Environmental effects - IV (radiation effects)

Lecture 11

W.K. Tobiska

Space Environment Technologies

Announcements

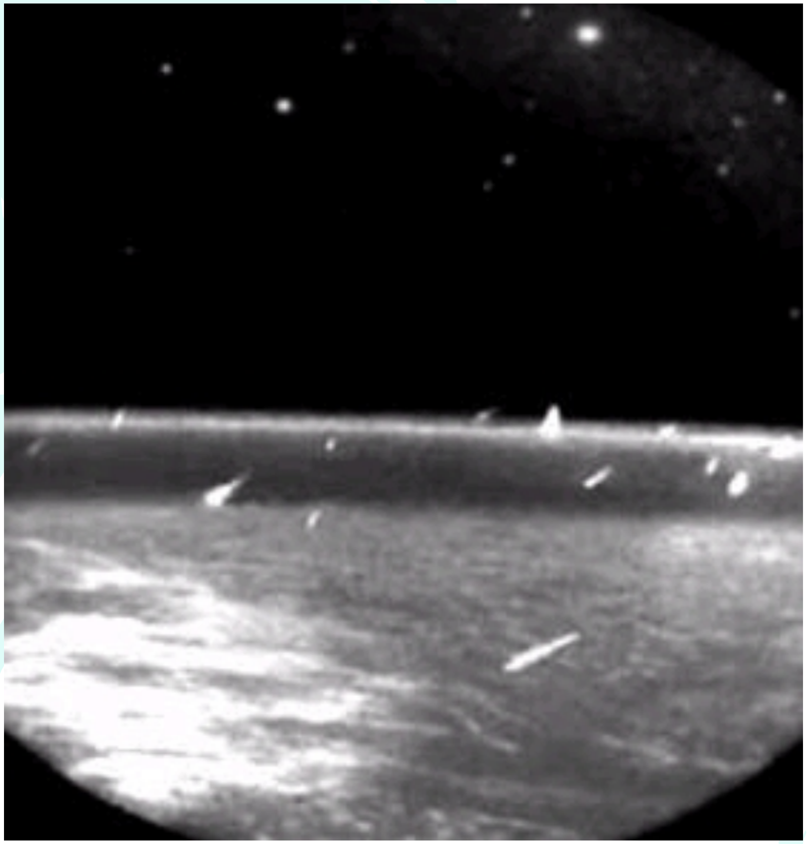
Contributions

– Why 28V? Your question as to why satellites operate at 28V has direct correlation to my work and I wanted to respond. I took a little time today and walked around my building and asked a number of engineers & scientists what the reason for +28V was. It seems that even though a few people had worked in this industry for upwards of 30 years, no one could give me a definite, solid answer. Some suggested it had to do with power distribution and voltage/current combinations. Some reasoned it was a multiplication factor based on satellite battery voltages. Some even went so far as to say it was simply a random, even number! But the most likely reason is much simpler than that: history. When satellite development was first becoming an industry in the late 50s / early 60s, power, communication and computer technology was quite primitive. Most electrical components were inefficient and power hungry, and hence ran on voltages such as 24, 28, and even 32V. As the industry became marketable and began expanding, satellite components were designed to work with that "standard" in mind. Sensors and detectors, in particular, were developed to specifically operate off of that voltage. Now, as Integrated Circuits and low-power components are becoming easier to make, we have devices that operate at voltages down near, 1V. But this has not changed the sensor industry which still sees +28V as the norm. So basically, it always has been 28V, and unless there is a big push for lowering power consumption, I predict that the "standard" will remain for quite some time to come.

