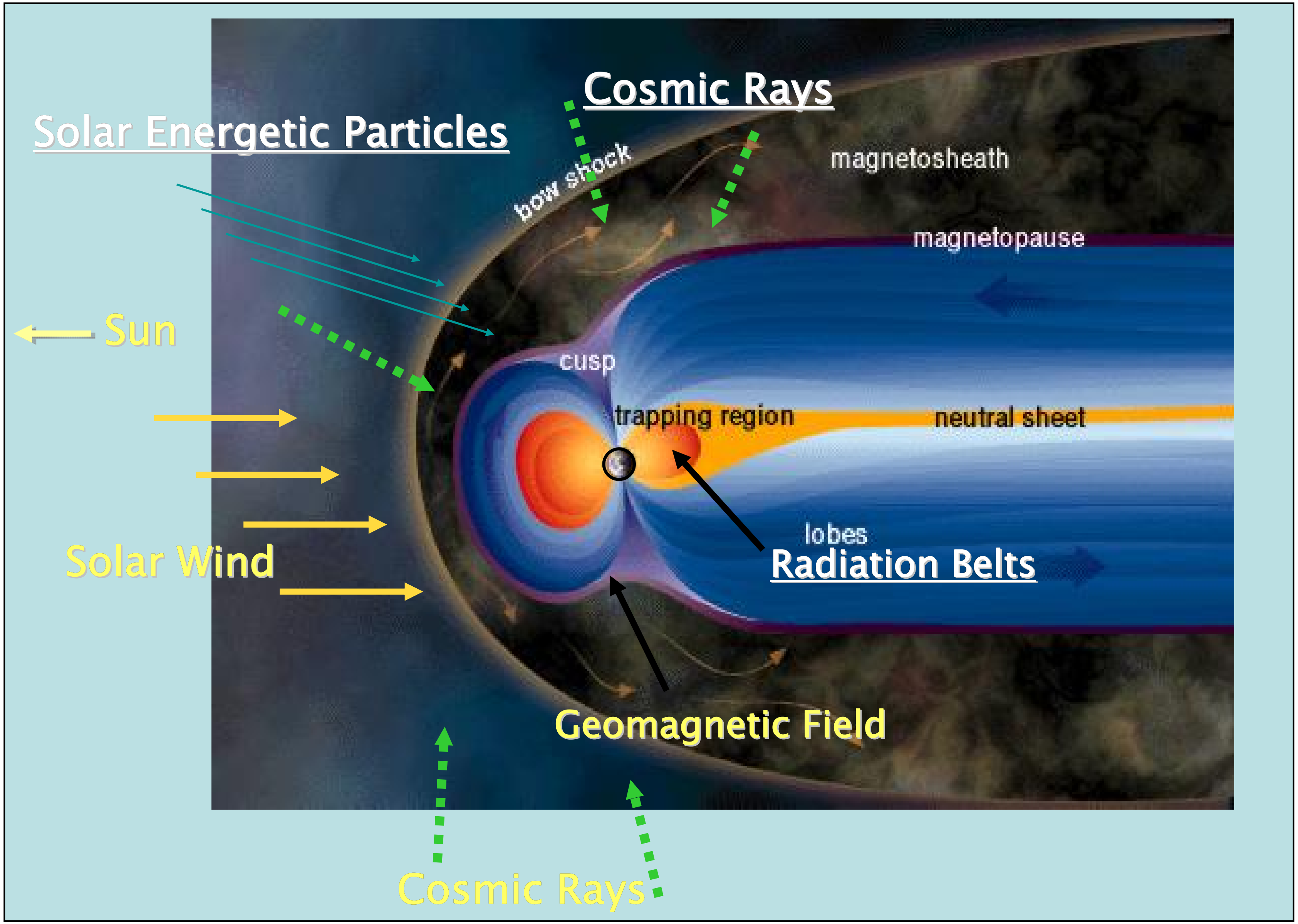
What is the "Space Enuironment"



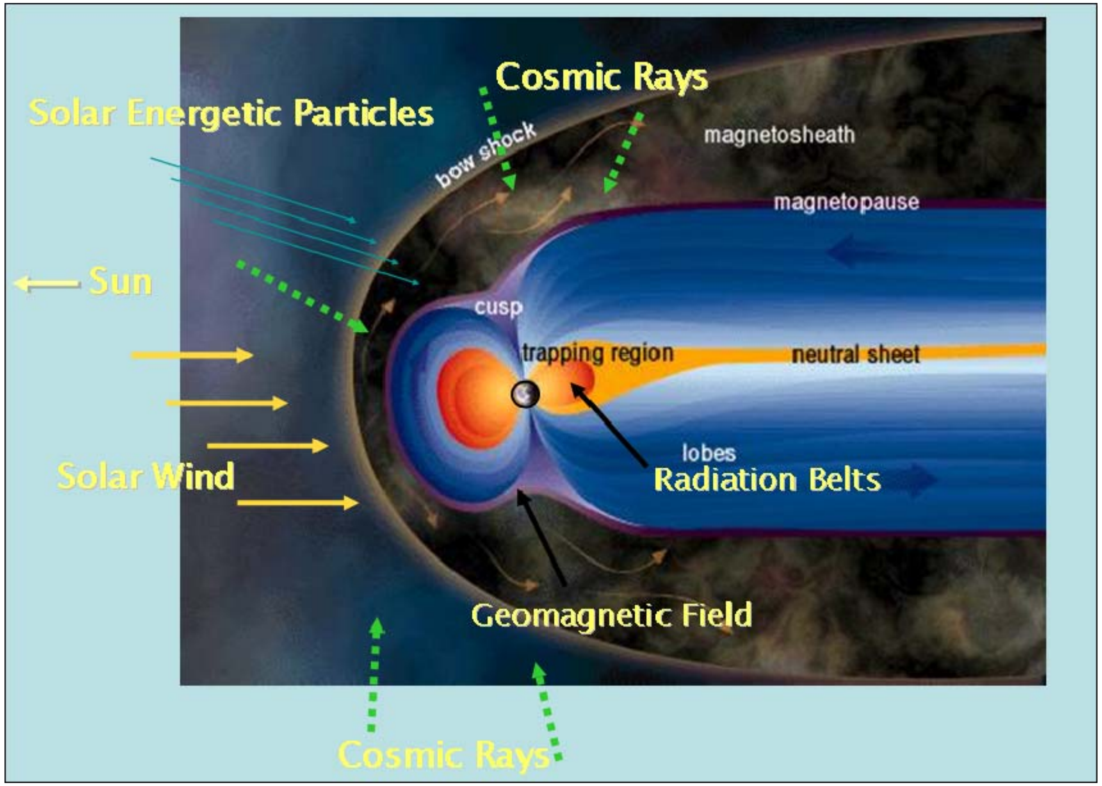
- When we refer to *space environment*, we do not normally include 2 important "environments":
  - Thermal (a major technical issue)
  - Gravity field (and microgravity conditions)
- But we also consider:
  - Atmospheres (esp. Earth, Mars)
  - Magnetic fields (Earth, etc.)
  - (Electric fields)

Radiation

Three main sources of radiation

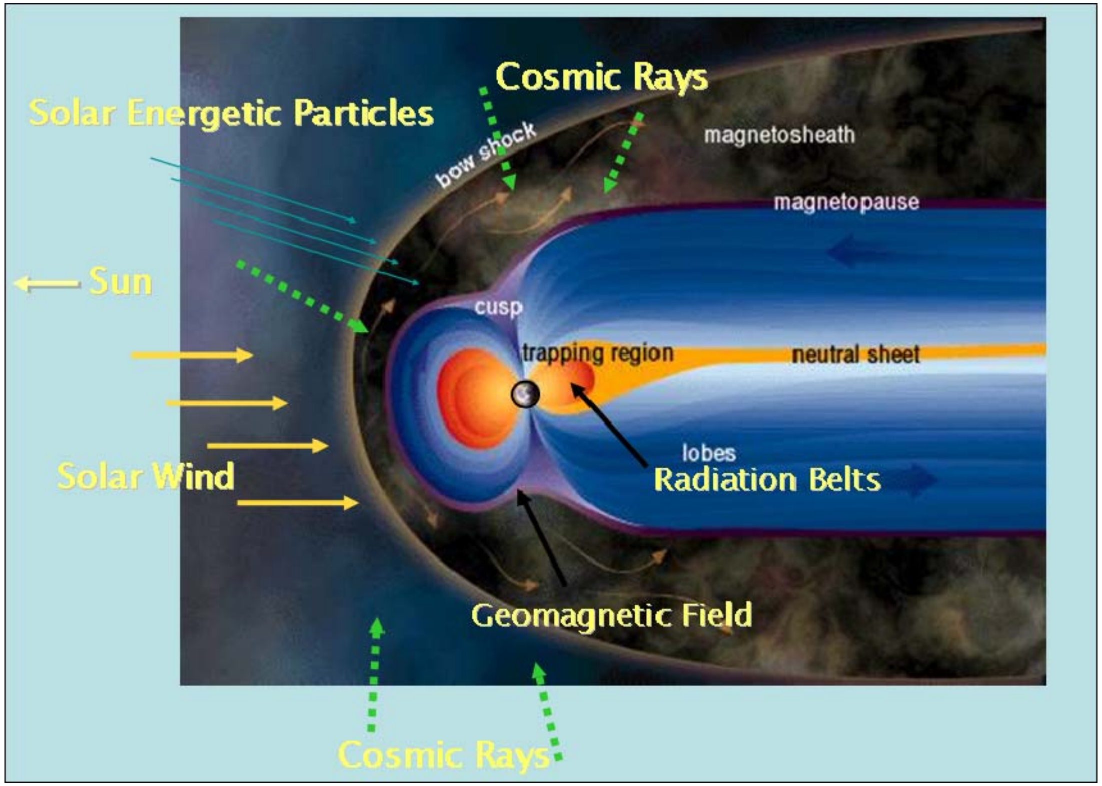


Three main sources of radiation

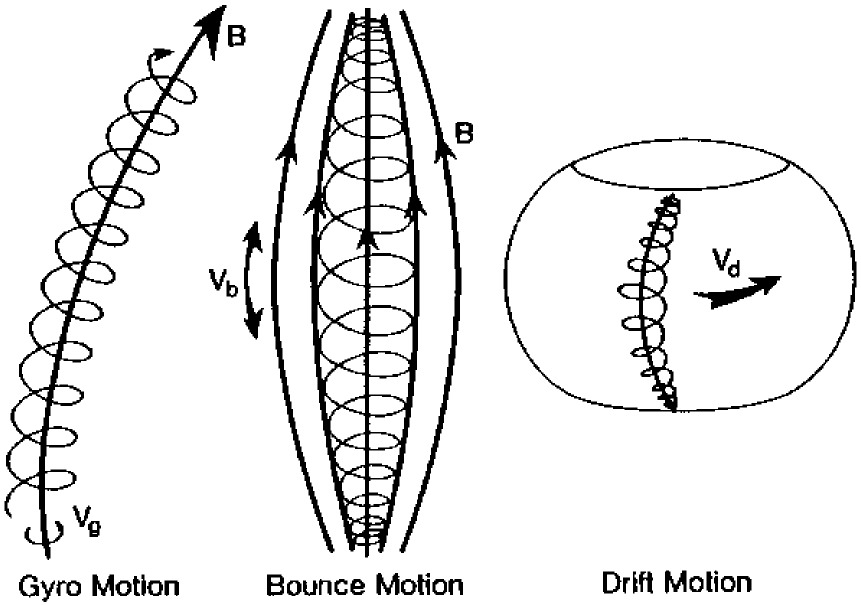


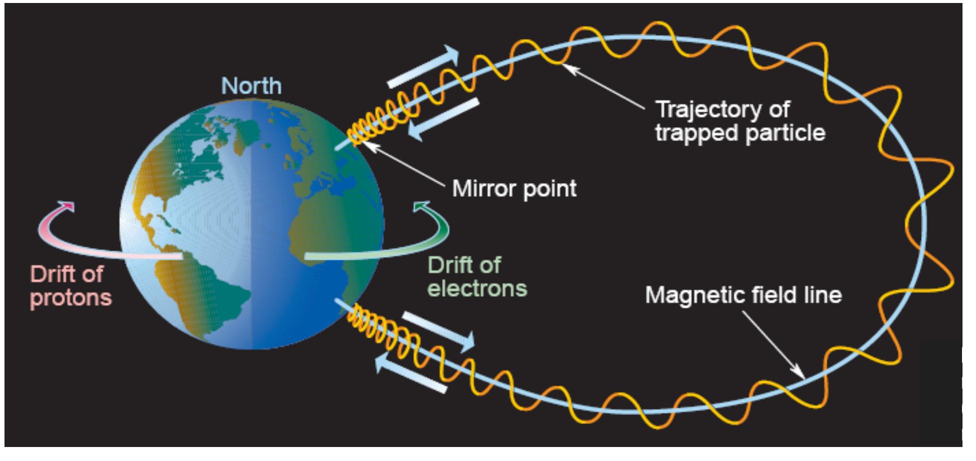
- Radiation Belts
  - High radiation dose
- Solar Particle Events
  - Sporadic but dangerous when they happen
- Galactic Cosmic Rays
  - Low flux but highly penetrating

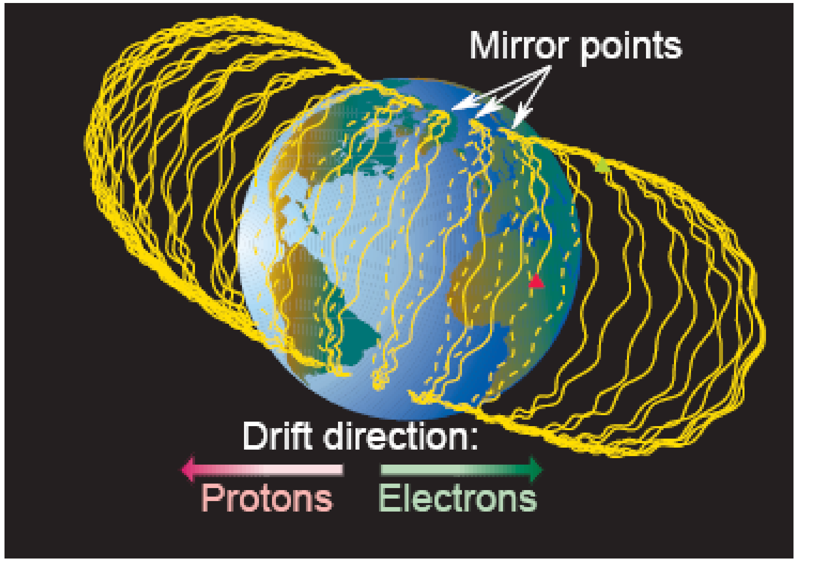
Three main sources of radiation



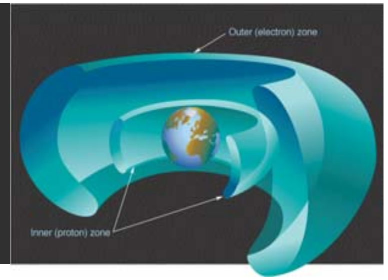
- Radiation Belts
  - High radiation dose
- Solar Particle Events
  - Sporadic but dangerous when they happen
- Galactic Cosmic Rays
  - Low flux but highly penetrating

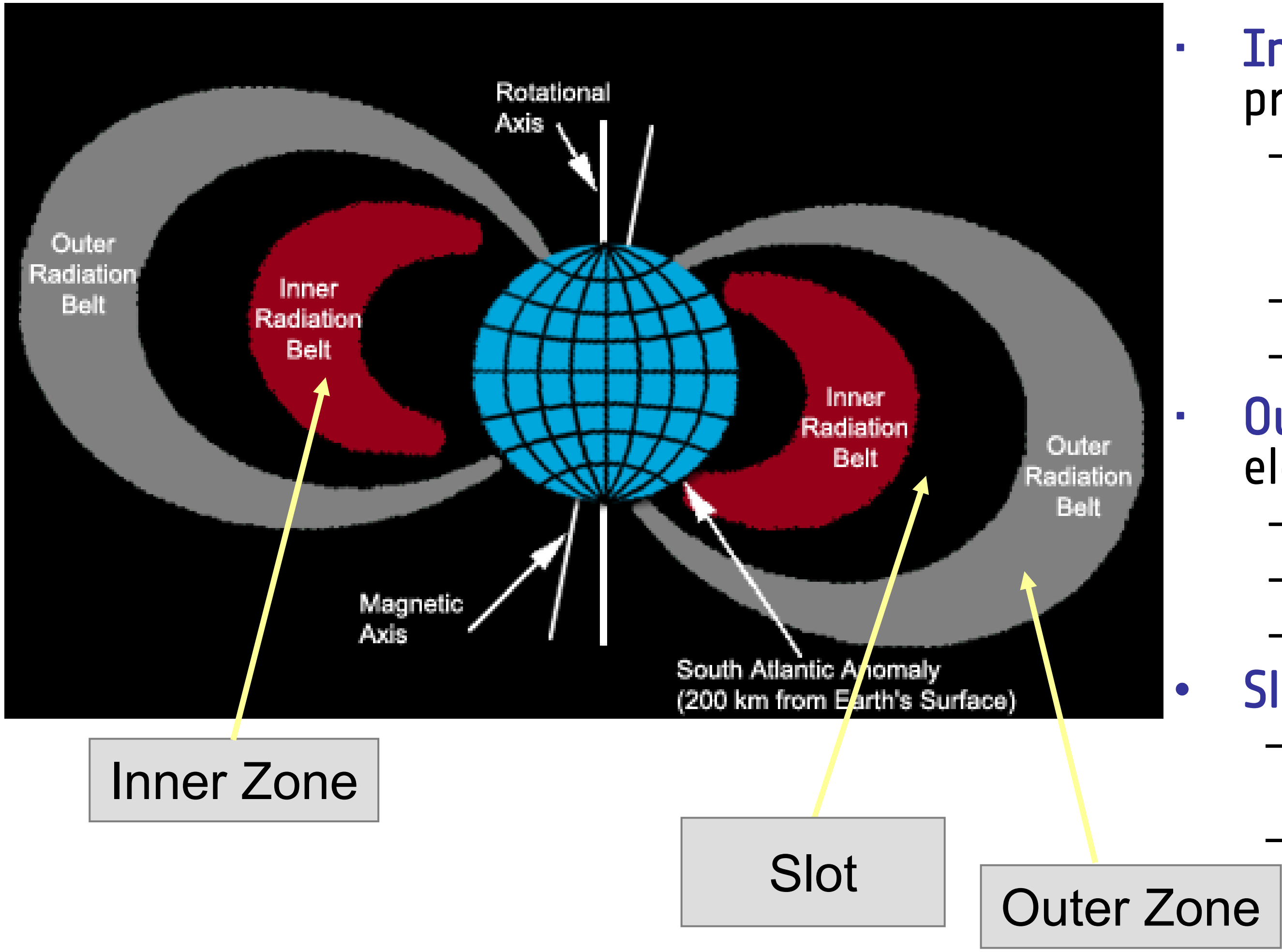

B
B
V_b
V_d
V_g
Gyro Motion
Bounce Motion
Drift Motion


North
Trajectory of
trapped particle
Mirror point
Drift of
protons
Drift of
electrons
Magnetic field line


Mirror points
Drift direction:
Protons
Electrons

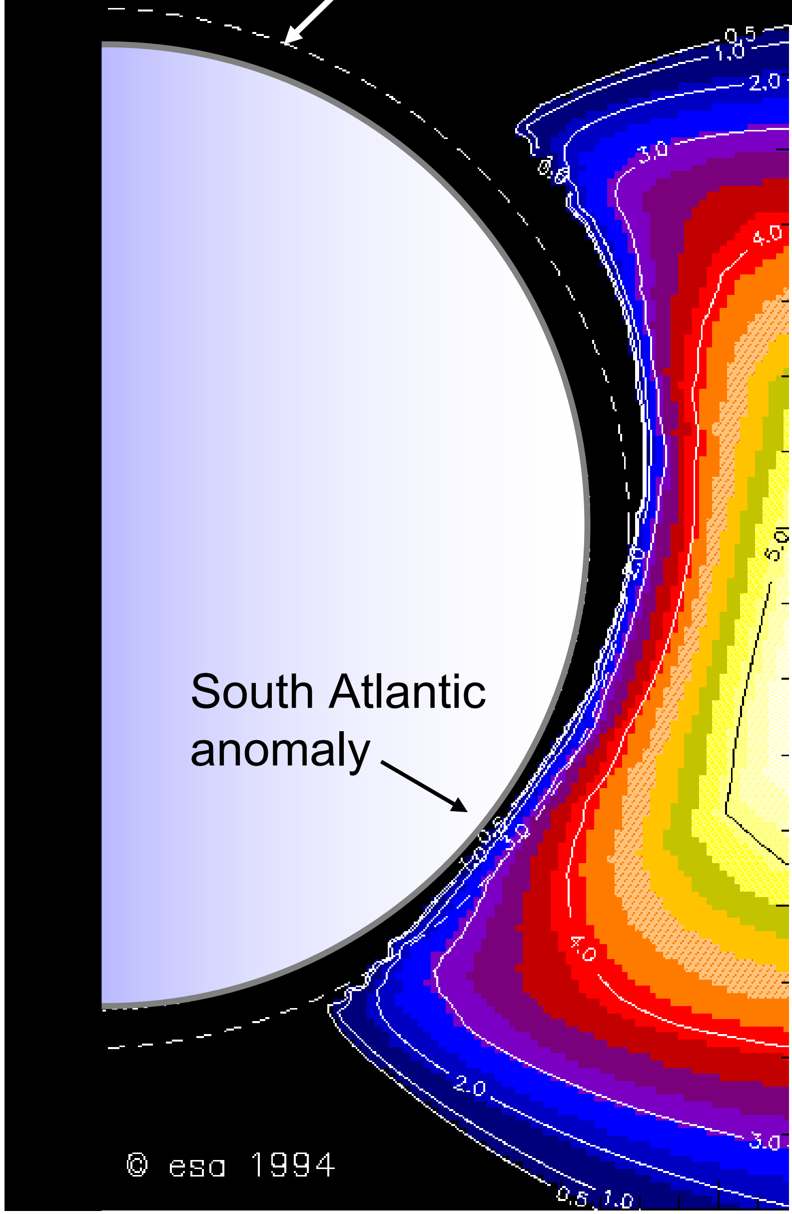
Radiation Belt Regions

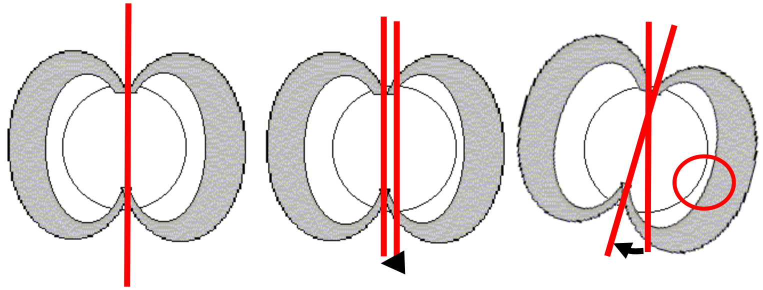


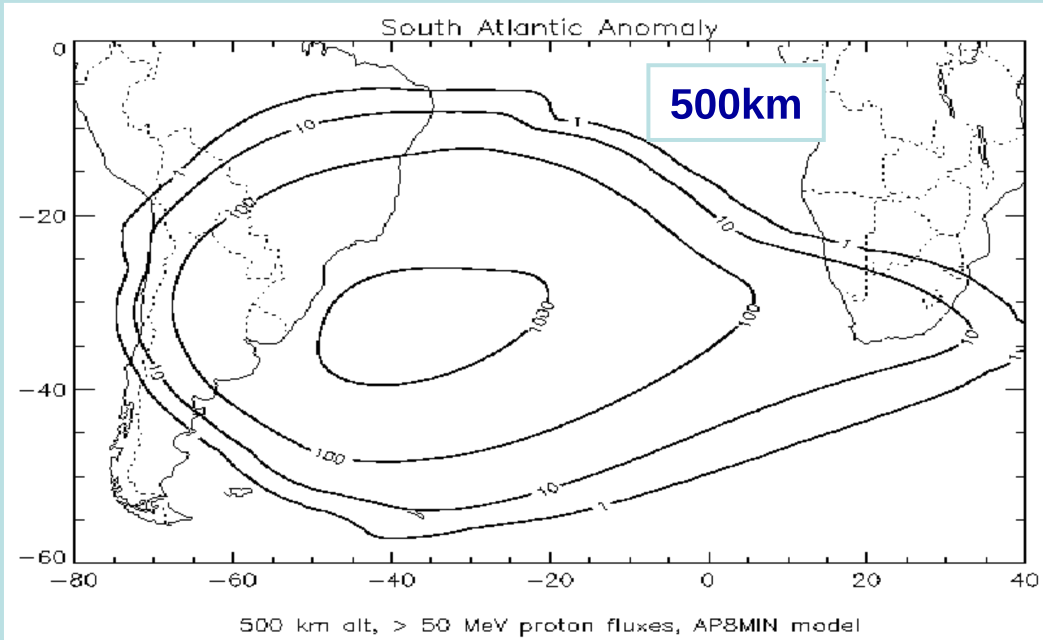


- Inner belt – dominated by protons
  - CRAND = Cosmic Ray Albedo Neutron Decay
  - ~static
  - 100's MeV
- Outer belt – dominated by electrons
  - Controlled by "storms"
  - Very dynamic
  - ~ MeV
- Slot
  - Usually low intensities of MeV electrons
  - Occasional injections of more particles

The South Atlantic Anomaly

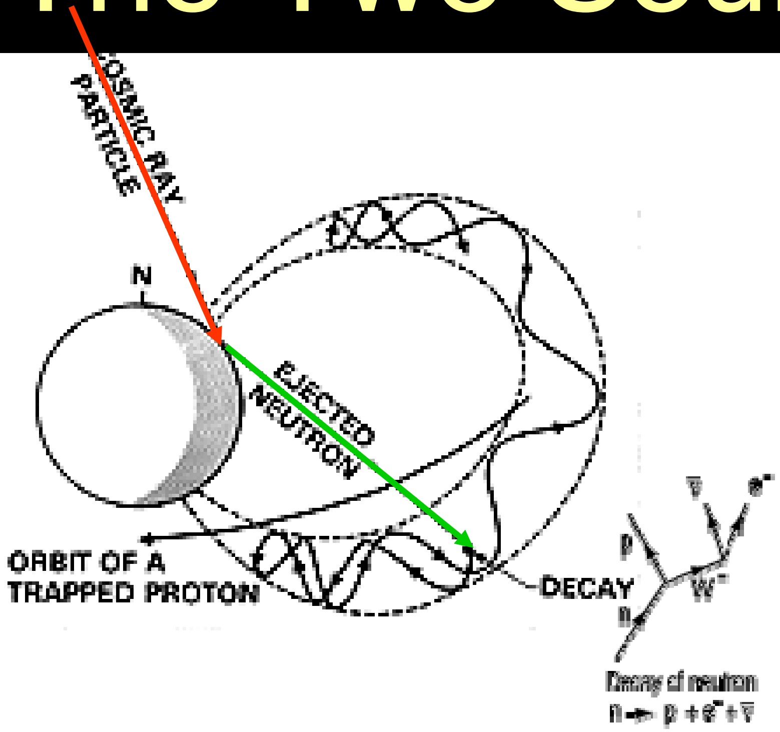


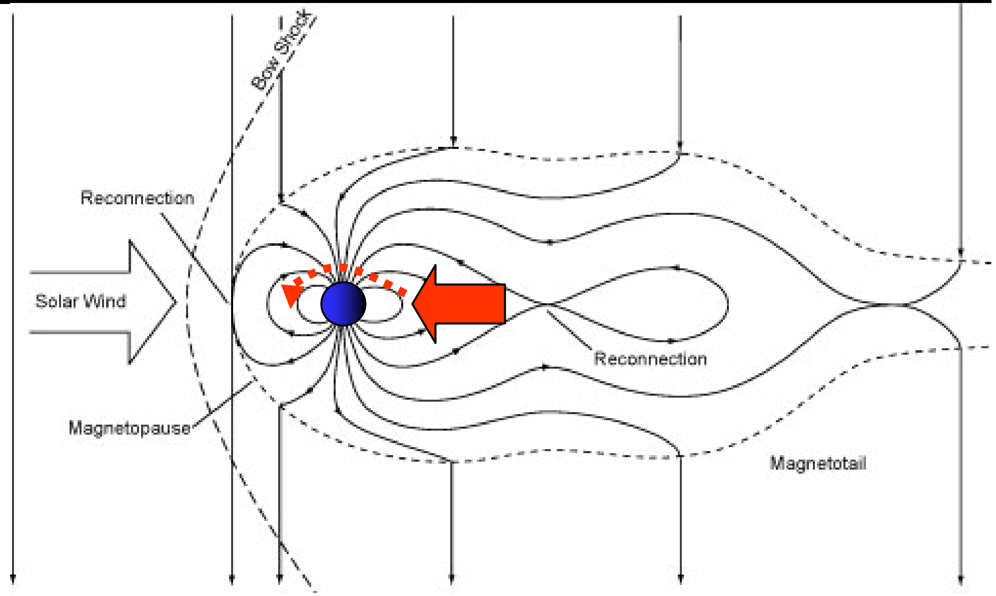




Earth's magnetic field is
an offset tilted and distorted dipole
→ Brings radiation belt down
in the South Atlantic

The Two Source Mechanisms





High Energy Protons (Inner Belt)

Cosmic Ray Albedo Neutron Decay

- Nuclear interaction in atmosphere
- Some products are upward travelling neutrons
- Decay (half life ~10min) into p, e^-
- Results in very stable population

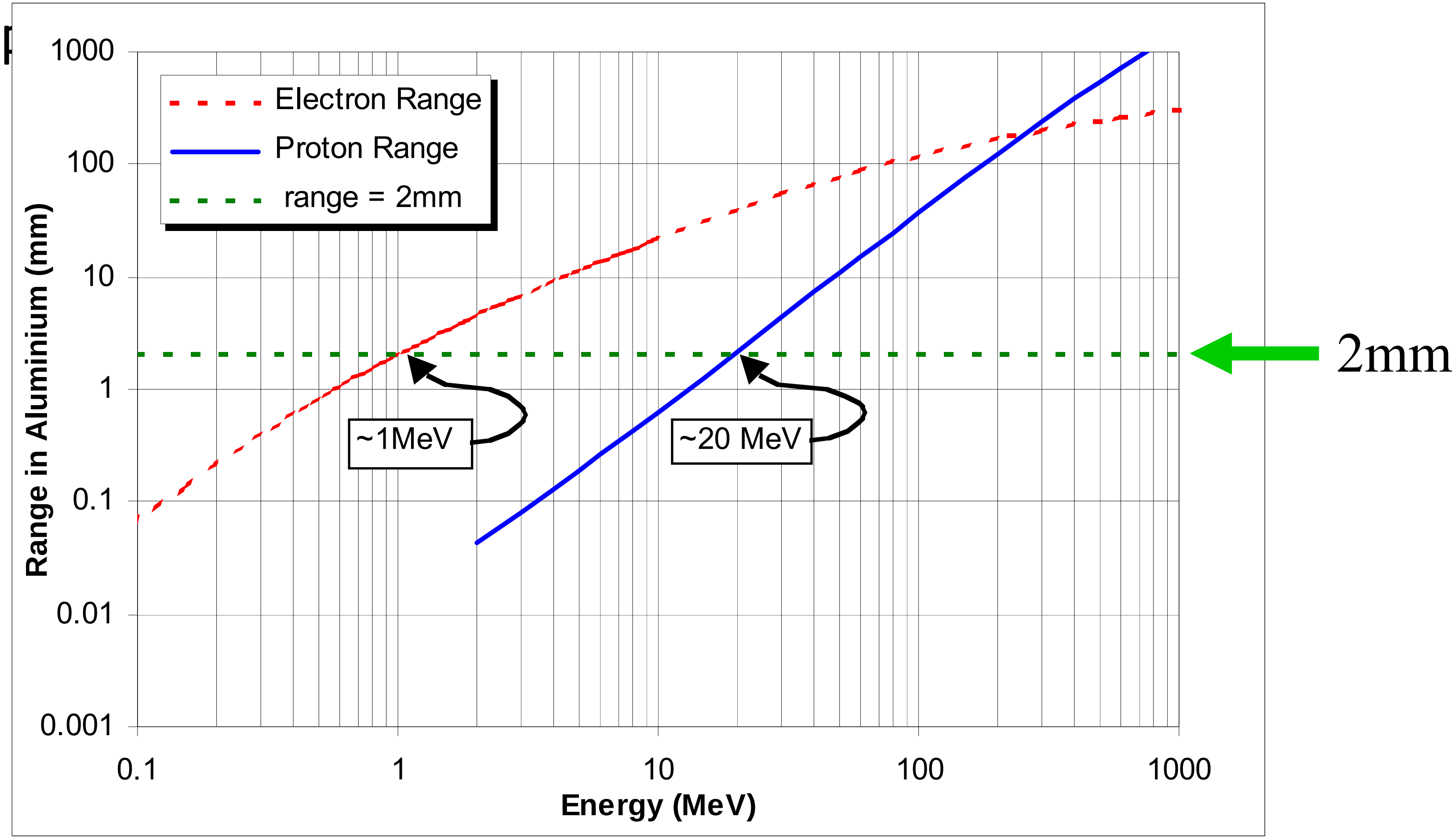
High Energy Electrons (Outer Belt)

Geomagnetic Storms

- Geomagnetic Tail loaded
- Reconnection results in earthward propagation & acceleration
- Subsequent acceleration through wave-particle interactions
- Transport through radial diffusion
- Loss in storms
- Results in very dynamic population

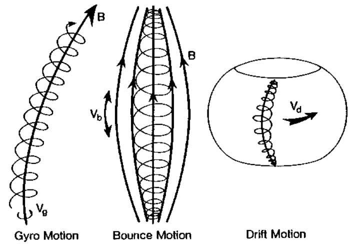
Characteristics of Particles

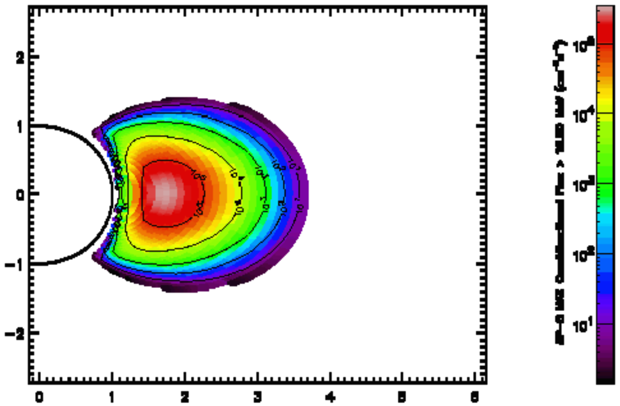
- Which particles cause the problems?
  - Penetrating; damaging => ~MeV electrons; 10's of MeV

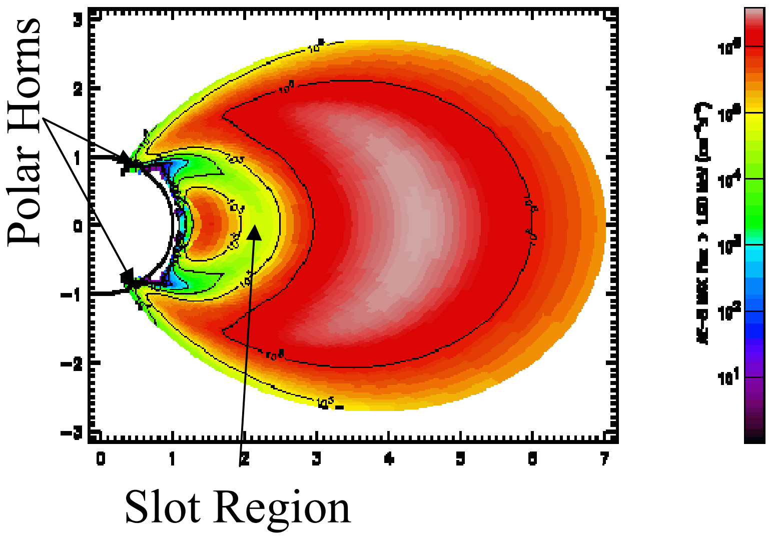


Characteristics of Radiation Belt Particles

- electrons 0.5 - 5 MeV; protons up to 100's MeV
- gyration period $t_c = 2\pi m/(eB)$; radius of gyration of $R_c = mv^2/(eB)$.





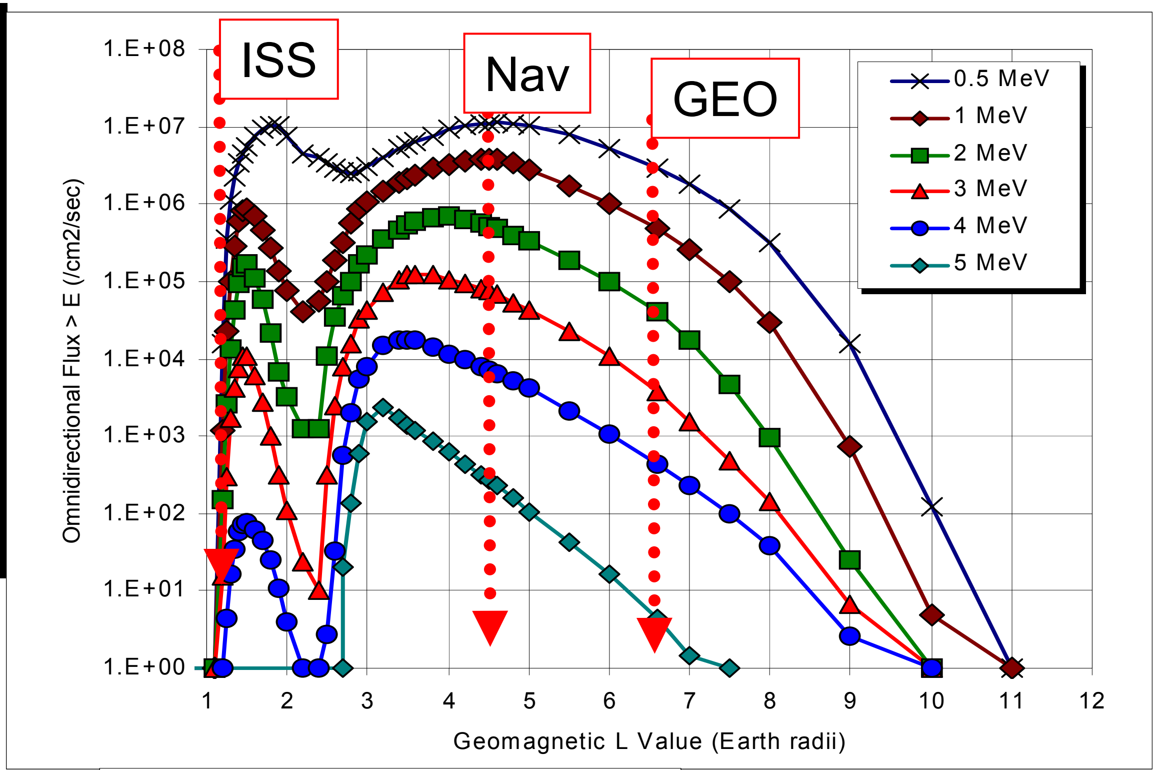


Characteristics of typical radiation belt particles

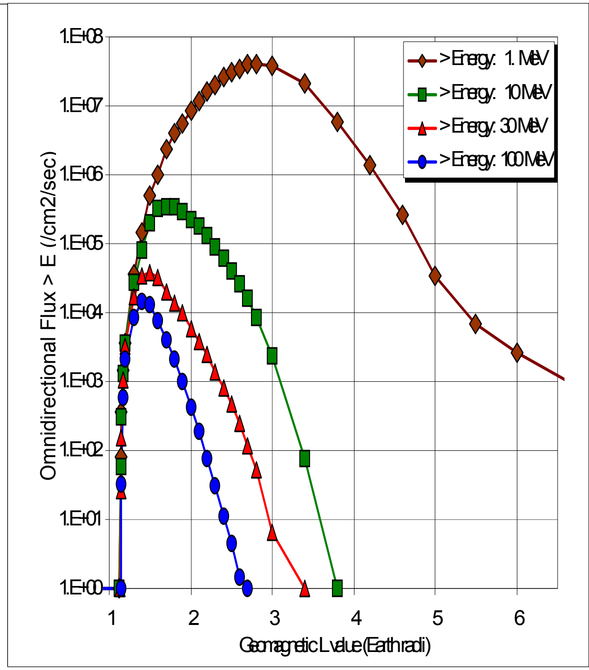
	Particle	
	1MeV Electron	**10MeV Proton**
Range in aluminium (mm)	2	0.4
Peak equatorial omni-directional flux ($cm^{-2}.s^{-1}$)*	4×10^6	3.4×10^5
Radial location (*L*) of peak flux (Earth radii)*	4.4	1.7
Radius of gyration (km)		
@ 500km	0.6	50
@ 20000km	10	880
Gyration period (s)		
@ 500km	10^{-5}	7×10^{-3}
@ 20000km	2×10^{-4}	0.13
Bounce period (s)		
@ 500km	0.1	0.65
@ 20000km	0.3	1.7
Longitudinal drift period (min)		
@ 500km	10	3
@ 20000km	3.5	1.1

* derived from the models discussed later

Models of Radiation Belts provide Engineers with Quantitative Data



electrons

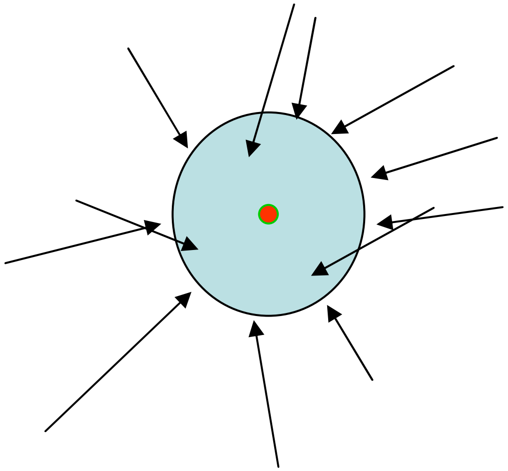


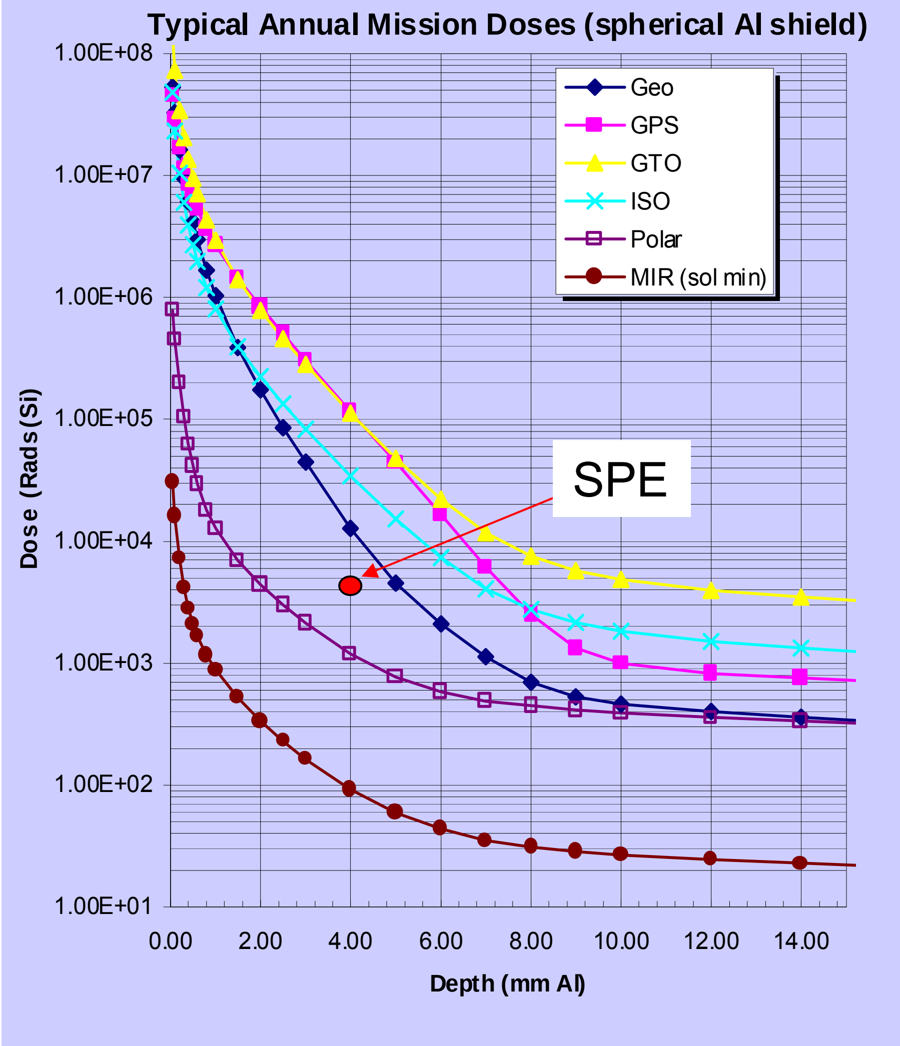
protons

- Based on data from 1960's-1970's
- Work on-going to update them
- Long-term averages; but the outer belt is very stormy

To be Useful: Convert Flux to Dose

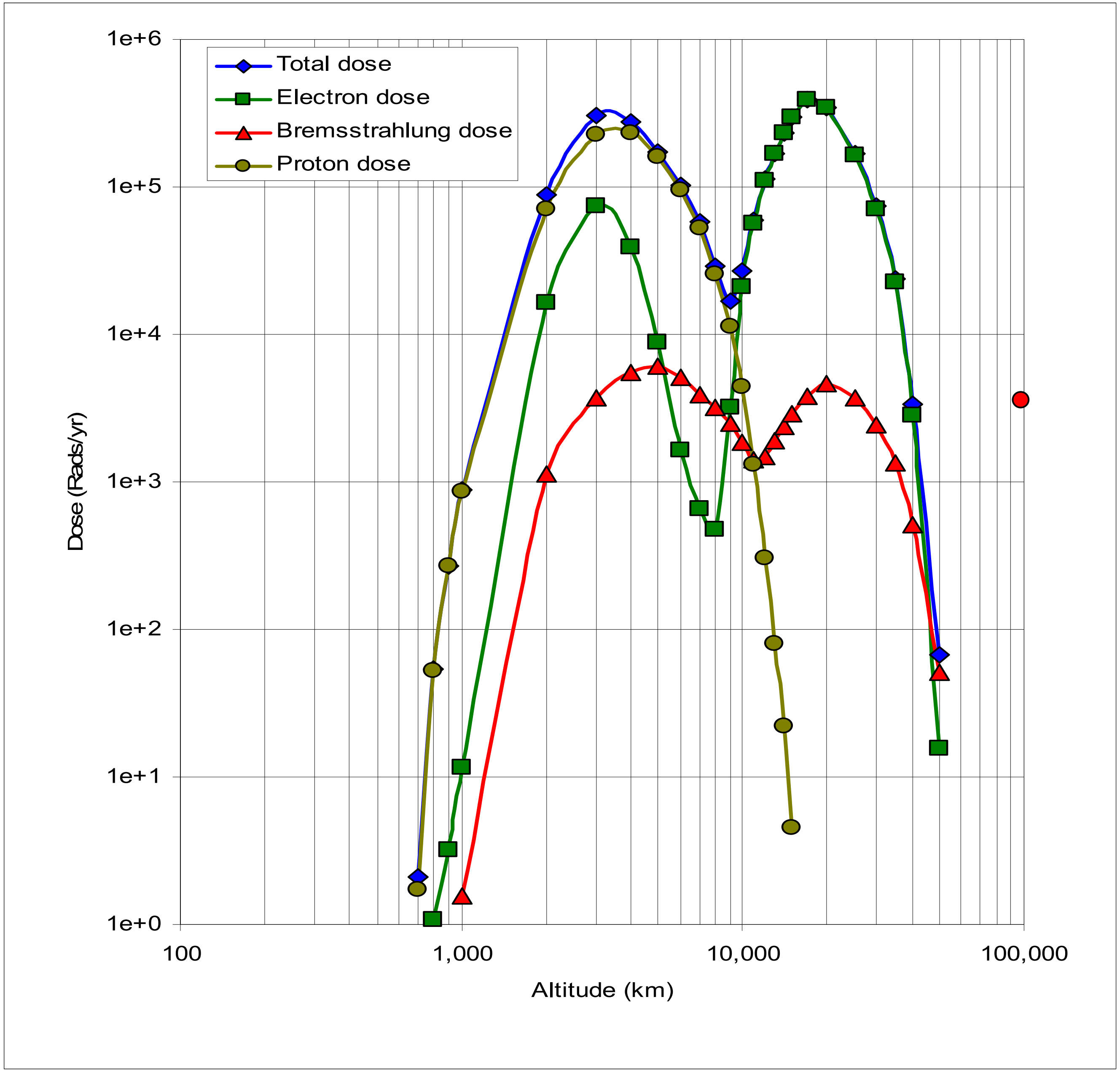
- The ionizing dose environment is normally represented by the dose-depth curve.
- dose as a function of shield thickness in as a function of spherical shielding about a point.