Announcements

Contributions

- Leonid meteor peaks in early morning hours the third week of Novembers
- Image of Earth's Plasmasphere http://www.aip.org/png/html/plasmasphere.html
- Space elevators and the radiation environment
  - http://space.newscientist.com/article/dn10520-space-elevators-first-floor-deadly-radiation.html



Announcements

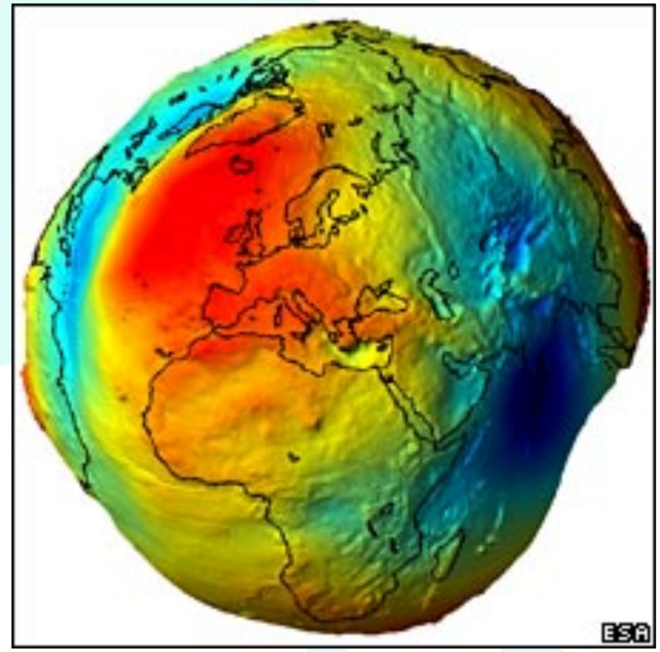
Contributions

- NASA Ref Pub 1375 on examples of charging anomalies: http://trs.nis.nasa.gov/archive/00000292/01/rp1375.pdf
- NASA Ref Pub 1354 protecting against charging: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19950013364_1995113364.pdf
- JAXA HD multimedia downloaded from their first lunar satellite Selene Earth Rise Movie http://space.jaxa.jp/movie/20071113_kaguya_movie01_j.html
- Earth Set Movie http://space.jaxa.jp/movie/20071113_kaguya_movie02_j.html
- 4 new planets recently found outside our solar system from Hubble http://www.cnn.com/2008/TECH/space/11/13/new.planets/index.html