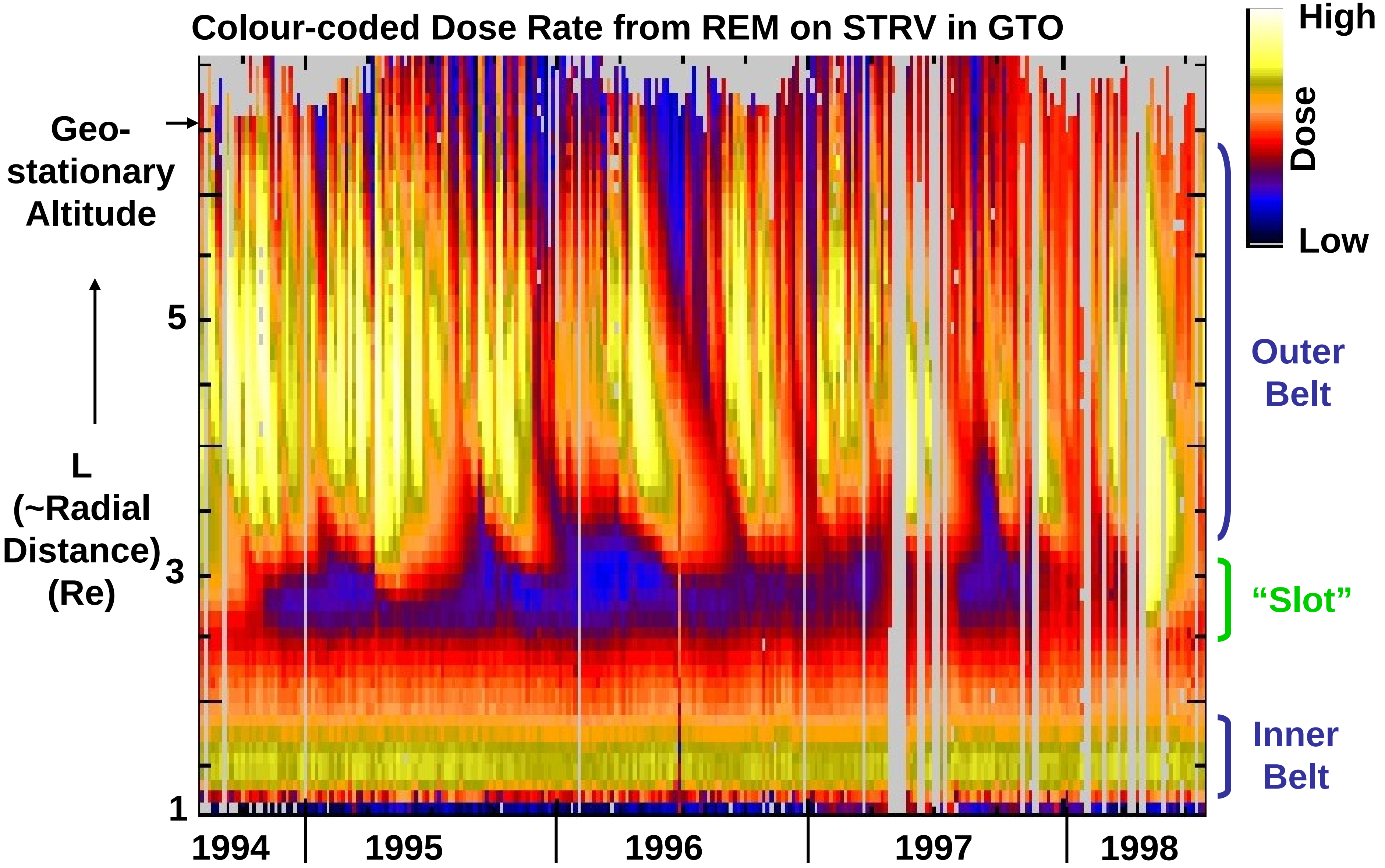


Modern electronic components can fail at a few krad (men die at 100's)

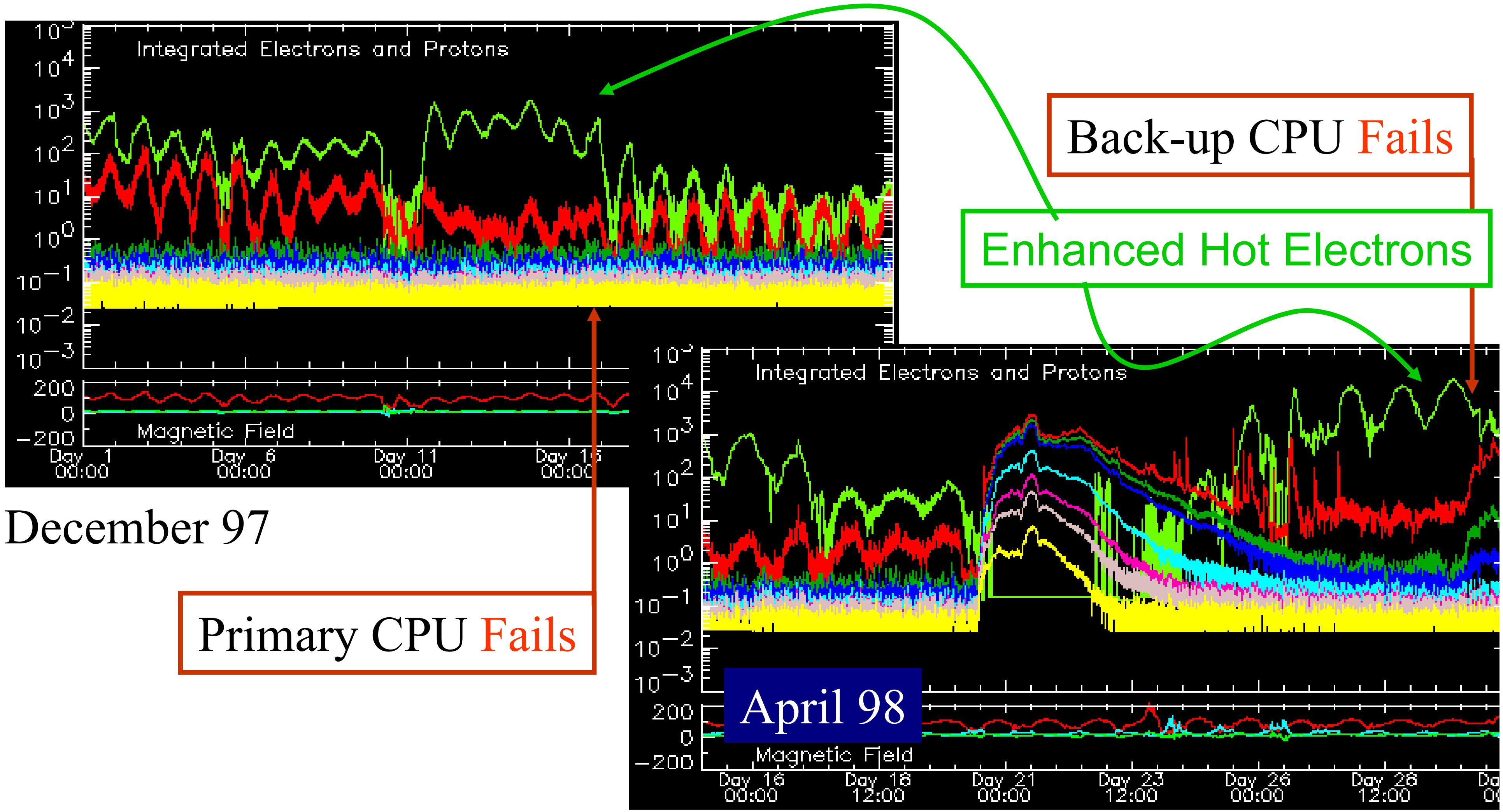
- Circular equatorial orbits for 1 year
- Doses behind 4mm



A Radiation Monitor Crossing the Belts for ~5 Years

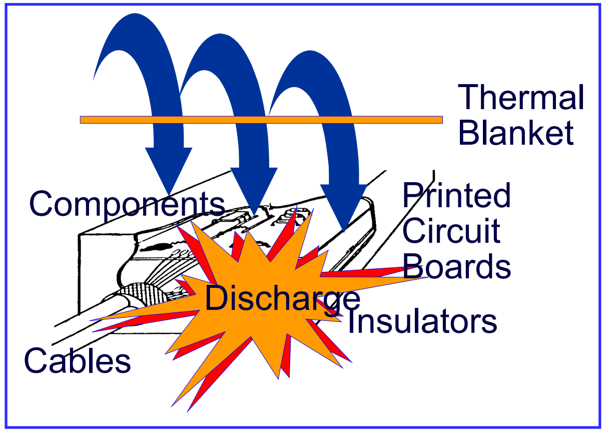


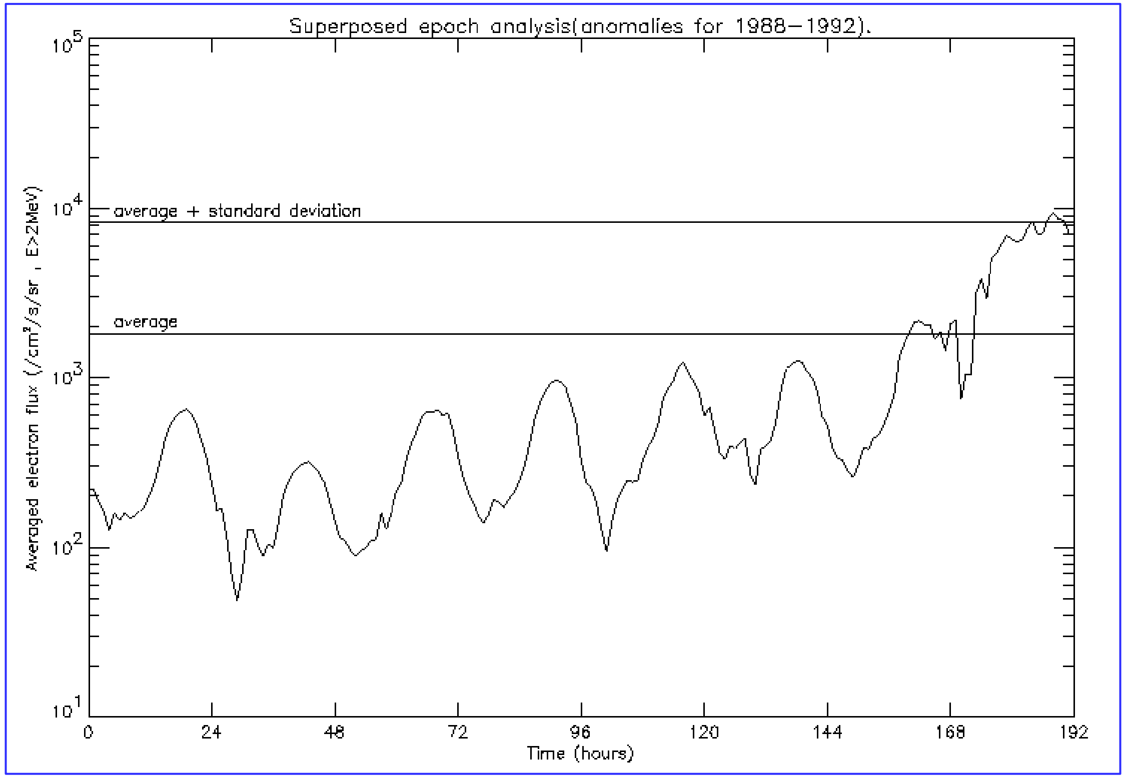
Failure of Equator-S Spacecraft due to "killer electrons"



"Internal" electrostatic charging

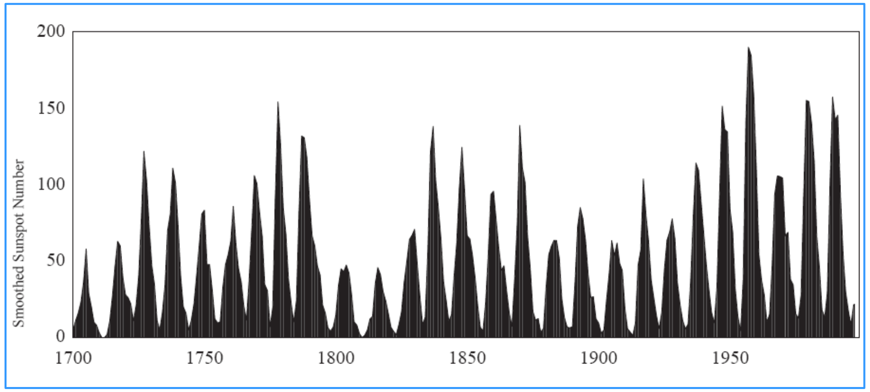
MeV electrons penetrate material and build up an electrostatic charge





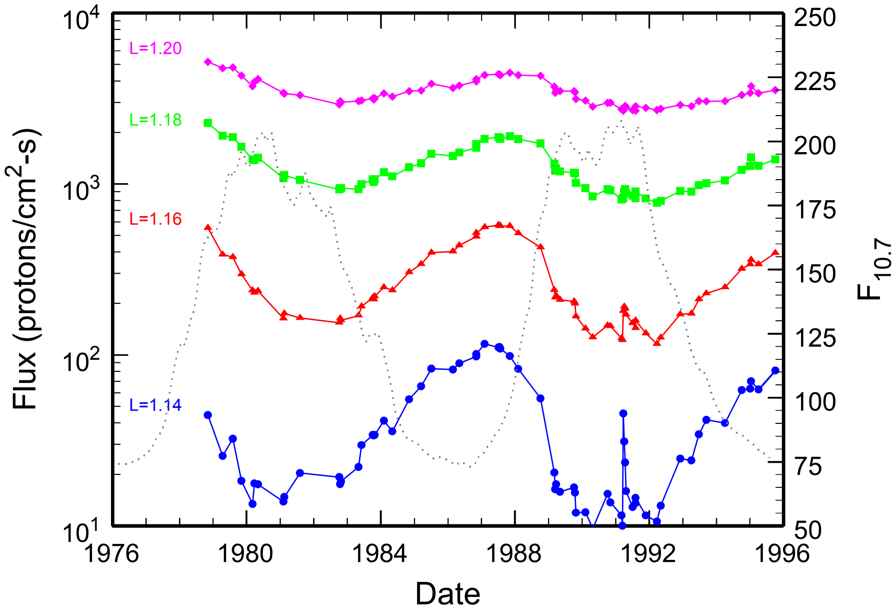
- Meteosat 3 (1988-1992) had many disturbances
- On average, environment was seen to get severe before an anomaly

11-year Solar Cycle Variations



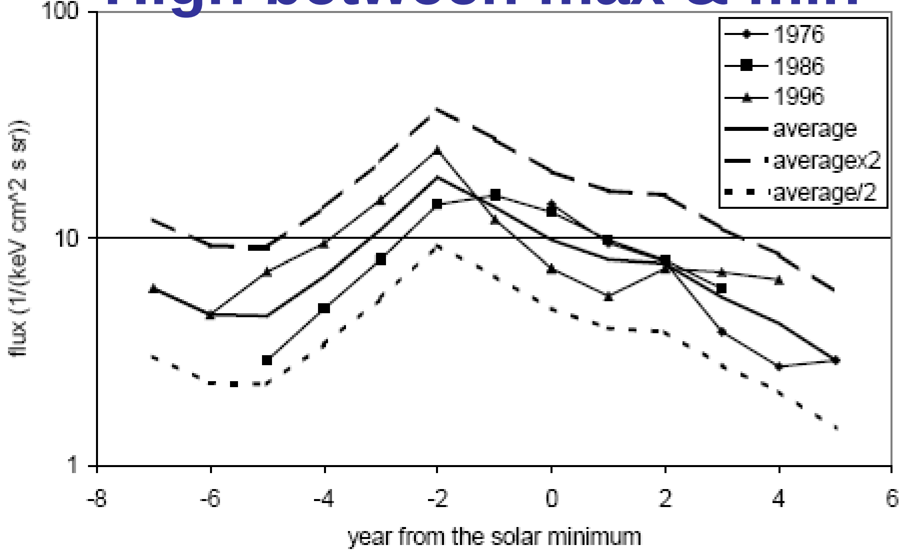
Low altitude protons:

- Controlled by the atmosphere
- Atmosphere expands with increasing solar heating at solar max → soaks up protons
- **High at solar min!**



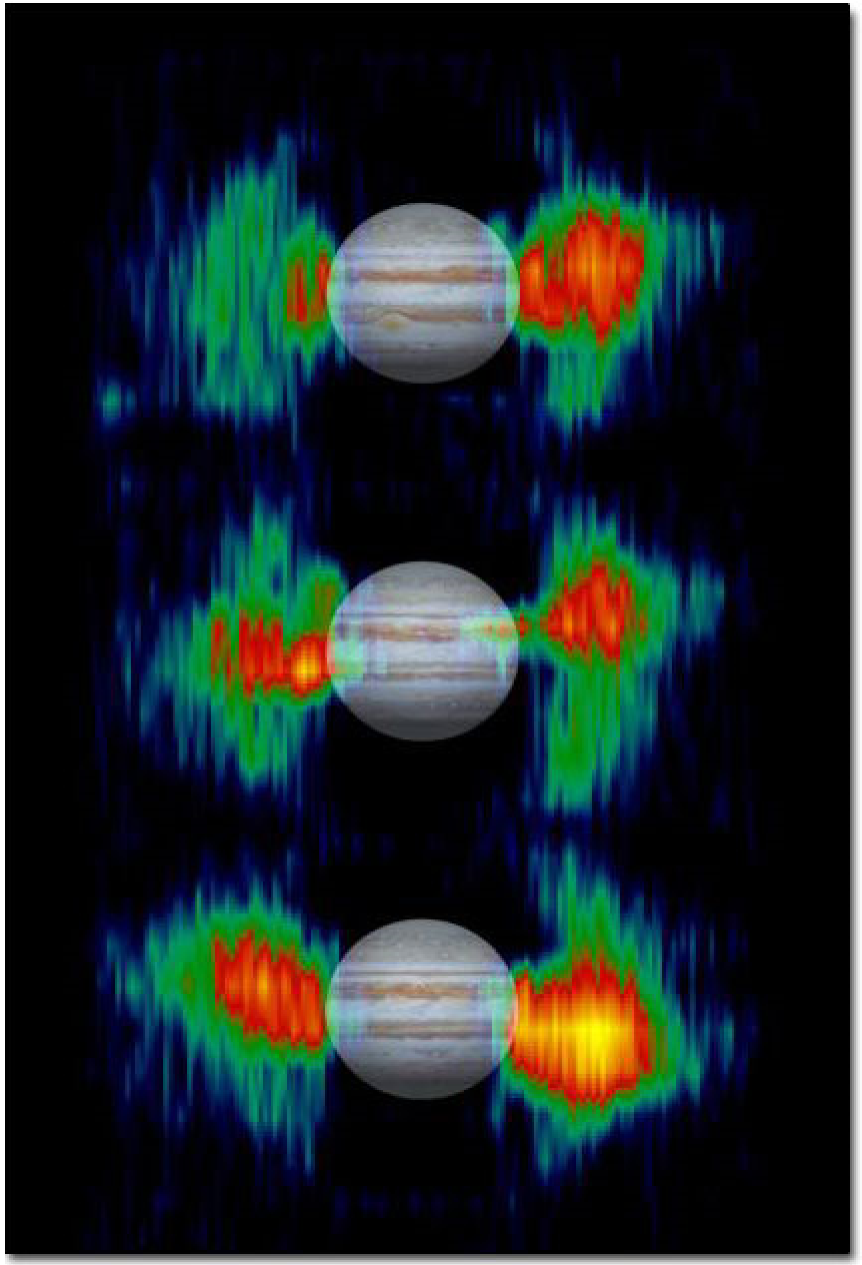
High-altitude electrons:

- Controlled by storms
- Coronal holes and high speed streams after solar max have greatest effect
- **High between max & min**