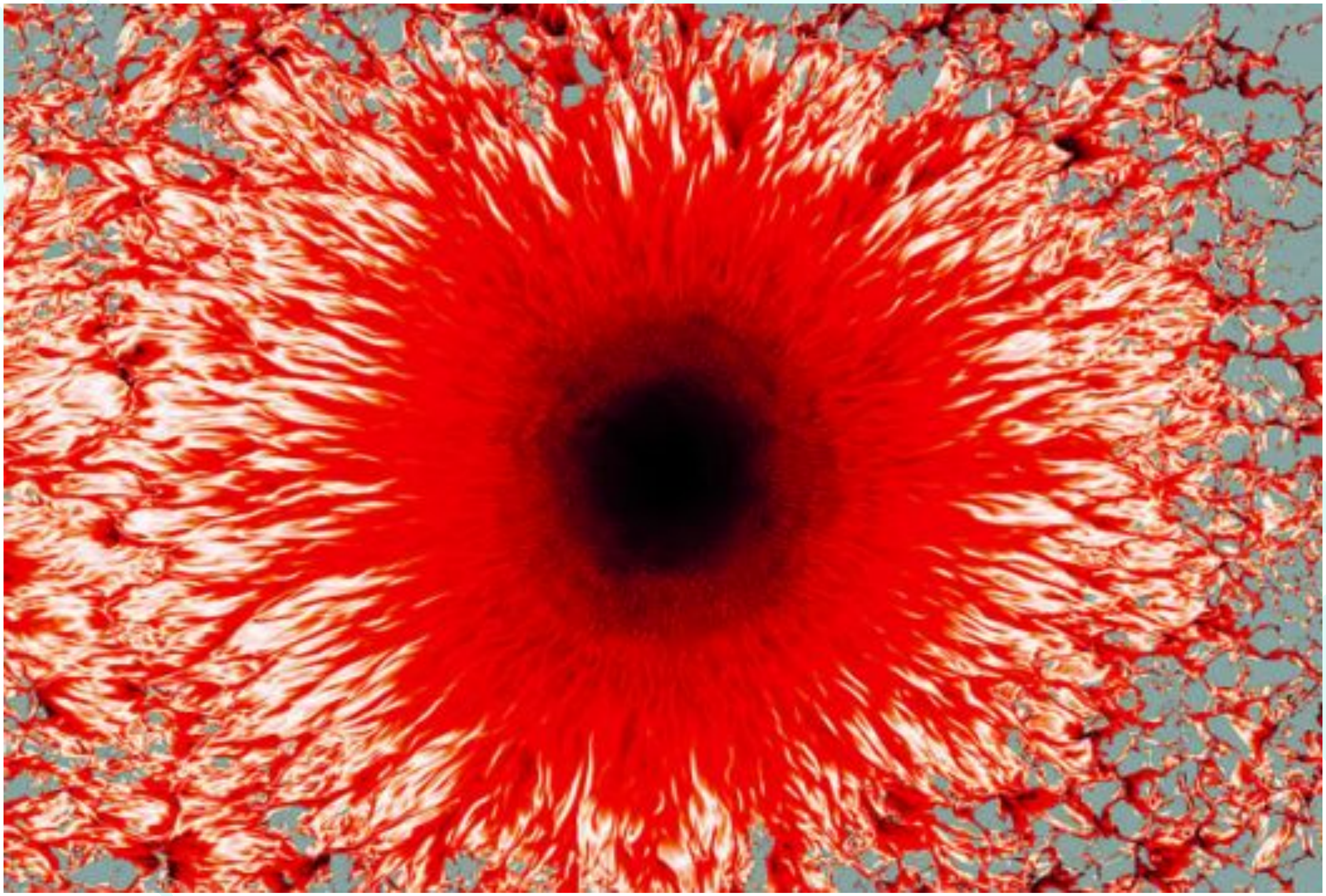
Announcements

Contributions

- GOCE satellite gravity mapping http://news.bbc.co.uk/2/hi/science/nature/8268942.stm
- Space Weather Could Scrub Manned Mars Mission http://news.nationalgeographic.com/news/2005/08/0809_050809_marsmission.html
- Higher than expected cosmic ray flux during solar minimum http://www.nasa.gov/topics/solarsystem/features/ray_surge.html



Theoretical sunspot



Earth from Rosetta

Announcements

Announcements

Lecture Overview

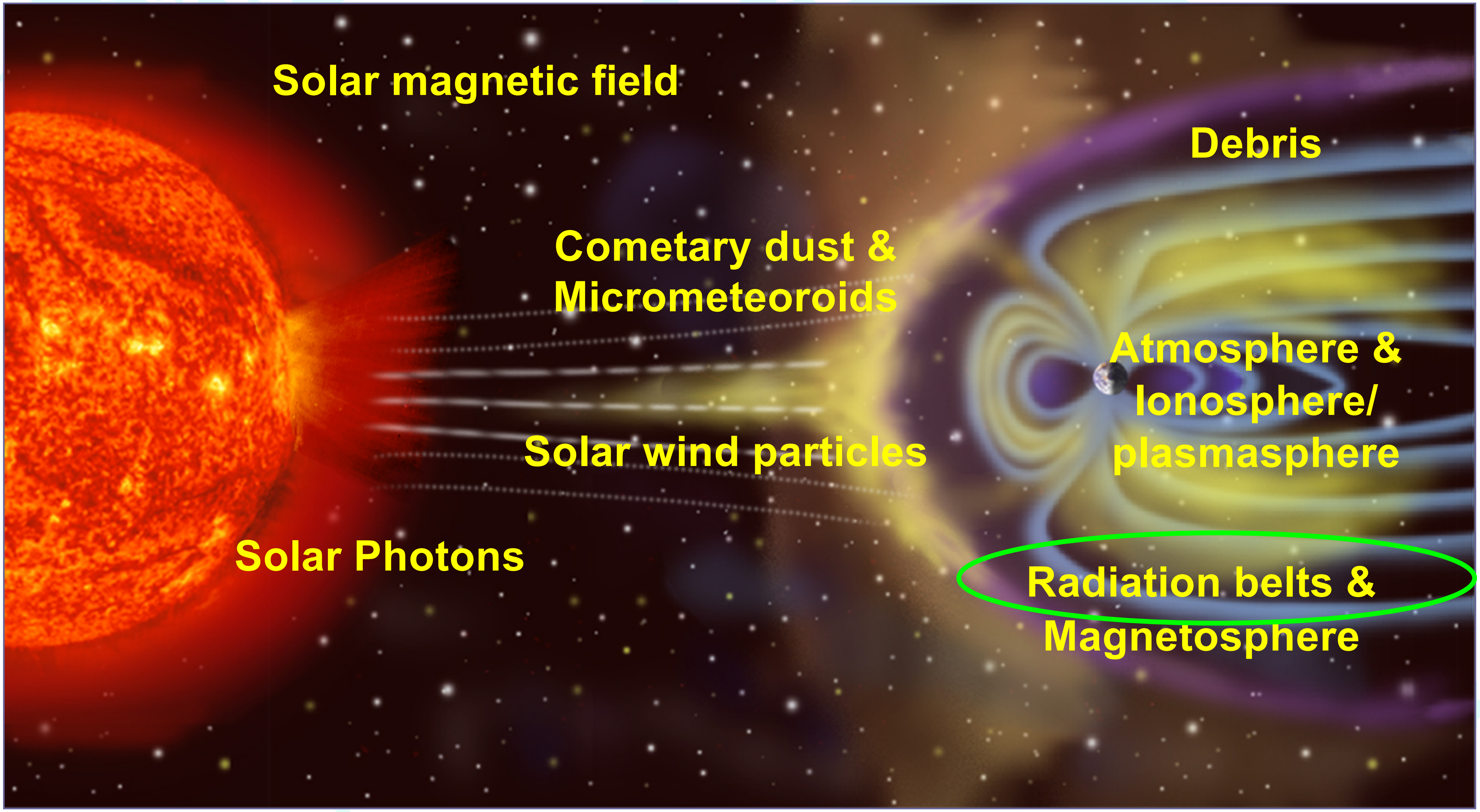
Environmental effects (radiation effects)

- Radiation physics
  - Radiation-surface interactions (photons, **electrons, ions, neutrons**)
- Radiation environment characteristics
  - Radiation units (gray, Rad, dose)
  - Van Allen belts, solar energetic photons, solar energetic particles, galactic cosmic rays, trapped particles, cutoff rigidities
  - Radiation (charged particle) effects
  - Surface impacting effects (conducting material, solar arrays, optical surfaces)
  - Penetration effects (single event upsets, latchup, deep dielectric charging)
  - Example events satellite (Mar1991, Jan 1994 (Anik), May 1998 (Galaxy-4), Oct 28-31 2003) and aviation
  - Linear energy transfer, doses, radiation shielding, radiation hazards
- Standards, guidelines, models (AE9, AP9, JPL, CRÈME, L2-CPE)