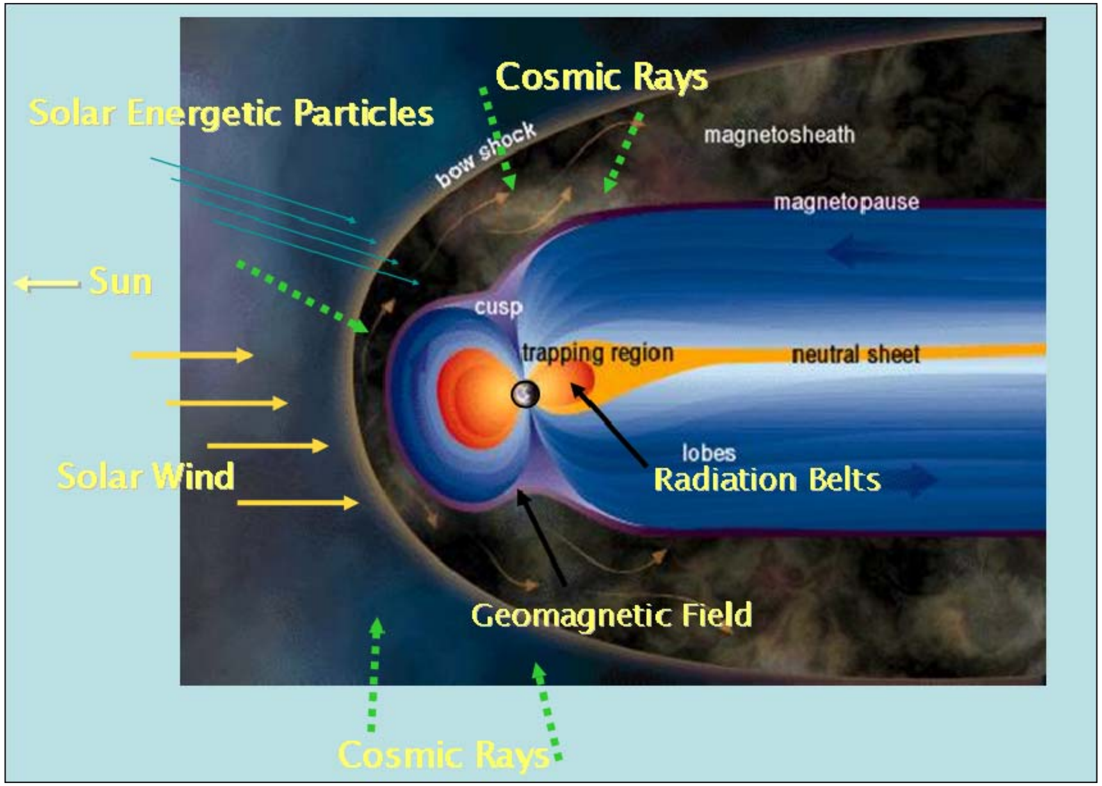


Other planets

- Jupiter has a very severe radiation belt
- ESA is studying a possible mission to the Jovian system
- Intensive work on-going to understand and cope with the environment
- Saturn also has a significant RB environment



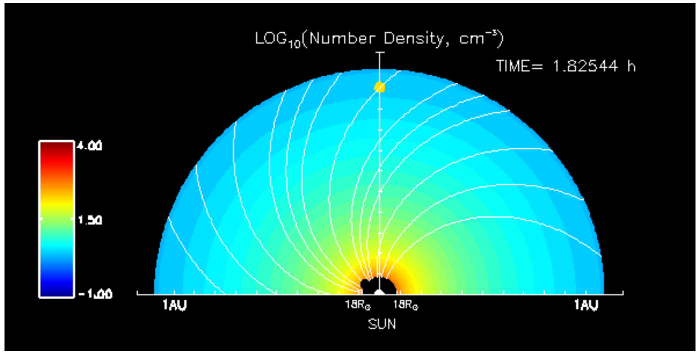
Three main sources of radiation



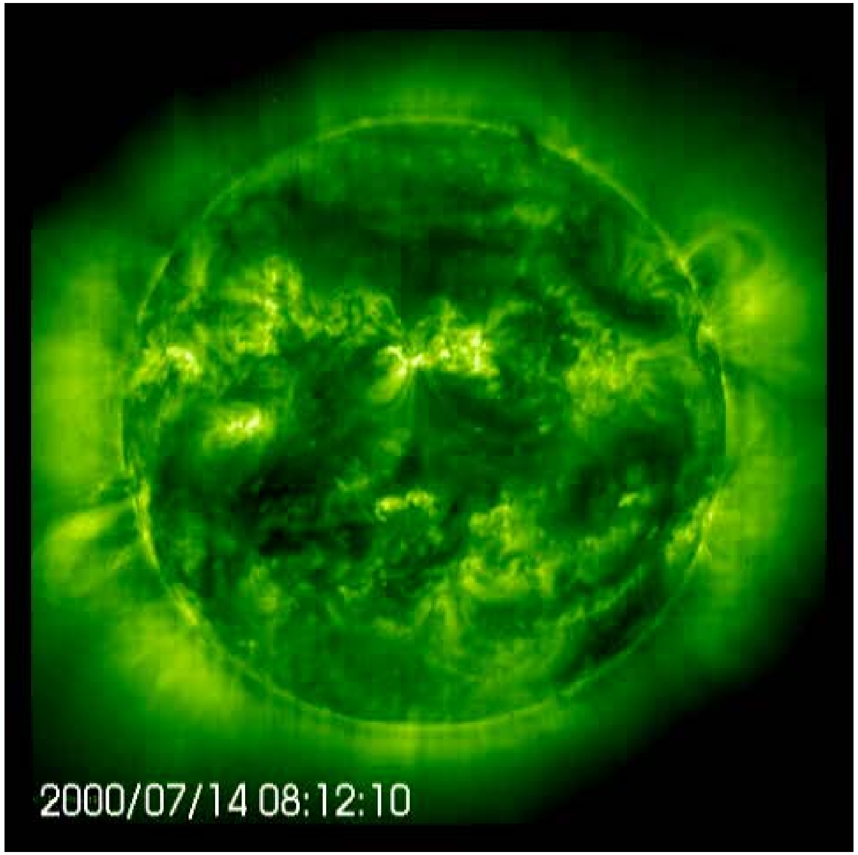
- Radiation Belts
  - High radiation dose
- Solar Particle Events
  - Sporadic but dangerous when they happen
- Galactic Cosmic Rays
  - Low flux but highly penetrating

Solar Particle Events

- Associated with energy release on the Sun
- Particles can be accelerated near to the Sun and all the way to Earth in the plasma "shock" wave

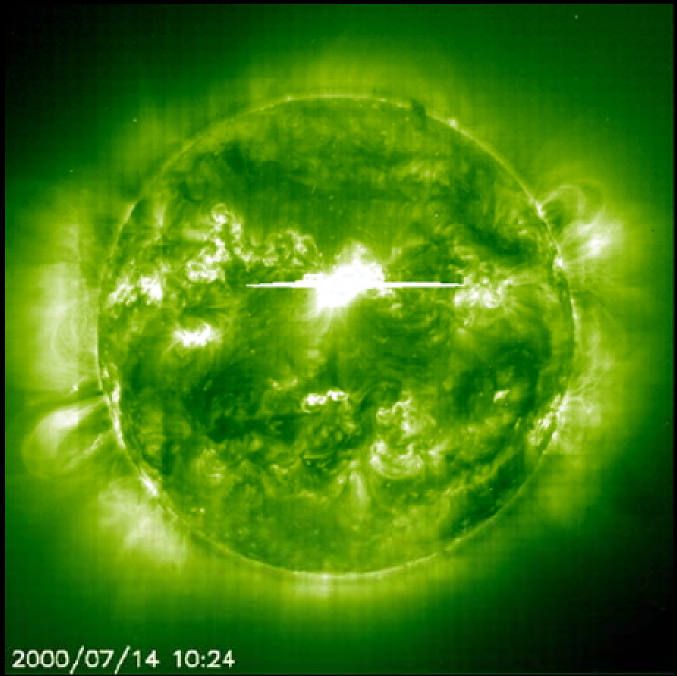


- Often associated with "flares"
- First particles can arrive in minutes
- High fluxes can last for days
- Geomagnetic field shields some orbits

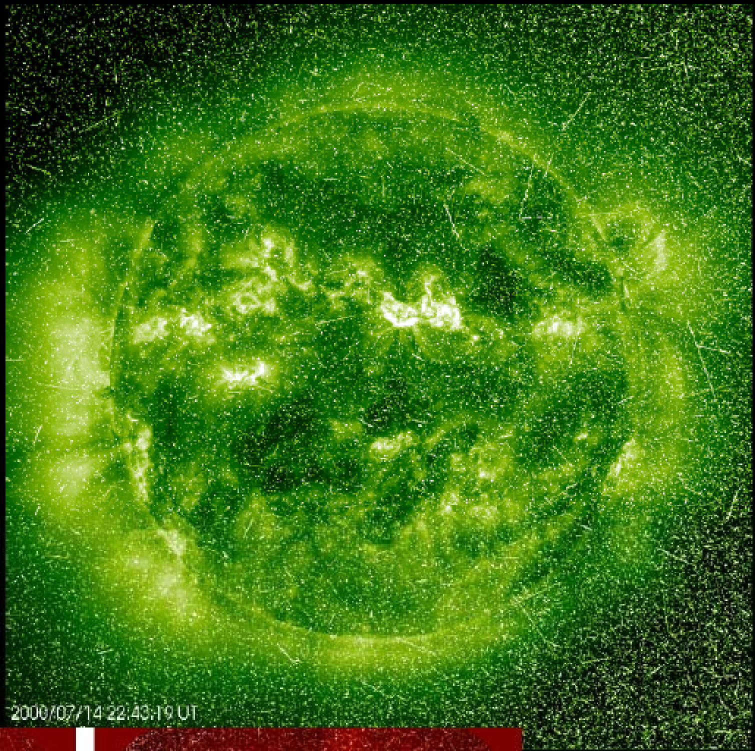


link

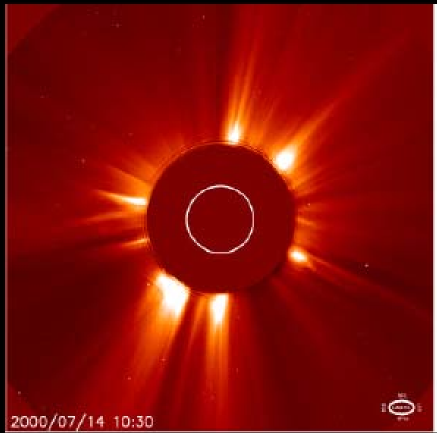
A strong solar flare triggers the largest particle storm of this solar cycle near solar maximum

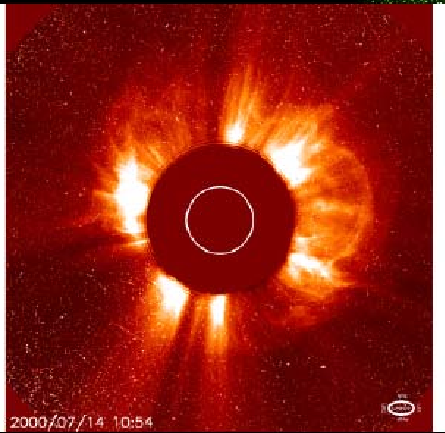


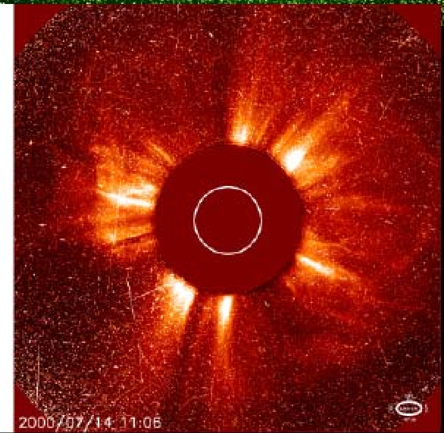
A powerful flare flashes . . .