Homework

The planetary space environment

The space environment



Credit: Steele Hill/NASA

Radiation physics

Radiation-material interactions

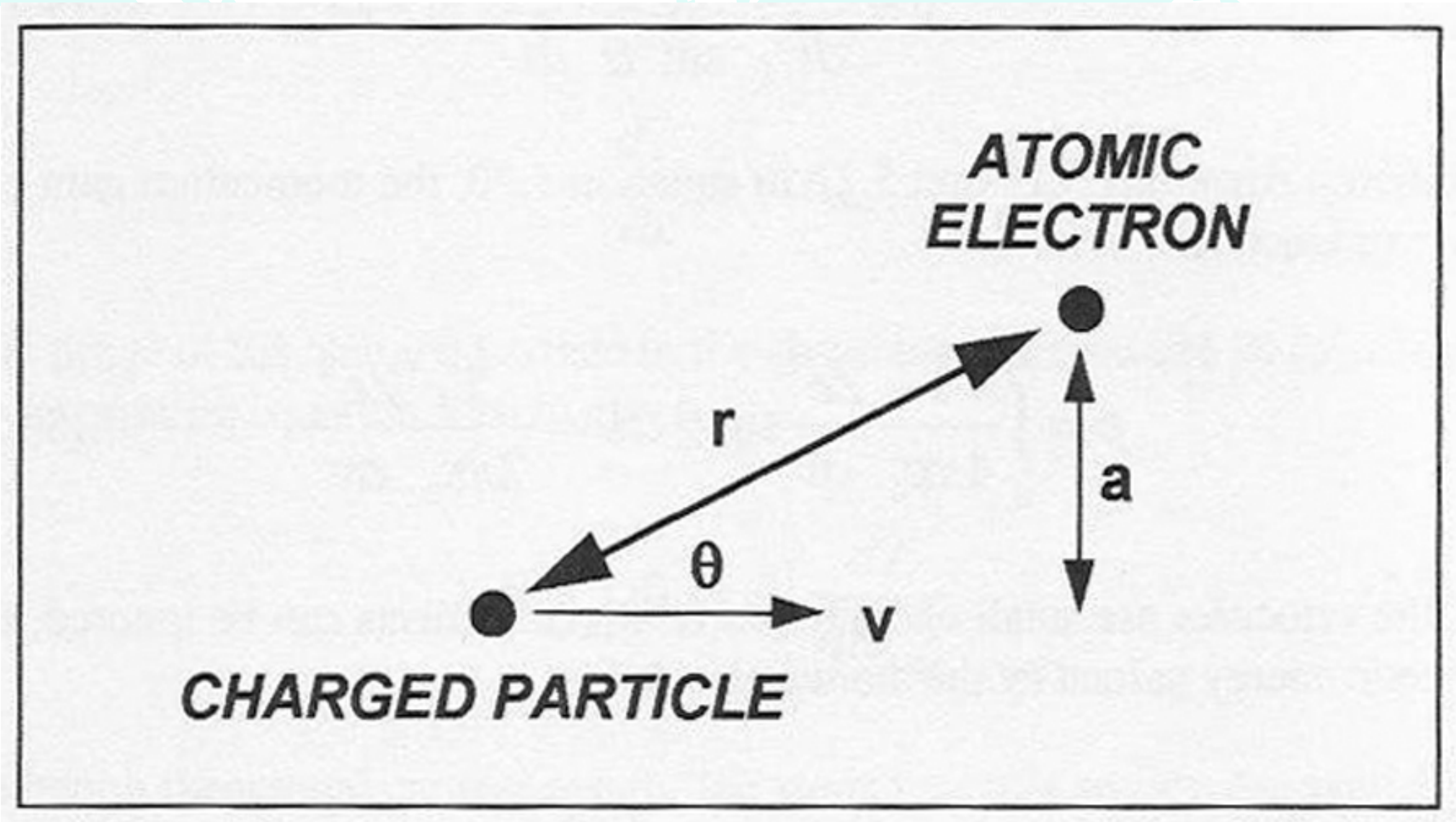
- Radiation interactions imply **high energy** particles and photons (100 keV – 10 GeV) as opposed to **low energy** interactions discussed earlier (0.01 eV - 1 keV)
- Deep penetration of solid surfaces only possible with high energy particles and photons
- **Particle interactions** (covered in this lecture)
  - Electron bombardment
  - Ion bombardment
  - Neutron bombardment
  - Radiation damage by particle impact