and hours (even days) later high-energy protons were still smacking SOHO



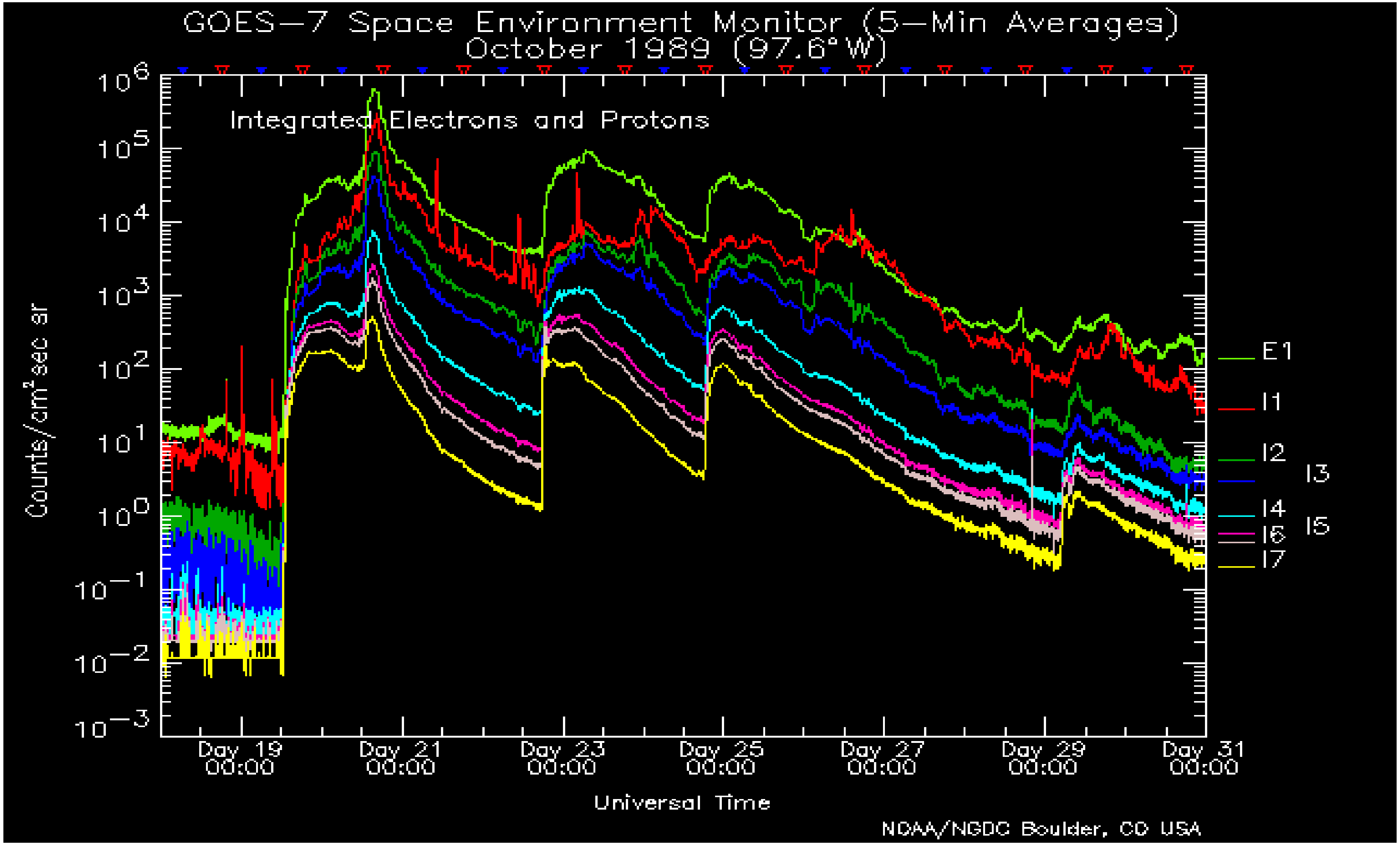




Protons unleashed by the flare begin striking SOHO in minutes

October 1989: Example of a very large SPE

Multiple events, lasting ~10 days

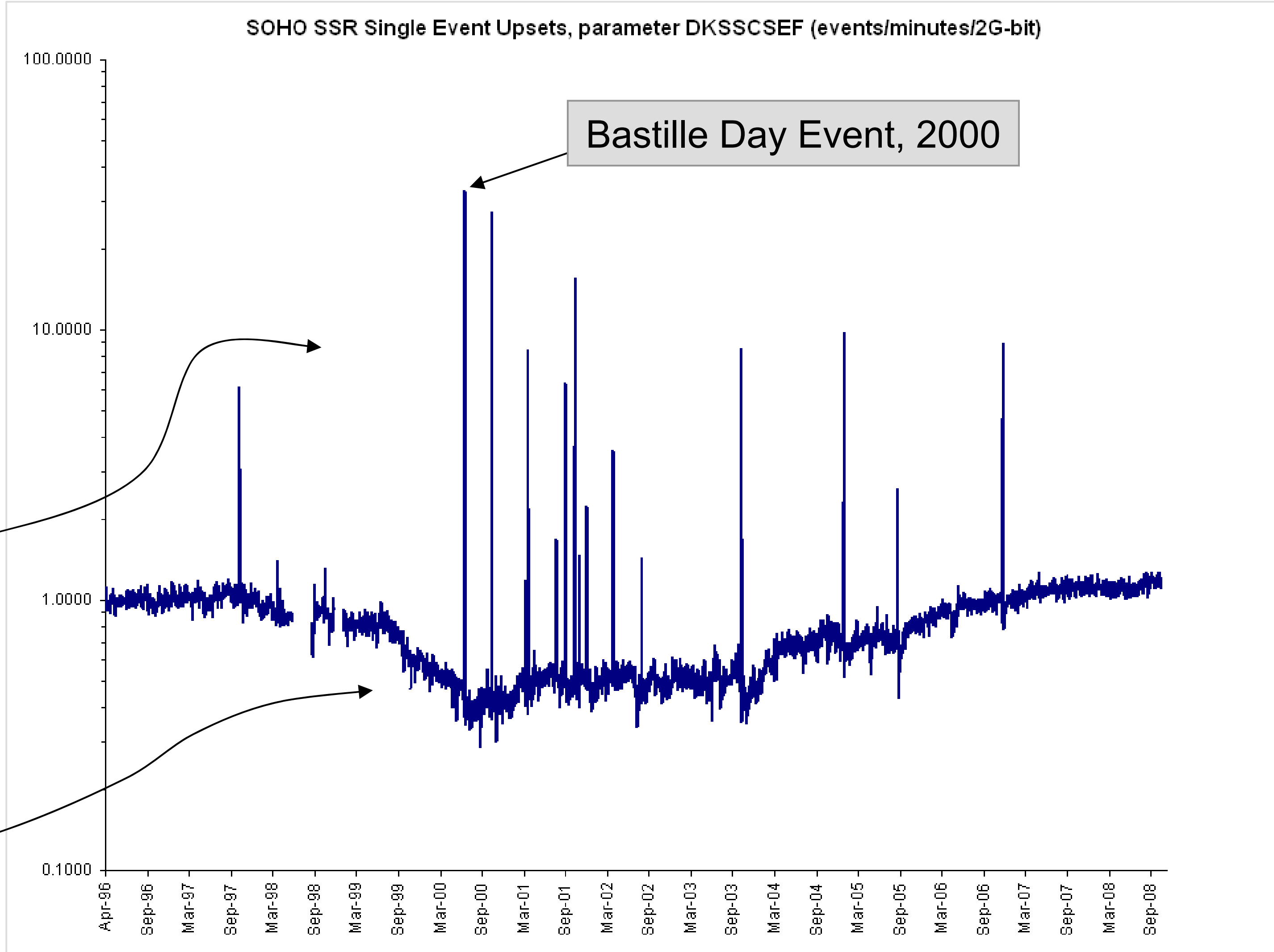


More Radiation Effects on SOHO

Errors in on-board memory: ***Single Event Upsets***

Caused by solar particle events

And background cosmic rays

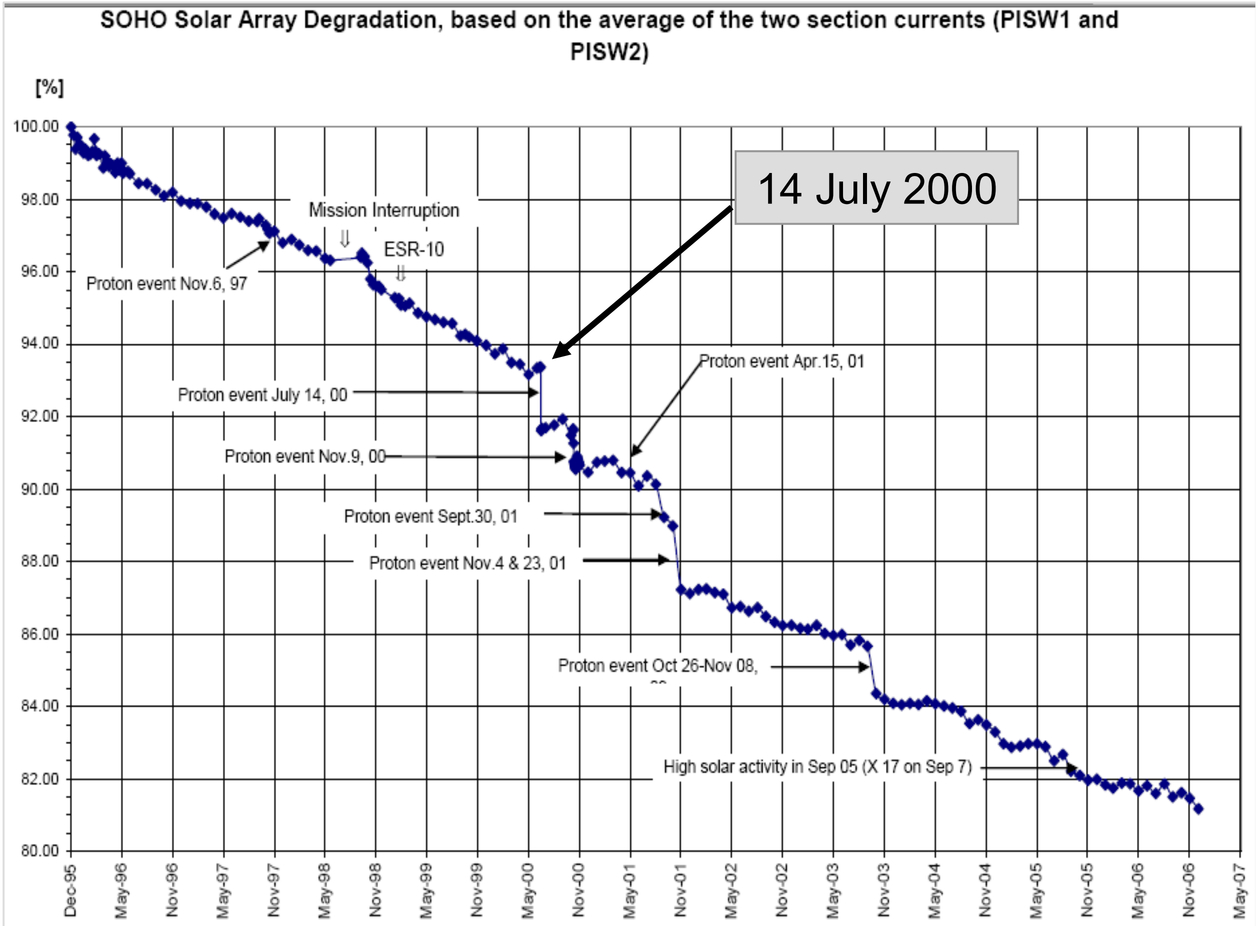


Courtesy ESA SOHO Team GSFC
Fleck, van Overbeek, Olive, …

More Radiation Effects on SOHO

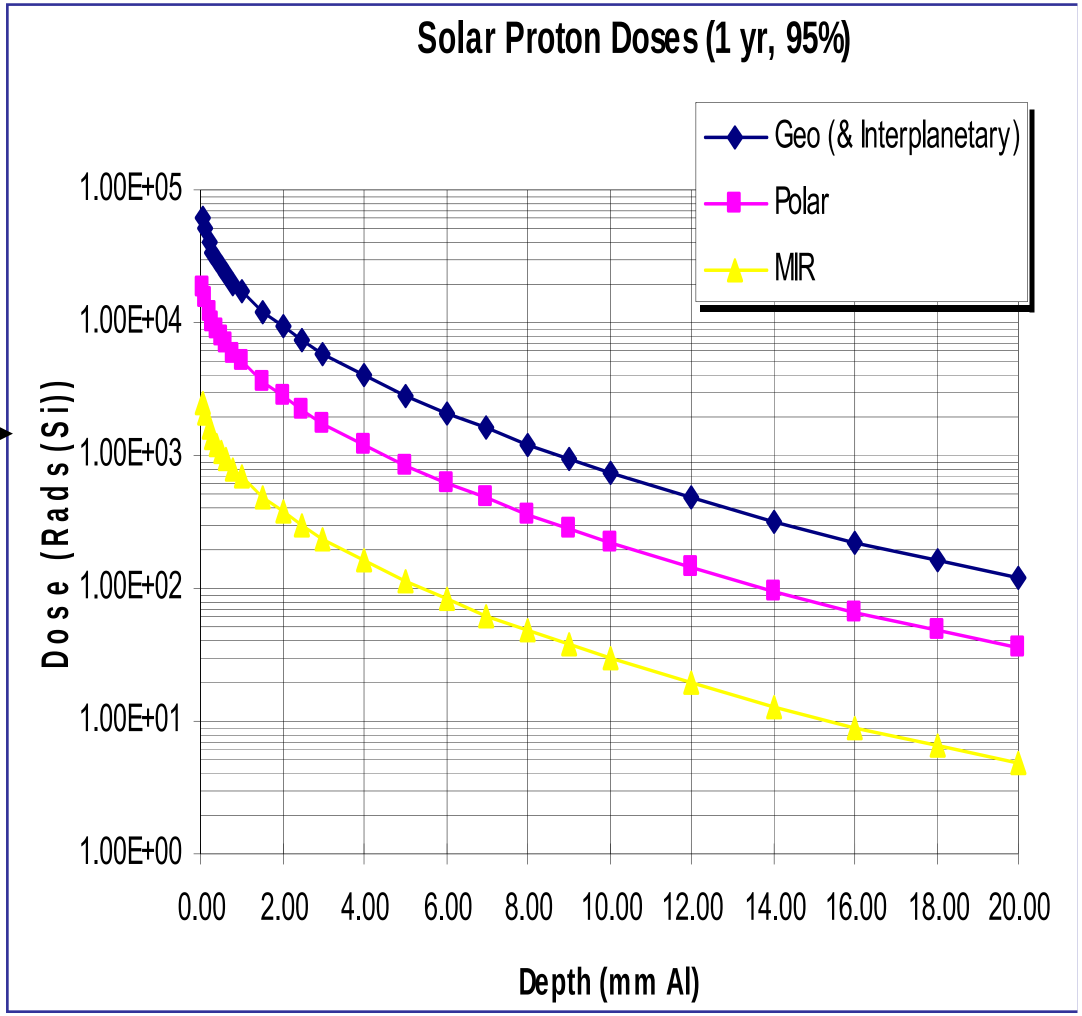
Solar Array degradation

- Steady degradation is normal ageing
- Steps are due to SPEs

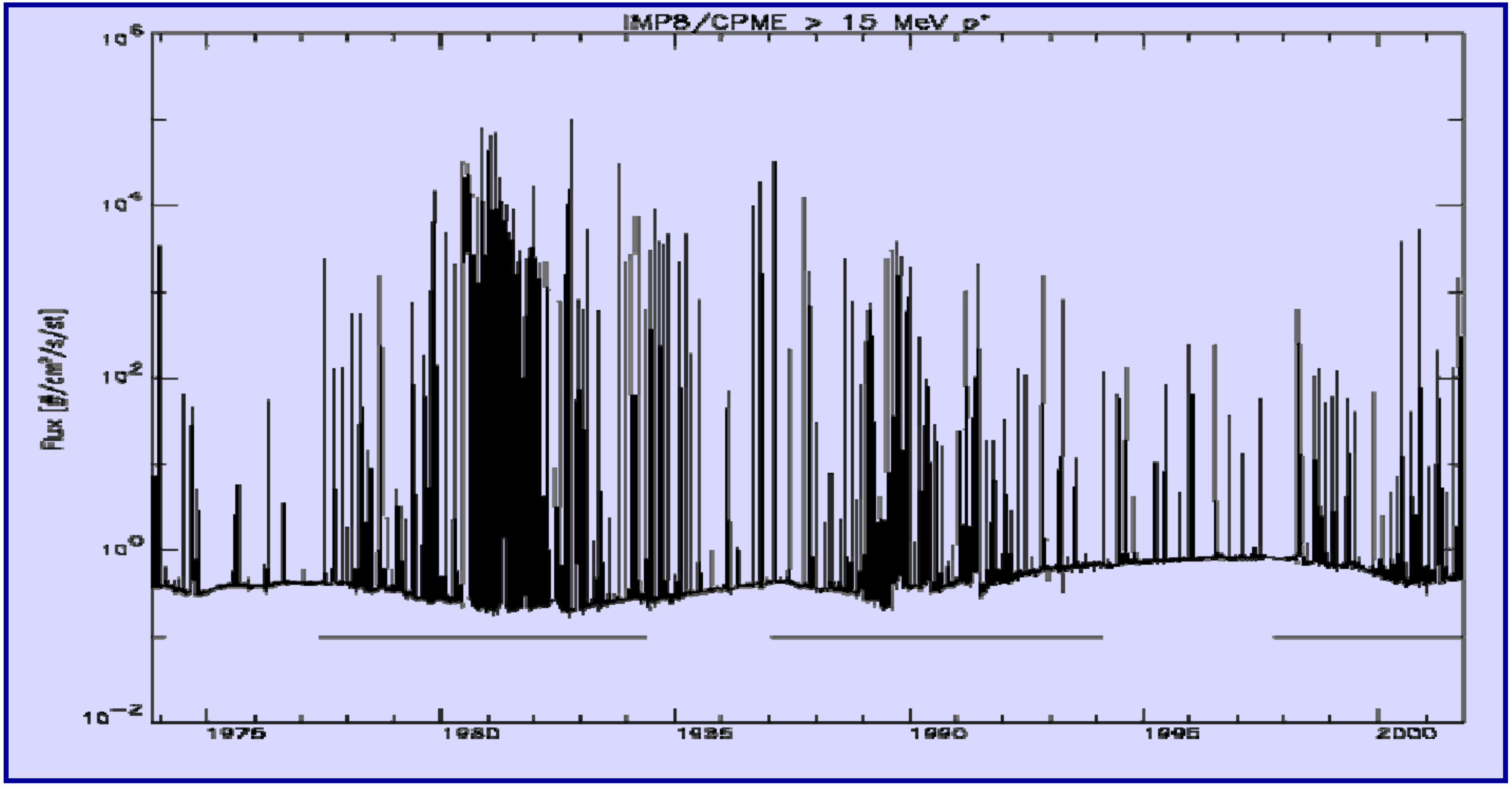


Statistical Models

- Give time-integrated fluence for given mission durations, orbits, “risk” level
- Fluence predictions converted to dose →
- Effect of “geomagnetic shielding”

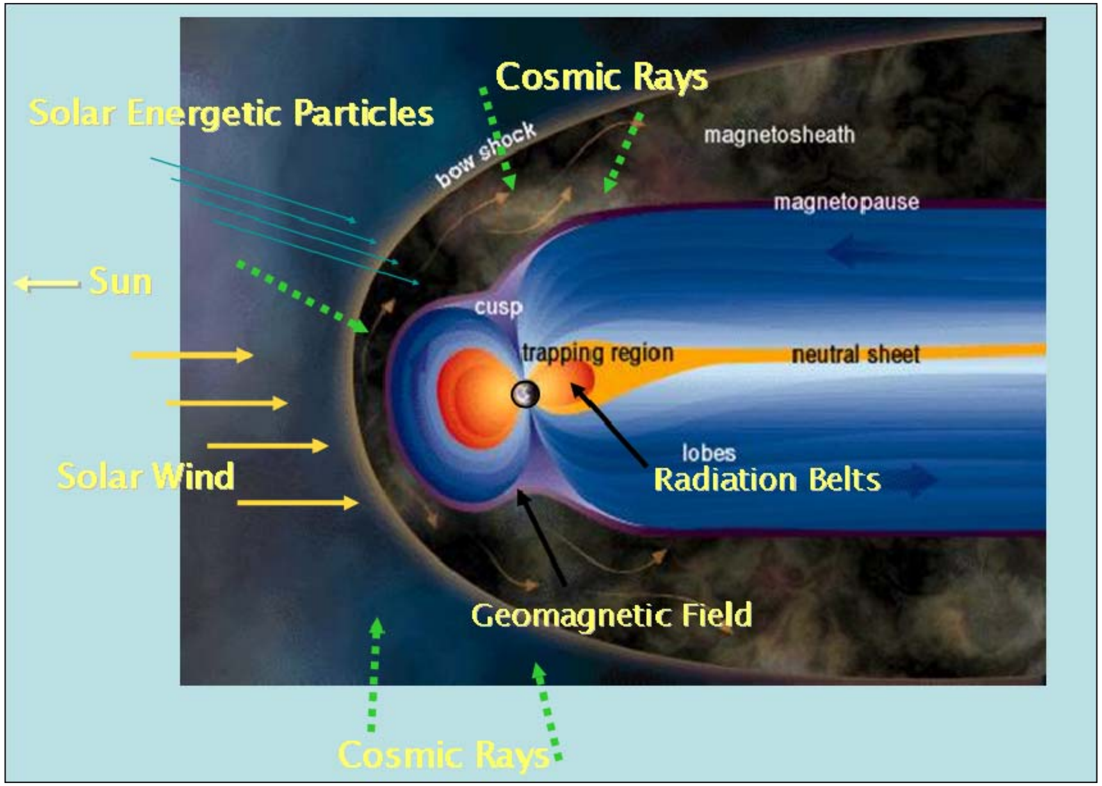


Long Term Record of Solar Particle Events



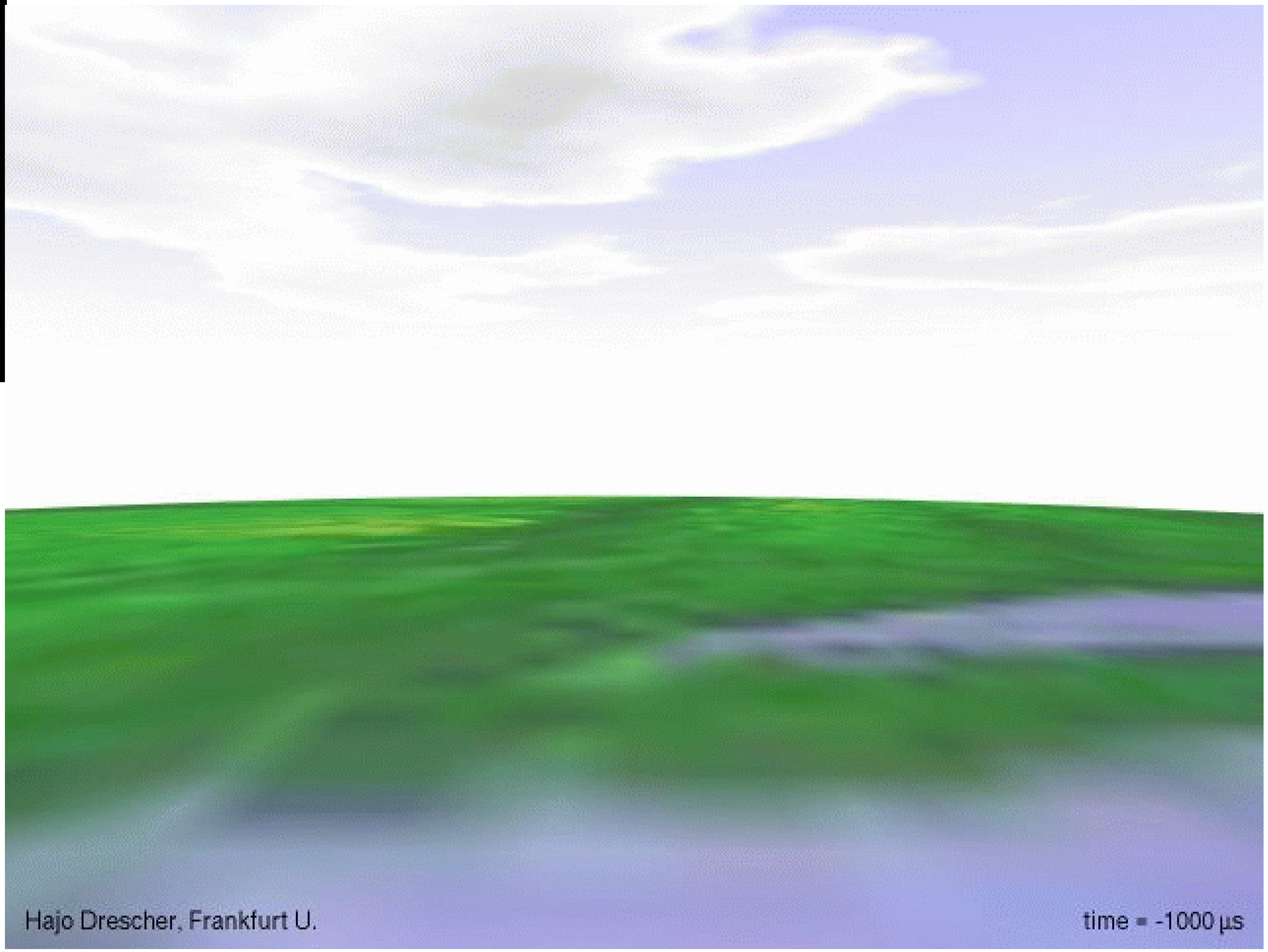
- More in "maximum" solar activity years
- Highly unpredictable
- Design for by making statistical assessments

Three main sources of radiation

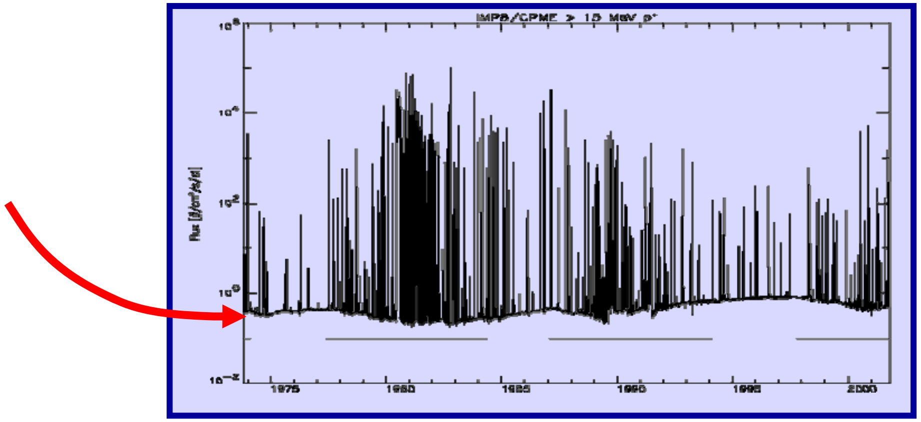


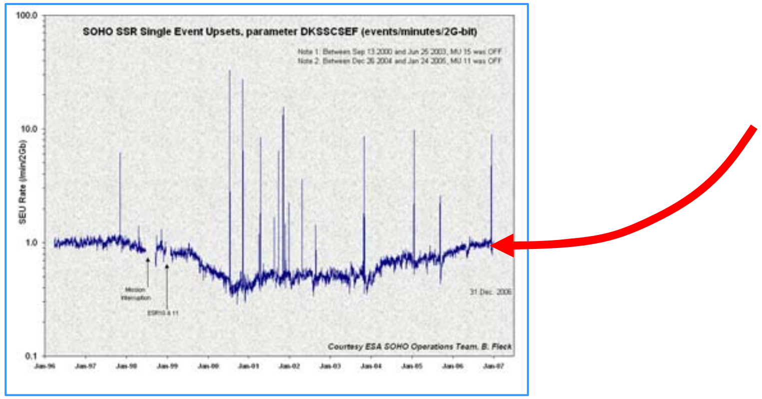
- Radiation Belts
  - High radiation dose
- Solar Particle Events
  - Sporadic but dangerous when they happen
- Galactic Cosmic Rays
  - Low flux but highly penetrating

Galactic Cosmic Rays



- Seen as a baseline on particle measurements and SEUs
- Low flux of very high energy heavy ions
- Very penetrating and ionising in matter
- Geomagnetically shielded



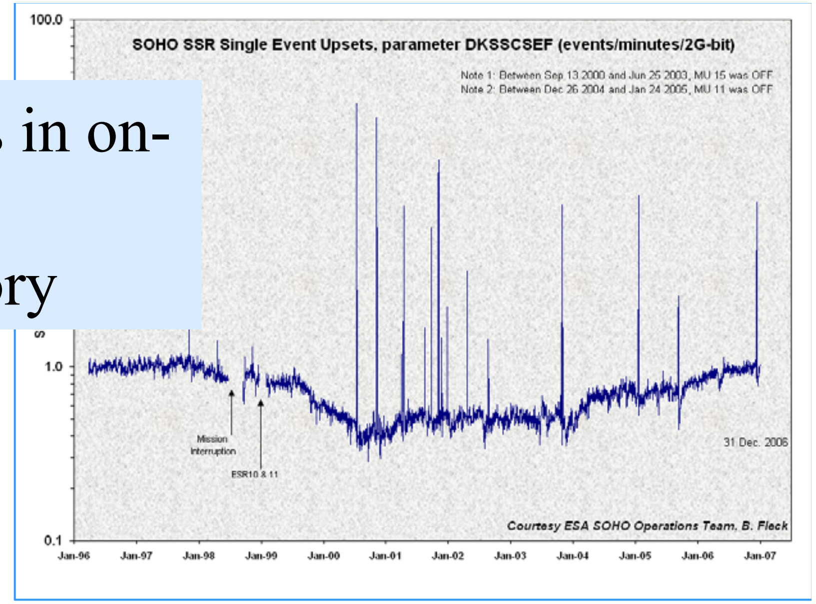


Summary of Radiation Effects

Effect	Assessment Parameter	Main Interaction
Component Degradation	Ionizing Dose	Ionization
Solar Cell Degradation	Non-ionizing dose	Displacements
SEU	Rate	Ionization
Radiation Background	Rate	Ionization
Optoelectronic Degradation	Non-ionizing dose	Displacements
Astronaut Hazards	Dose Equivalent	Ionization
Internal Charging	Fields	Ionization

We saw examples from SOHO

Errors in on-board memory



Solar array degradation

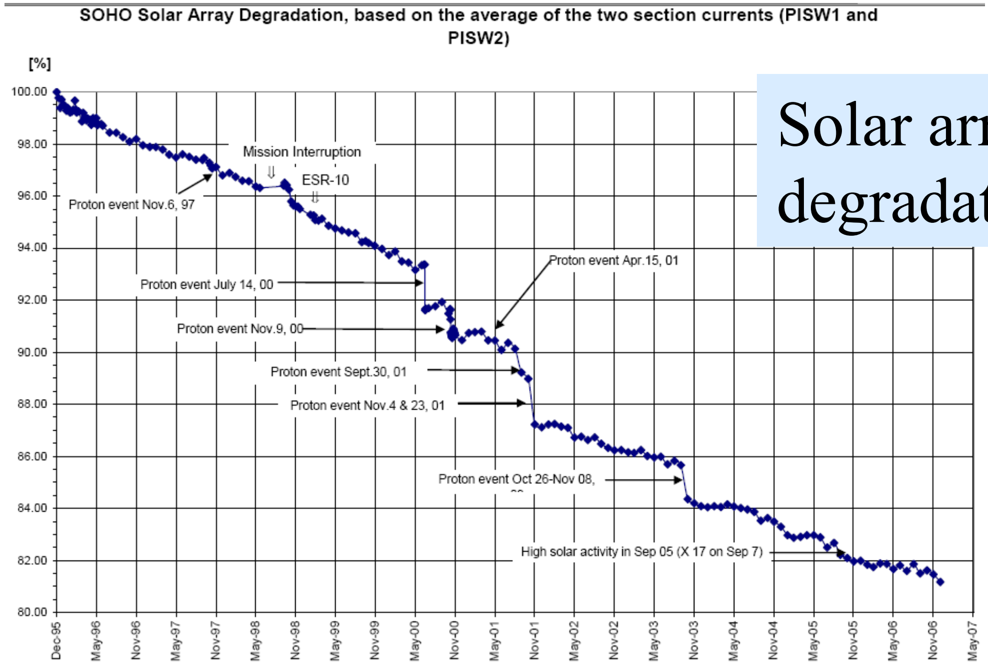
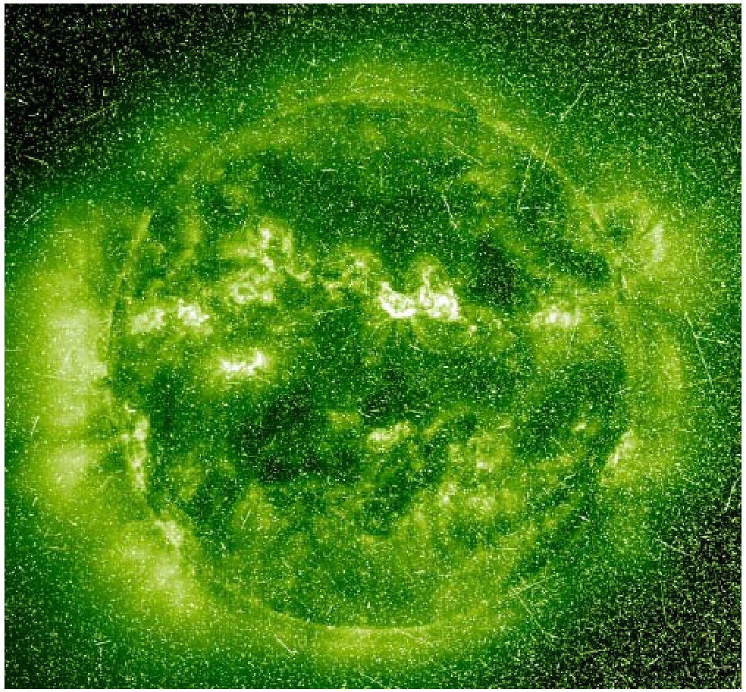
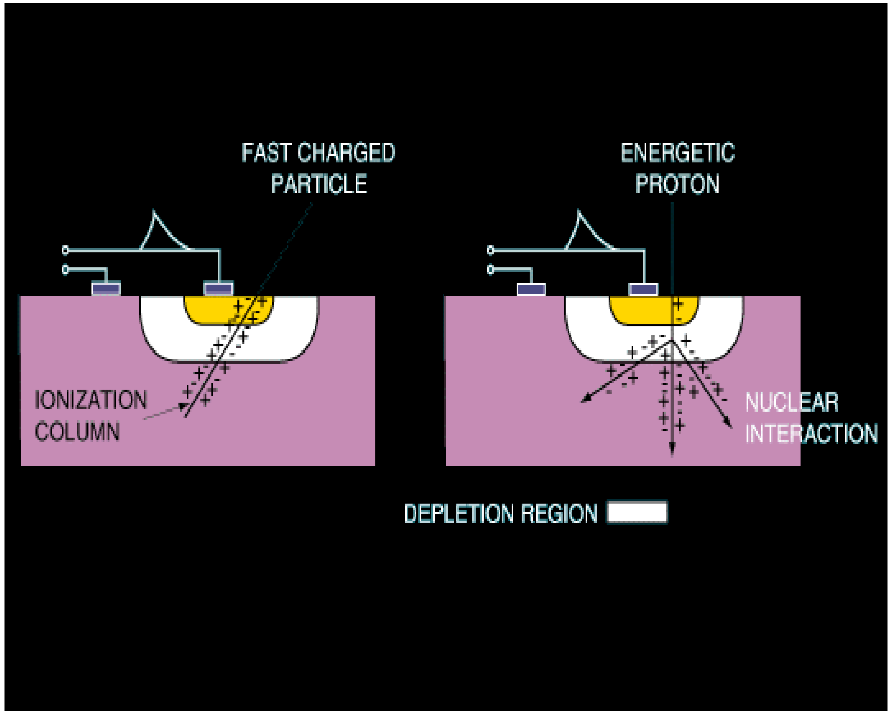


Image background noise



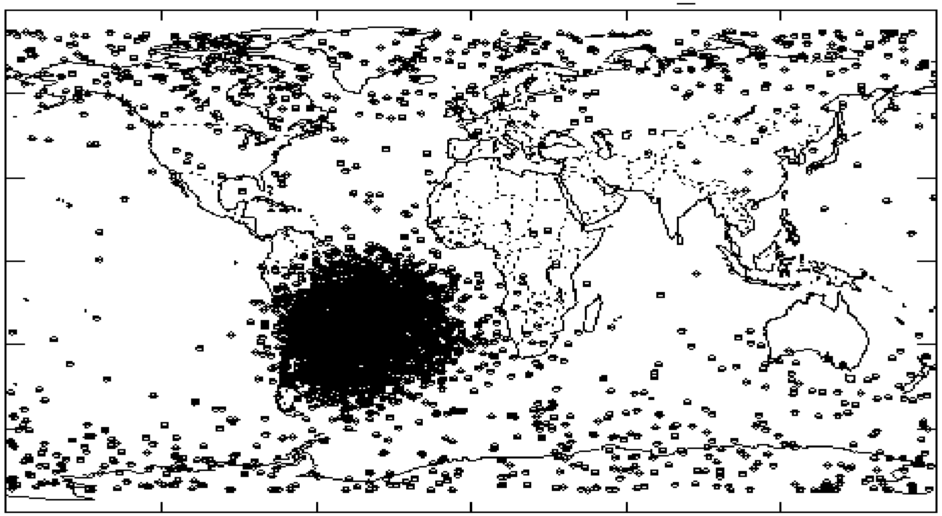
"Single-event" effects

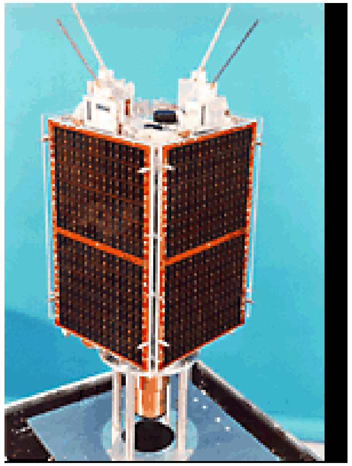
- A particle crosses ("hits") a (small) sensitive target
- The energy deposited causes a noticeable effect:
  - ionisation charge causes a bit to "flip" (SEU) e.g. SOHO memory
  - pixels of a CCD are "lit up" by creation of free charge e.g. SOHO CCDs
  - DNA is damaged
- Component SEU is a growing problem
  - Intensive work on component testing at accelerators during a project's development



Two basic mechanisms

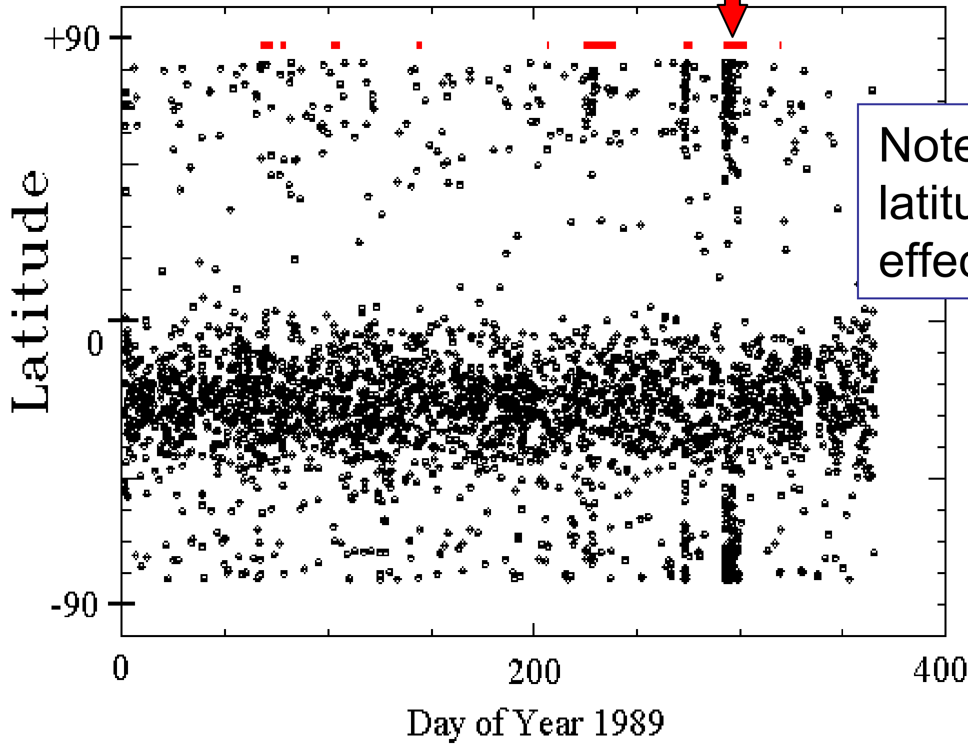
SEUs on UoSAT-3 microsatellite memory





Mapped

Time behaviour



Note latitude effects

SEUs are from:

- Cosmic rays and solar ions at high latitude
- Radiation belt proton nuclear reactions in the South Atlantic anomaly

Manned Missions Away from LEO Risk High Doses

(prompt radiation sickness at ~100 REM (1 Sv); death at 400)

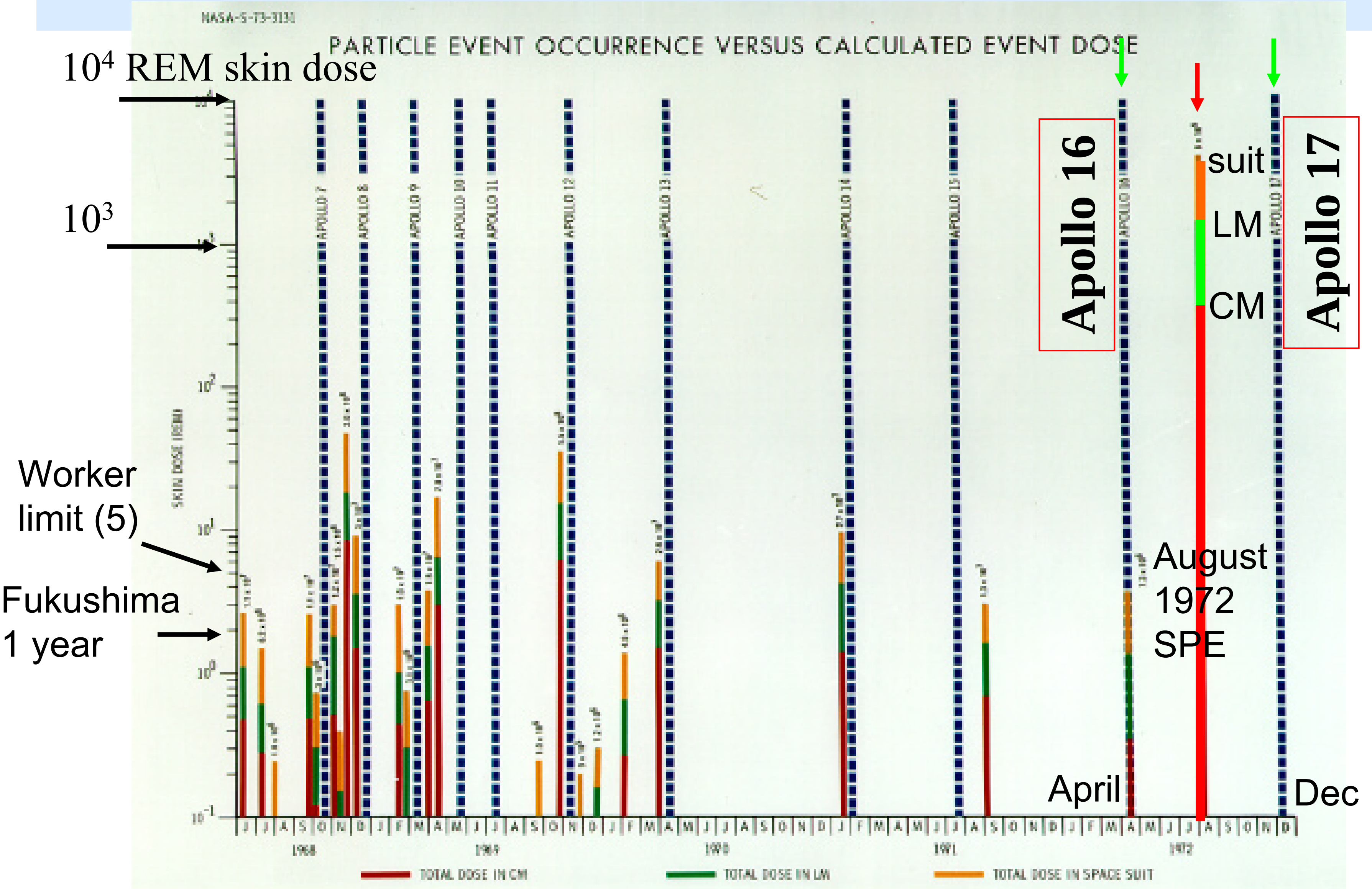
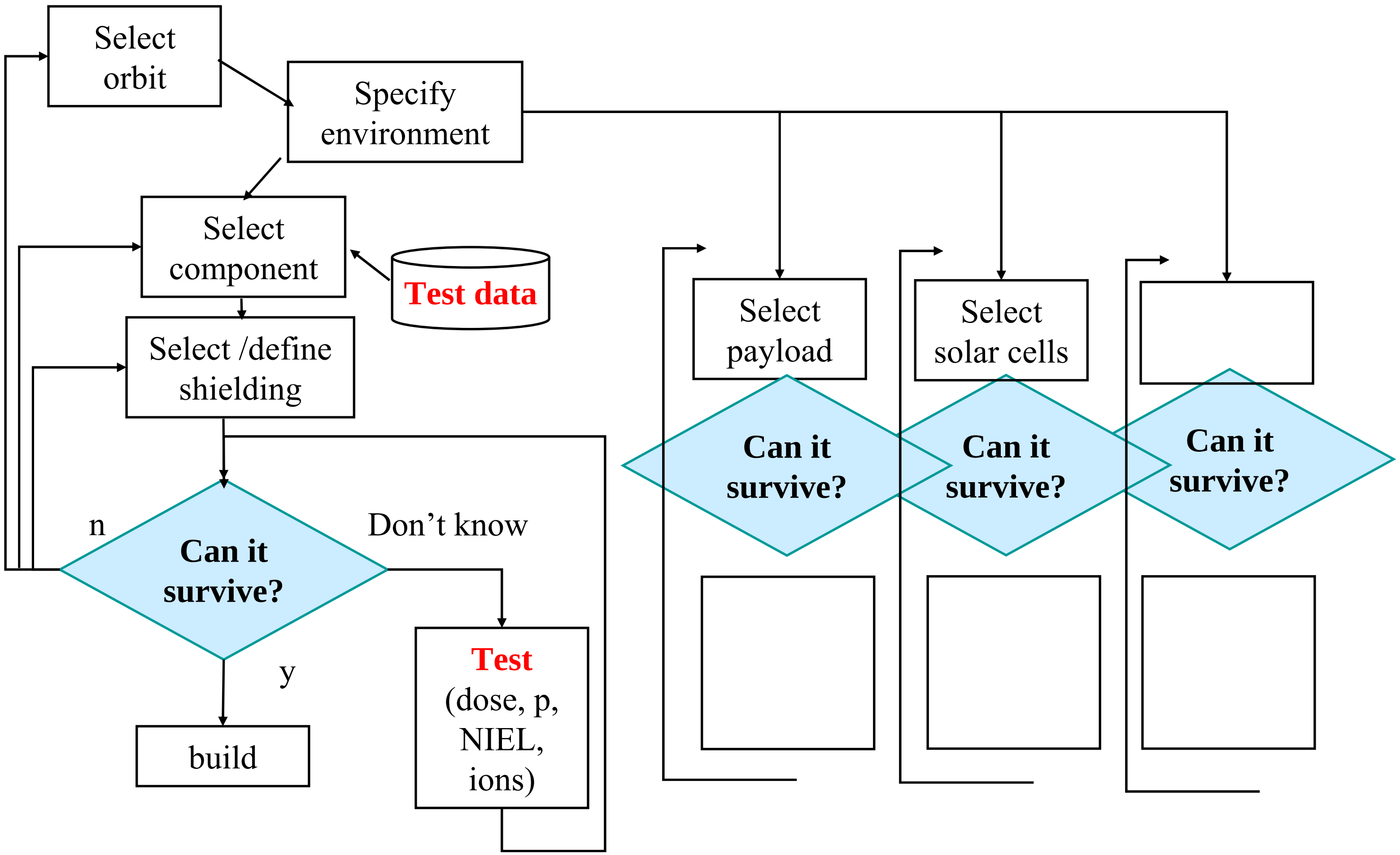


Figure 10. Solar proton events during the Apollo Program.

Basic Radiation Assessment Process - Testing is Crucial



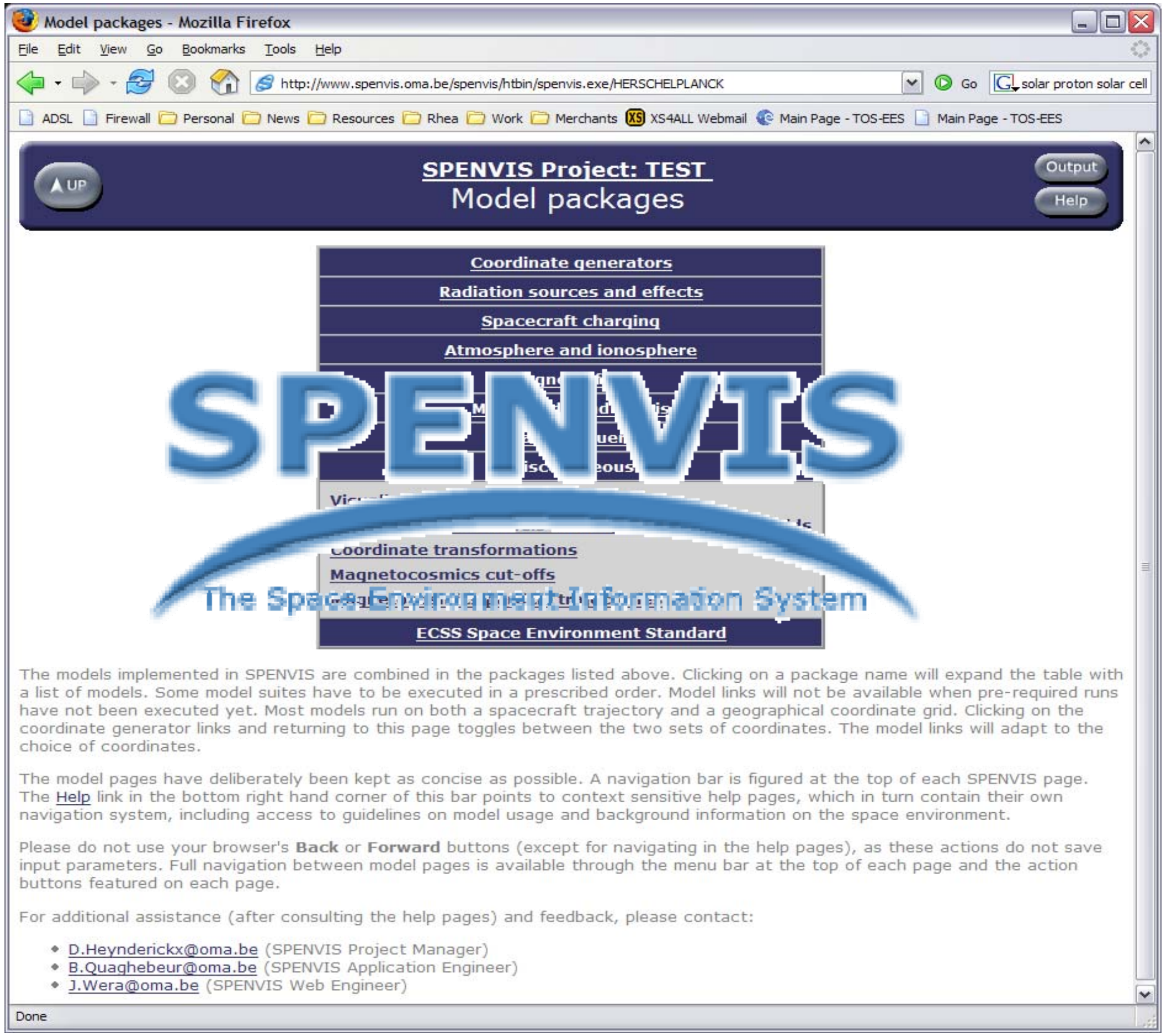
Models and Tools

Space Environment Information System

- Models of radiation belts, etc.
  - AE8
  - AP8
  - Flumic
  - CRRESELE
  - …
  - Have to be used together with a model of magnetic field (right one!) and orbit generator

- Calculation of resulting
  - Doses
  - NIEL
  - Solar array damage fluence
  - Single event effects

- Shielding tools:
  - Simple geometrical shielding
  - Multi-layer multi-material shielding (MULASSIS)



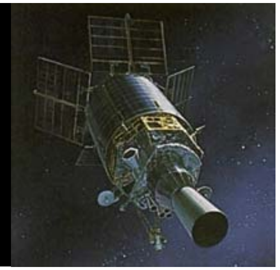
www.spenvis.oma.be

Plasma Environment and Effects

Spacecraft Surface Charging

- 27 February 1982: interruption (ESR) on Marecs-A Maritime Com. Sat.
- Main anomaly & other small ones coincident with geomagnetic "substorms"
- Anomalies caused by electrostatic charging $\longrightarrow$ discharge
  - large areas of dielectric thermal blankets
  - large differential charging
- Marecs-A and ECS-1 satellites had power losses on sections of solar arrays
- Telstar 401 failure on 10th Jan 1997 following storm on 7th
- ANIK-E1 & E2 failures in 1994 and 1996

Spacecraft Charging Anomalies first seen in the early 1970's



- ATS-5 (weather technology satellite, launched 1969 into GEO)
- Directly observed high-level charging of its surfaces in hot plasma environments
- Around that time military and early communications satellites in GEO (DSCS, DSP, Intelsat, Skynet, Symphonie) had many anomalies.

Spacecraft Electrostatic Charging Effects

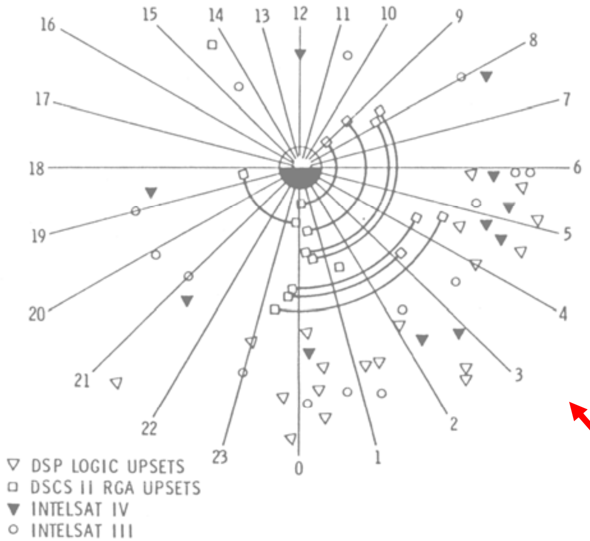


Fig. 1 Local time dependence of circuit upset for several DoD and commercial satellites.

98 D.L. REASONER, W. LENNARTSSON, AND C.R. CHAPPELL

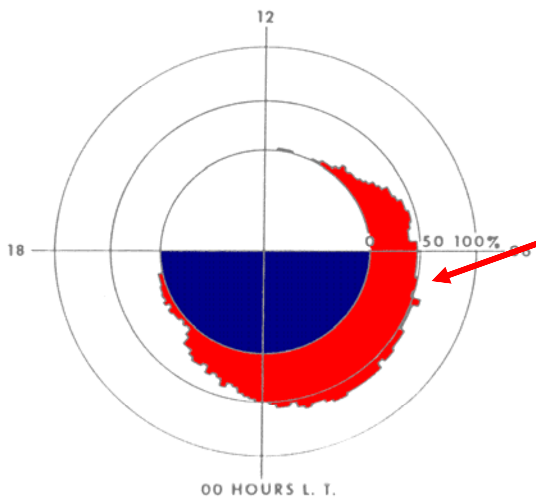


Fig. 7 Local time distribution of ATS-6 spacecraft charging events.

Sustained Arc on EOS-AM1 (Terra) Q-Board (Ferguson, NASA Glenn)

- Anomalies in '70's and '80's found to correlate with locations of "hot plasma"
- Anomalies on solar arrays in '90's '00's traced to plasma interactions too.