Electron-material interactions

Energetic electron bombardment

- Electrons with > 1 MeV can produce atomic displacements in solids
- Electrons at these energies use relativistic mechanics to describe the motions
- Interactions occur with nuclei of solid through Coulomb potential
  - Nucleus is much larger than the electron
  - Only electron momentum is altered
  - Electron is deflected through angle θ in the center-of-mass coordinate system

Electron-material interactions



Electron-material interactions

Energy transfer from impact

Electrons transfer an energy, T, to the nucleus in these collisions by (11-1) where P is the electron momentum, m_e is the electron mass, c is the speed of light, M is the nucleus mass, and E is the kinetic energy of the electron.

$$T = \frac{2MP^2}{(M + m_e)^2} \sin^2 \frac{\theta}{2}$$

$$= \frac{2P^2}{M} \sin^2 \frac{\theta}{2} \qquad \textbf{(11-1)}$$

$$= \frac{2m_e}{Mm_e c^2}(E + 2m_e c^2) E \sin^2 \frac{\theta}{2}$$

Electron-material interactions

The electron kinetic energy is given by (11-2) where v is the electron velocity.

$$E = m_e c^2 \left[\frac{1}{\sqrt{1 - |v/c|^2}} - 1 \right] \quad (11\text{-}2)$$

E_d is defined as the minimum energy required to produce an atomic displacement in a particular solid

$$E_d = 2 \frac{m_e}{M} \frac{E_t}{m_e c^2} (E_t + 2 m_e c^2) \quad (11\text{-}3)$$

where E_t is minimum electron energy able to transfer an energy E_d to the solid nuclei; $E_d \sim 25$ eV in many materials

Electron-material interactions

Material	Displacement Energy, E_d (eV)
Aluminum	32
Carbon: Diamond	80
Carbon: Graphite	24.7
Copper	22-25
Germanium	31, 14.5
Gold	28
Iron	24, 37
Nickel	24
Silicon	12.9
Silver	> 40
Titanium	29
Tungsten	> 35

Credit: Ketsdever

Electron-material interactions

Scattering cross section

To determine the number of atoms displaced by an electron impact, the scattering cross section of the nucleus with the incident electron is required

If T_m is defined as the energy required to displace only **primary atoms** (atoms struck directly by incident impacting electron with mass M which doesn't include scattered electron impacts and is an energy only slightly larger than E_d) then

$$T_m = \frac{2P^2}{M} \quad (11\text{-}4)$$

Electron-material interactions

Scattering cross section

It can be shown that, using the energy T_m, the scattering cross section σ_d is given by 11-5 where Z is material atomic mass number, β is v/c, and γ is $(1-\beta^2)^{1/2}$