13% of failures in space power systems are due to discharges

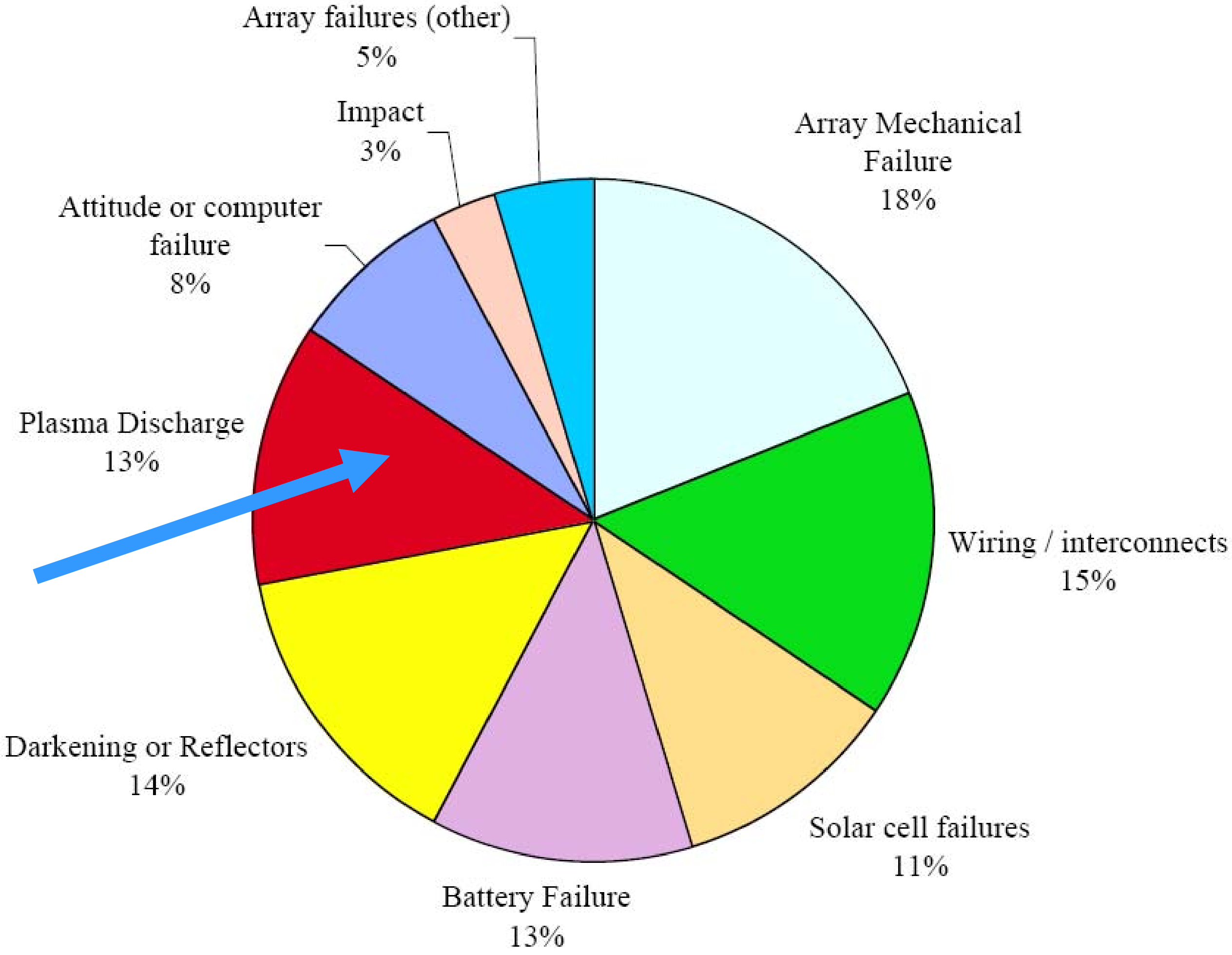
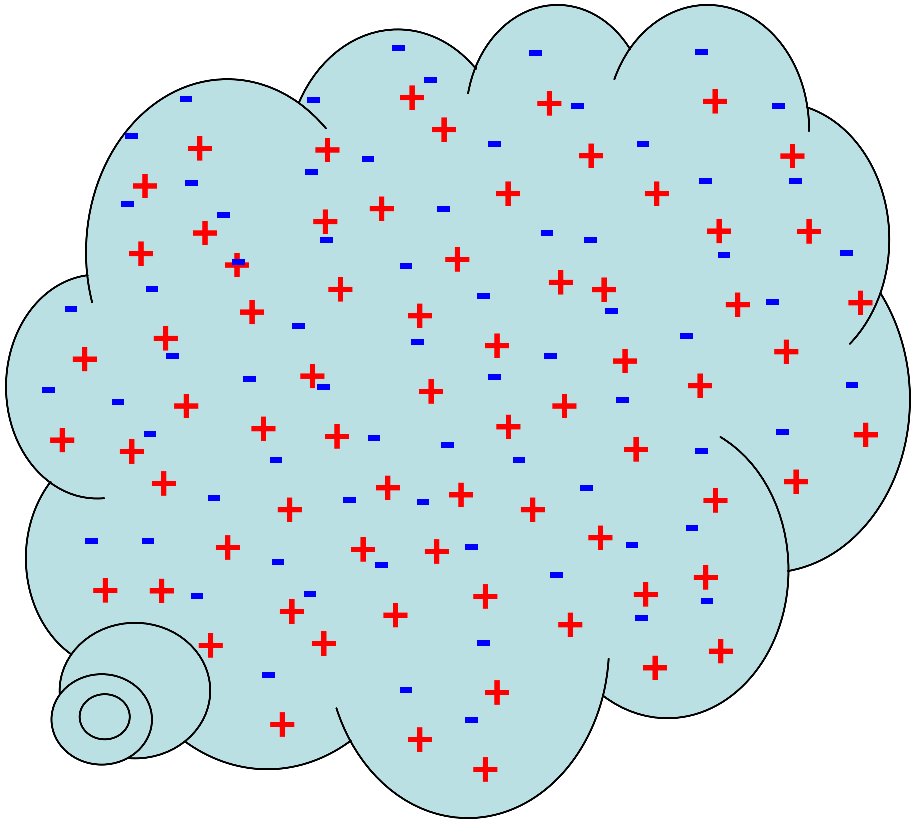


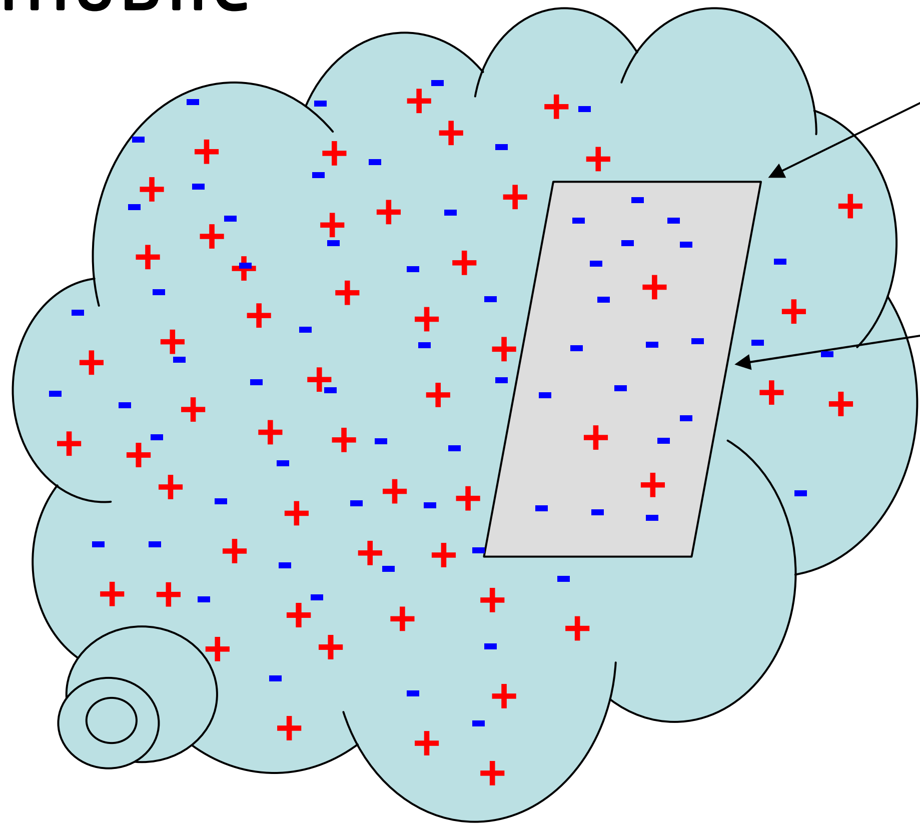
Figure 1. Number of power-related failures, by cause

Hot Plasma and Spacecraft Charging

- A plasma is a "gas of free electric charges"
  atoms $\longrightarrow$ ions, electrons



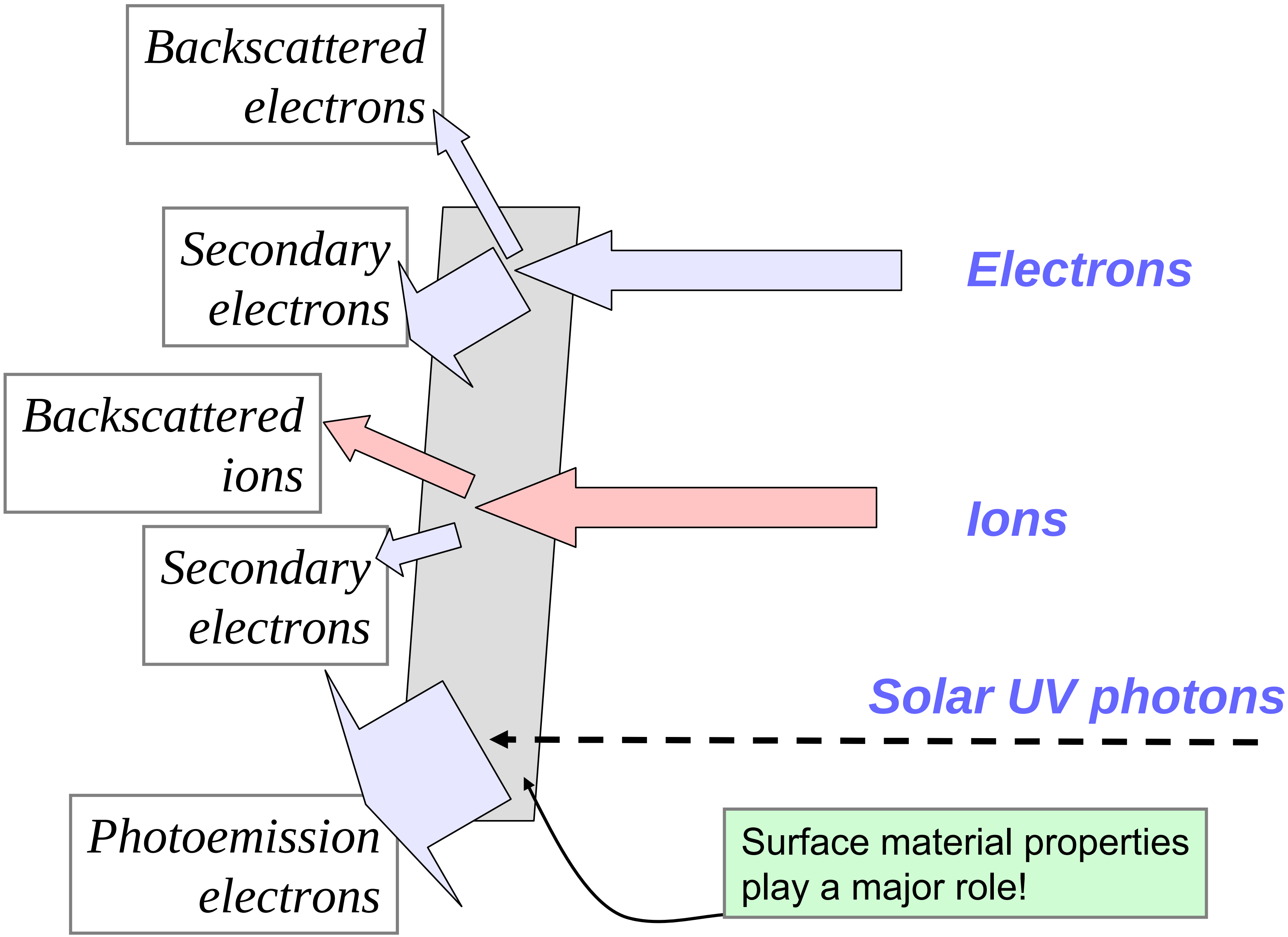
- Electrons are lighter, more mobile



Objects usually collect more negative charge

Objects acquire a negative “voltage” sufficient to balance currents (~ electron energy (in electron Volts))

$$I_e(V_f) + I_i(V_f) = 0$$


Backscattered electrons
Secondary electrons
Backscattered ions
Secondary electrons
Photoemission electrons
Electrons
Ions
Solar UV photons
Surface material properties play a major role!

Equilibrium potential determined by (attempt to achieve) current balance

$$I_e + I_i + I_{se} + I_b + I_{si} + I_{ph} + I_r = 0$$

environment

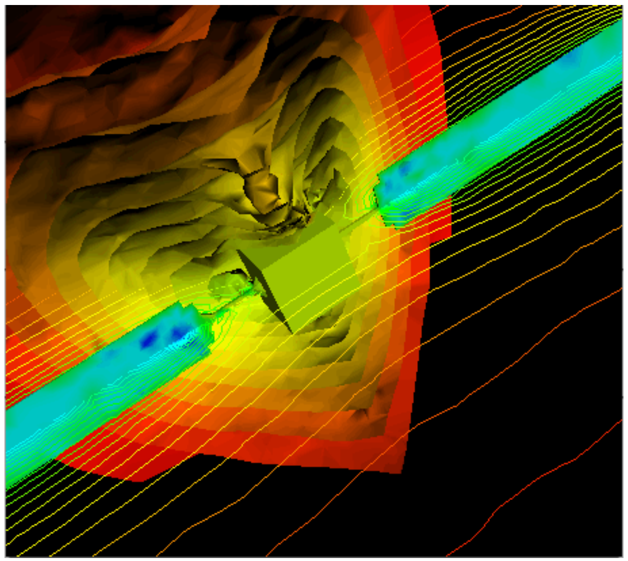
"secondaries"
- material dependent

surface-to-surface currents

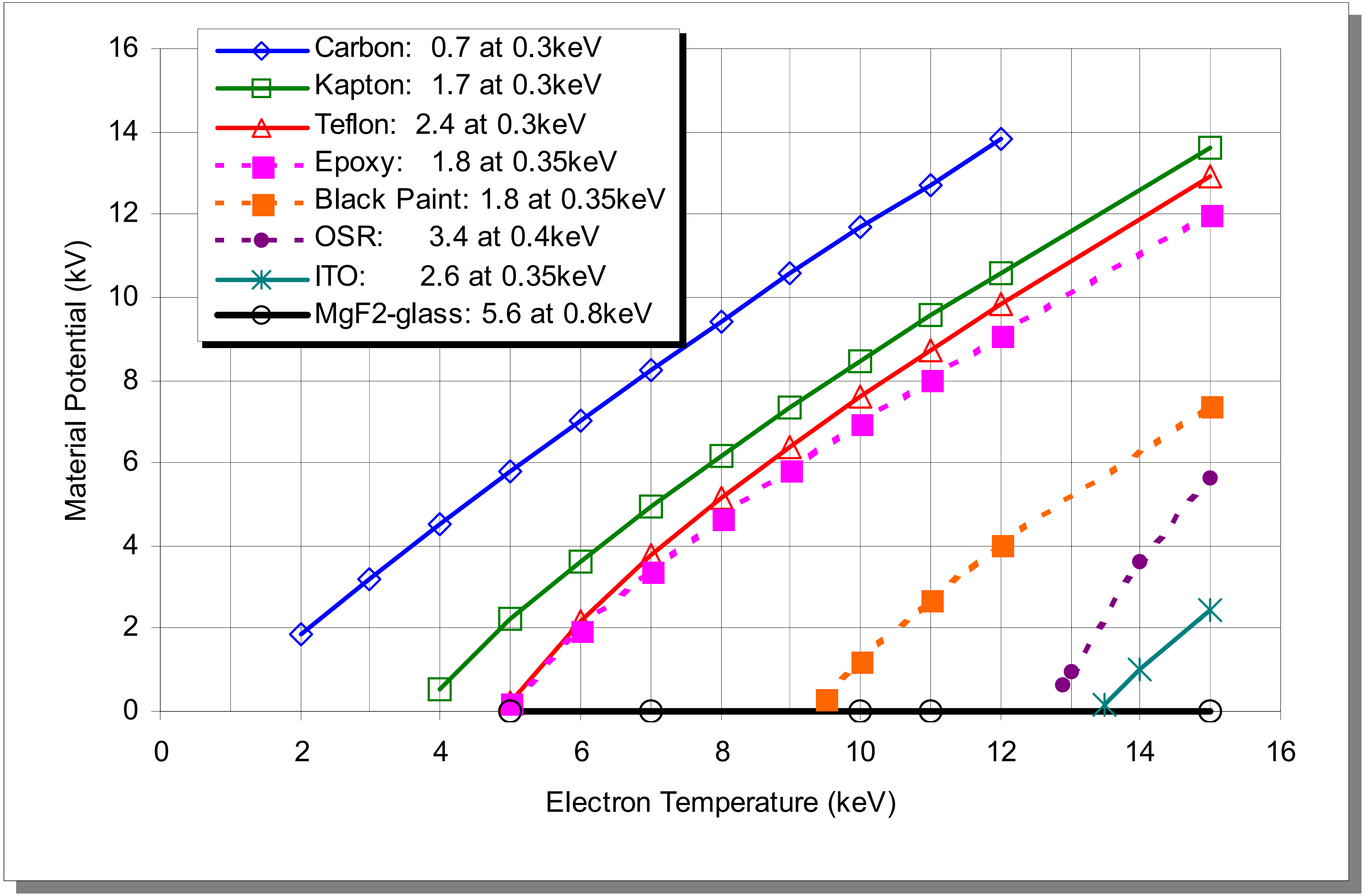
Currents are affected by geometrical factors:

- Shadowing from UV
- 3D electric fields features ("barriers")

Necessitates complex 3D simulations

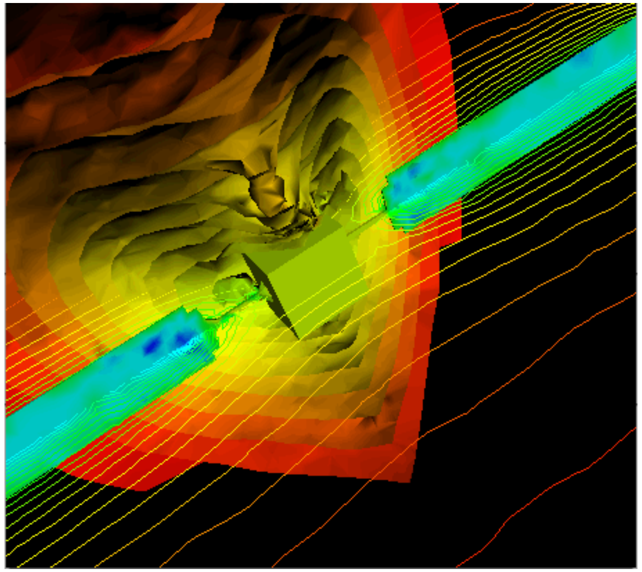


Material Dependence of Charging Levels



Other Issues

- Plasma interaction issues also include:
  - Electric propulsion interactions
  - Scientific (plasma) instrument interference

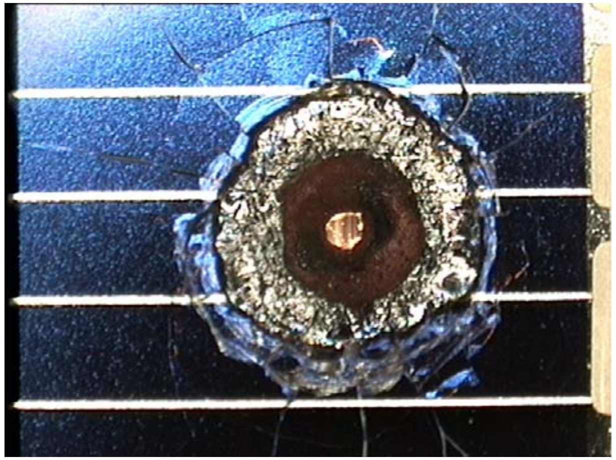


- Analysis techniques:
  - Current balance assessment of charging levels (can be simple, or 3D)
  - Full plasma simulation codes

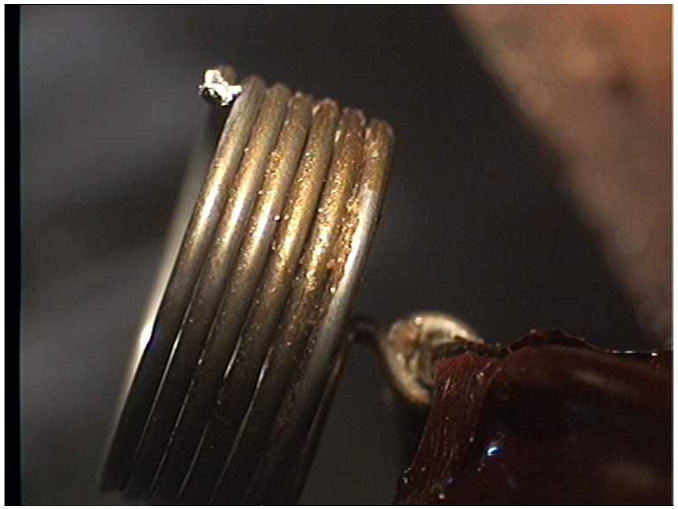
Meteoroids and Space Debris

HST Solar Arrays Retrieved in March 2002

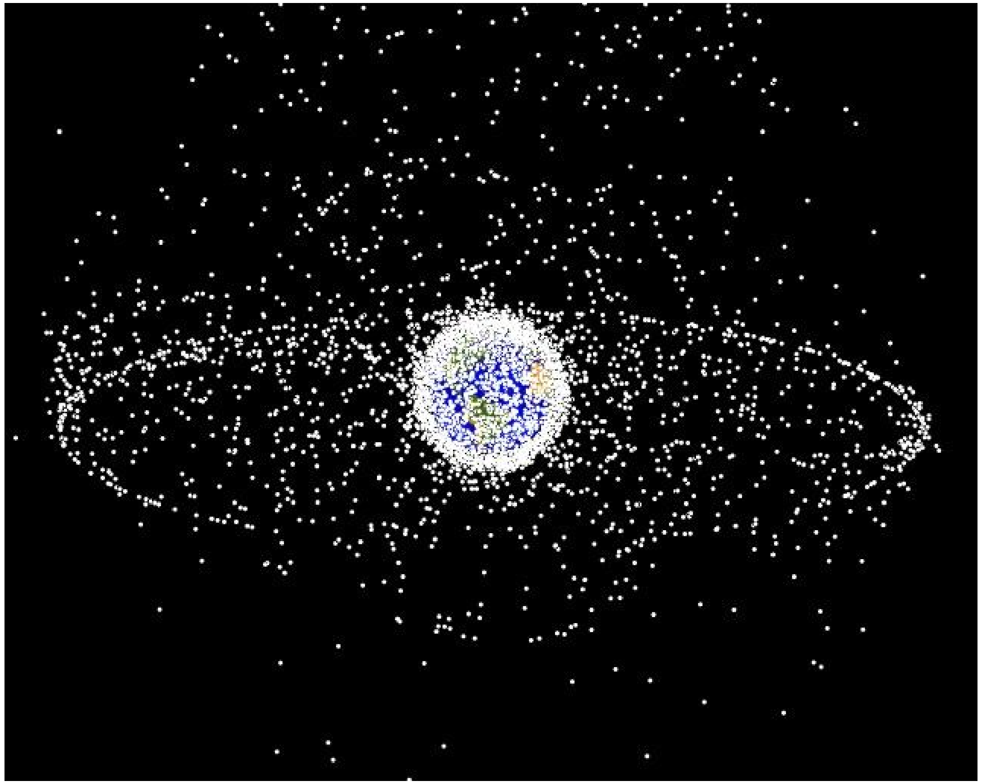
Example hole in HST solar cell (Crater size: 4 mm)



Spring of HST solar array cut by impact



Meteoroids and Debris



- Natural meteoroids are encountered everywhere.
- Space debris mainly below 2000 km altitude and in the geostationary ring.
- Typical impact velocities are 10 km/s for debris and 20 km/s for meteoroids.
- In LEO meteoroids dominate between 10 microns and 1 mm, debris for larger and smaller sizes.
- Rough fluxes (met + deb) at 600 km:
  - for D > 1 μ : 2000 / m^2/year
  - for D > 10 μ : 200 / m^2/year
  - for D > 100 μ : 4 / m^2/year
  - for D > 1 mm : 0.005 / m^2/year

More Orbital Debris Added as Russian Satellite Explodes

BECKY IANNOTTA, WASHINGTON

A disintegrating former Russian military satellite sent 500 pieces into space during three explosions between March and June, shortly after shuttle astronauts observed space debris damage to a handrail and tool that are used during spacewalks outside the international space station.

While there is no way to track where the debris that impacted the space station originated, NASA officials were closely watching pieces falling off the Russian Electronic Ocean Reconnaissance Satellite (Eorsat) to make sure it did not pose a risk to the station, said Gene Stansbery, manager of NASA's Orbital Debris Program Office at Johnson Space Center in Texas.

"The concern is [that the Eorsat] is in an orbit not too far above space station," Stansbery said. "The satellite is in that orbit during its lifetime and when it's finished it starts drifting down and alternately starts decaying. If it's fragmenting close to the space station then there's more likelihood of it hitting the space station."

The Eorsat, also dubbed Cosmos 2421, is the 50th of a satellite series first launched by Russia in 1974. Stansbery said this Eorsat is suspected to be the last one in orbit, but Russia has not provided information requested by NASA about the satellites — making it difficult to know

NASA analyze
dian manipulator De

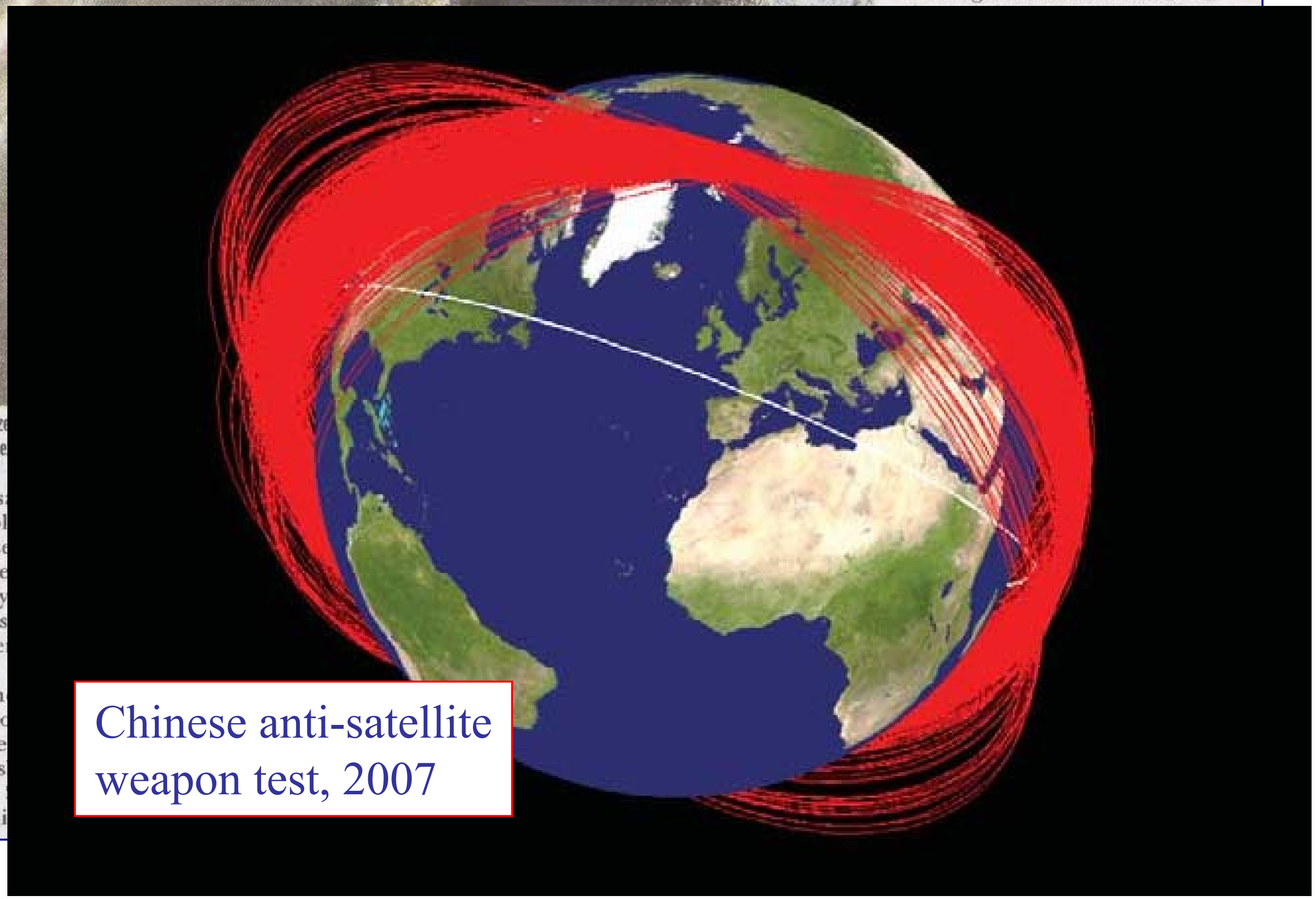
why these s
likely to expl
pan of this se
lites have e
once, usually
of their miss
one has bee
he said.

"It's som
fragment mo
and this one
times," Stans

The U.S.
Network, whi

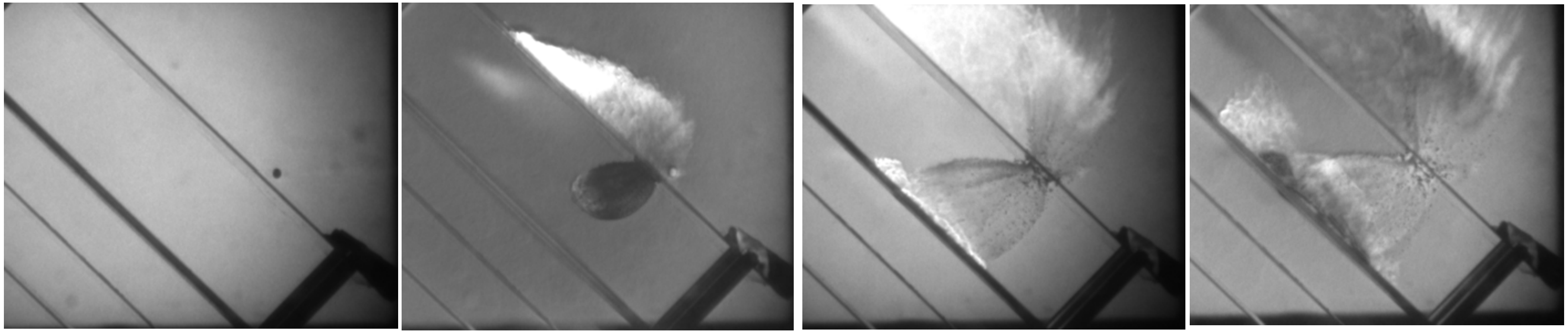
discovered the crater, prompting NASA to declare that location an area to be avoided by spacewalkers, said NASA spokesman Mike Curie.

The crater was one suspected of causing small tears on gloves during earlier spacewalks. Astronauts on subsequent missions swiped a swatch of the glove material across the



Chinese anti-satellite weapon test, 2007

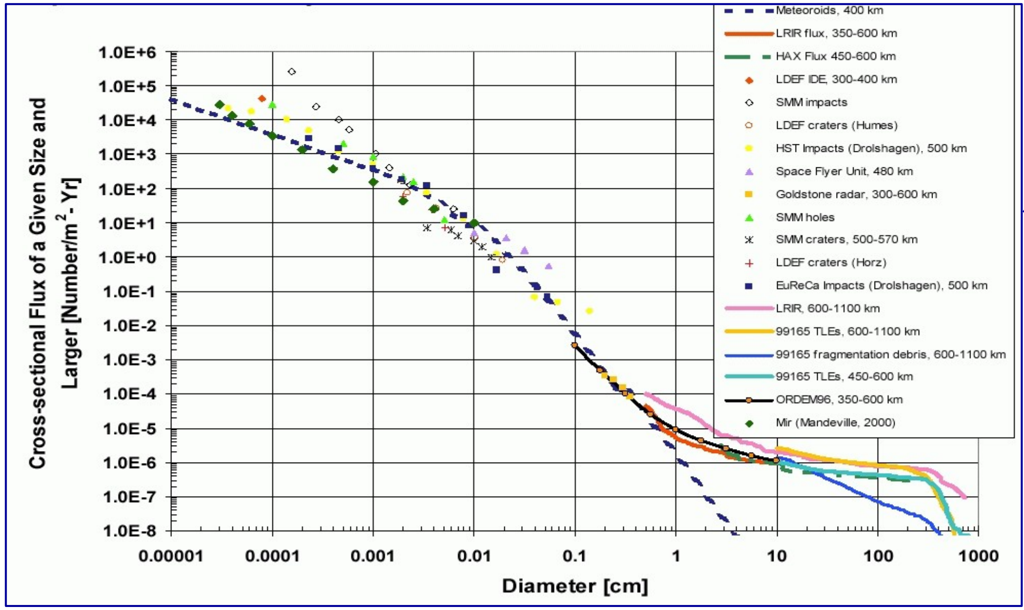
Hypervelocity particle impact generates a cloud of secondary debris



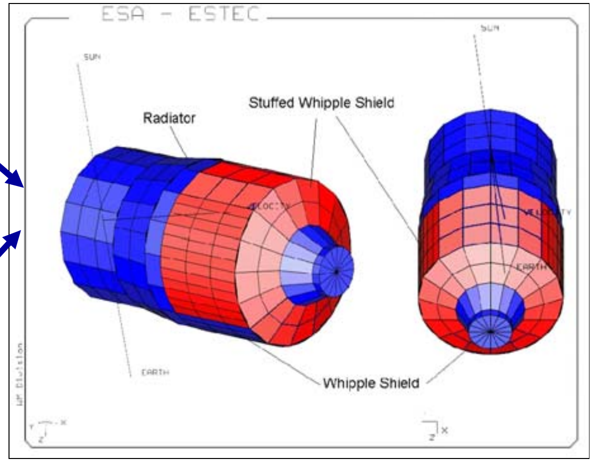
- Shielding strategy is to use multiple walls
  = “Whipple shield”

Analysis of Meteoroids and Debris Risks

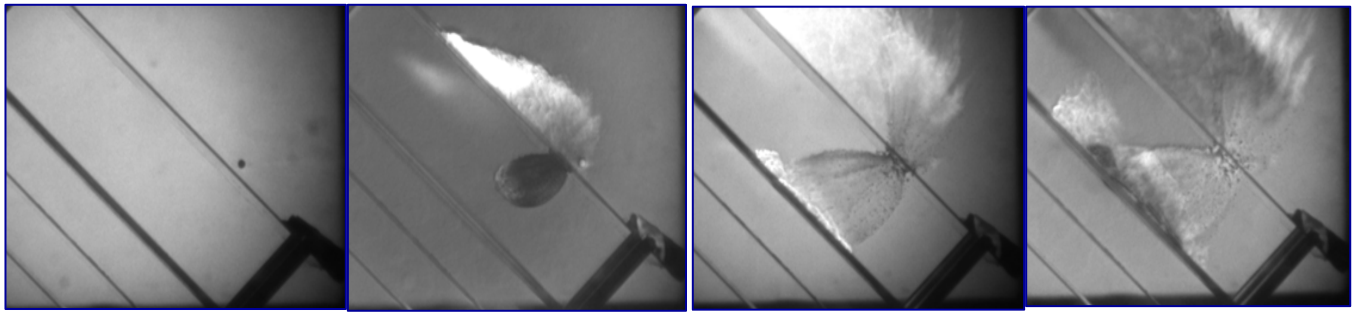
Population models



“Risk of damage” assessment (e.g. ATV)

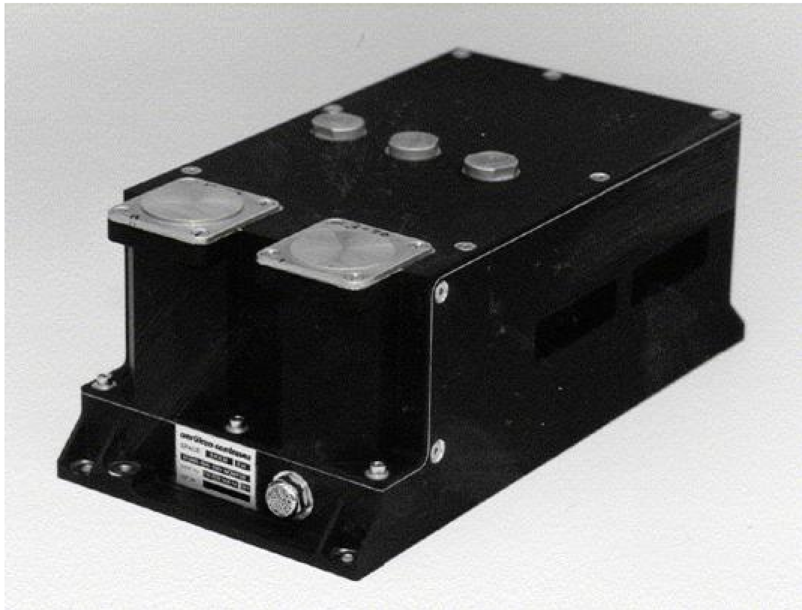


Damage characteristics (test, simulation)

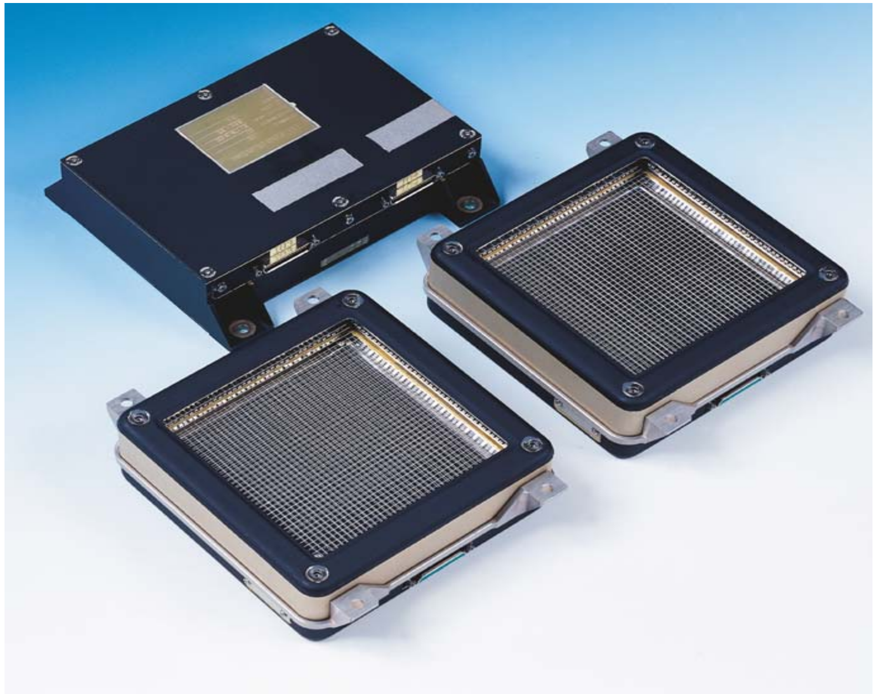


Environment Monitoring

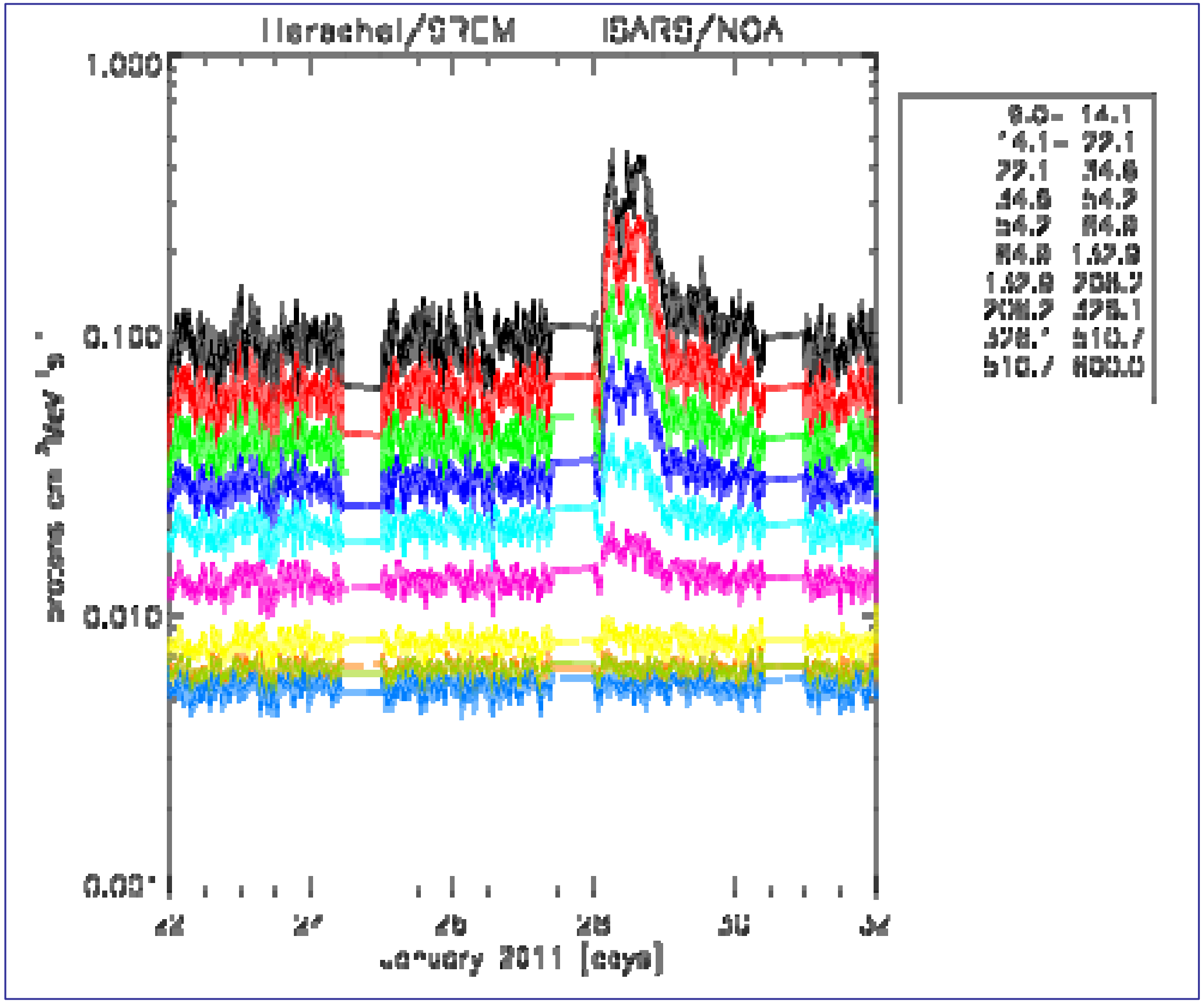
- To improve knowledge of environments
- To improve understanding of effects
- To support host spacecraft



Radiation monitors
(e.g. Proba, Integral, XMM,
Galileo, Herschel, Planck…)



Microparticle monitors
(e.g. Proba, Columbus(ISS))



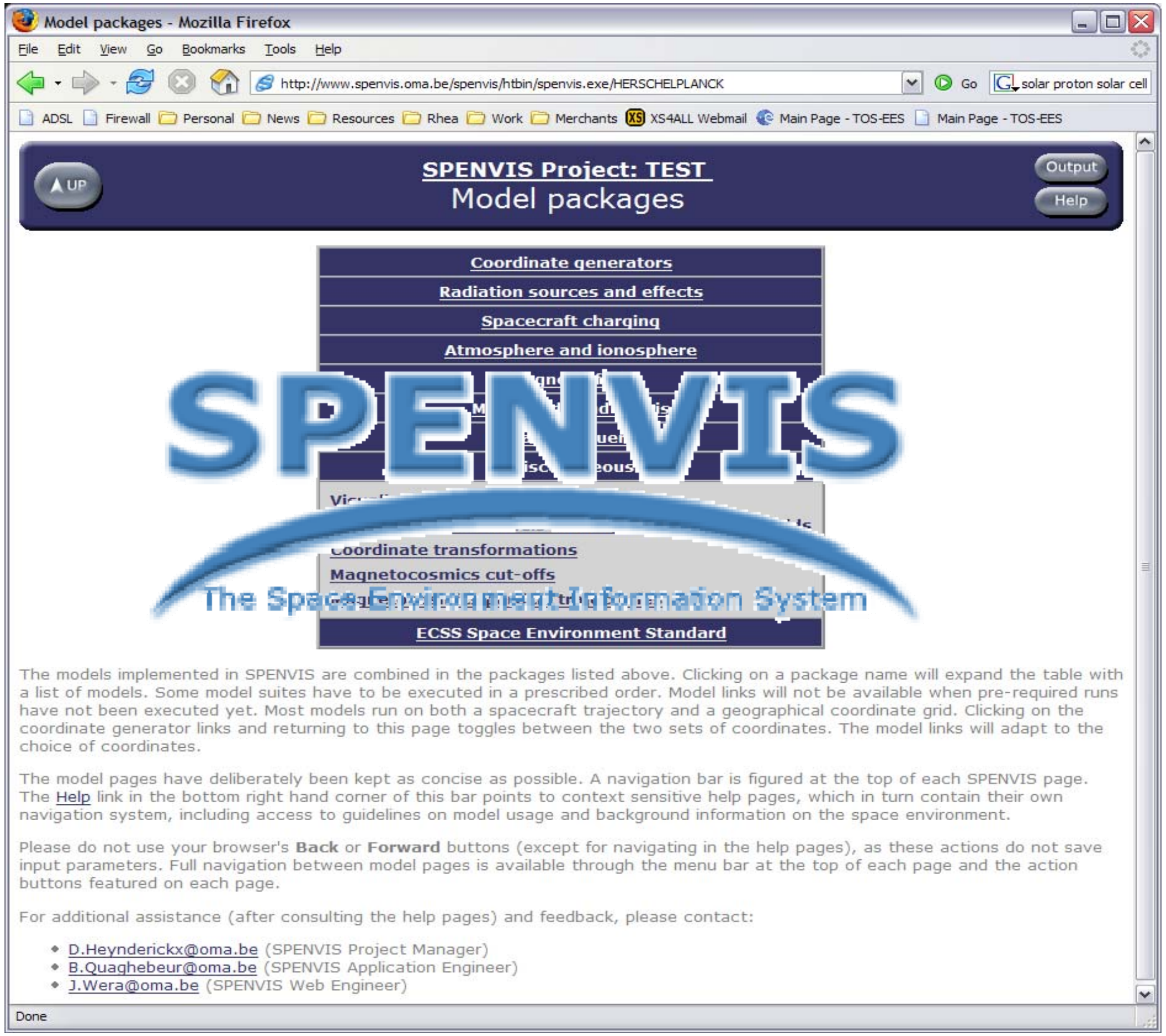
Herschel/SREM
ISARS/NOA
1.000
0.100
0.010
January 2011 (days)

What is done in the project "lifecycle"?

- Early phases:
  - orbit selection,
  - spacecraft/payload initial design under consideration
  - environment considered in trade-offs
  - establish environment specification (can iterate during project)
- Development phase
  - detailed analysis of problem areas (e.g. 3D radiation shielding);
  - close interactions with testing activities
  - assessment of "margins"
  - reviews
- In-flight:
  - Assessment of behaviour / anomaly investigation
  - Feedback; lessons learned

Space Environment Information System

- Analysis tools for all environments
- Includes many analysis methods
- Links to standards
- A lot of help and background information
- www.spenvis.oma.be



Available Standards

- ECSS-E-10-04
  Space Environment (revision)
- ECSS-E-10-12
  Methods for Calculation of Radiation Effects
- ECSS-Q-60-11
  Radiation Hardness Assurance
- ECSS-E-20-06
  Spacecraft-Plasma Interactions