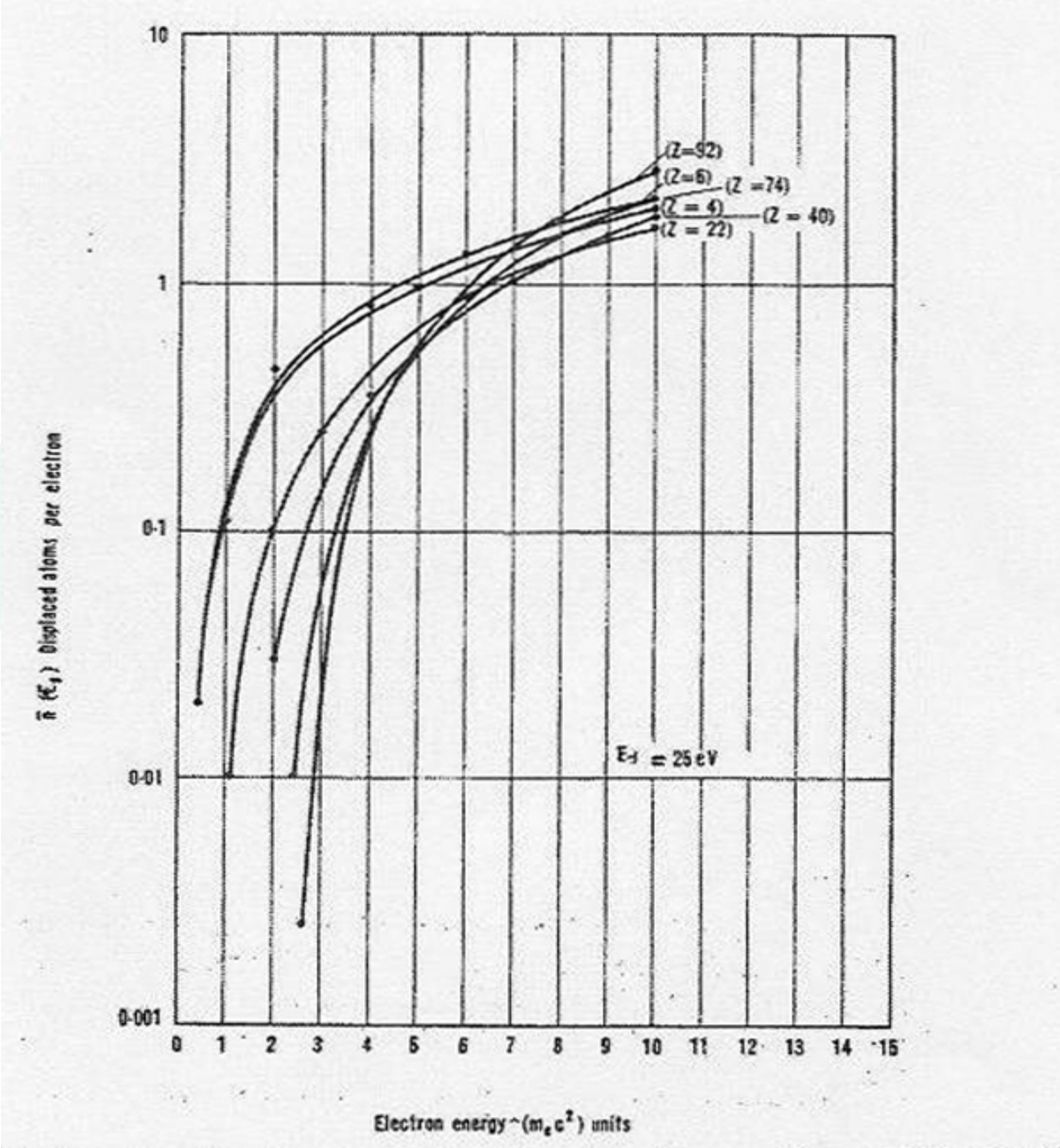
$$\sigma_d \approx \pi Z^2 \left(\frac{e^2}{m_e c^2}\right)^2 \frac{1}{\beta^4 \gamma^2} \left(\frac{T_m}{E_d} - 1\right) \qquad \textbf{(11-5)}$$

If the energy of the incident electrons produces only one displacement, then the rate of atomic displacement is

$$\frac{dn}{dt} = N_0 \sigma_d n_e v_e \qquad \textbf{(11-6)}$$

where N_0 is the solid number density and n_e is the electron flux (electrons/unit area/second)

Electron-material interactions



Credit: Ketsdever

Electron-material interactions

Linear energy transfer (LET)

The kinetic energy T of impacting high energy electrons can also be thought of as the energy needed to ionize (remove) atomic electrons (from the target material)

The change in kinetic energy per unit path length, dT/dx, is called the linear energy transfer (LET)

Total ionizing dose (TID)

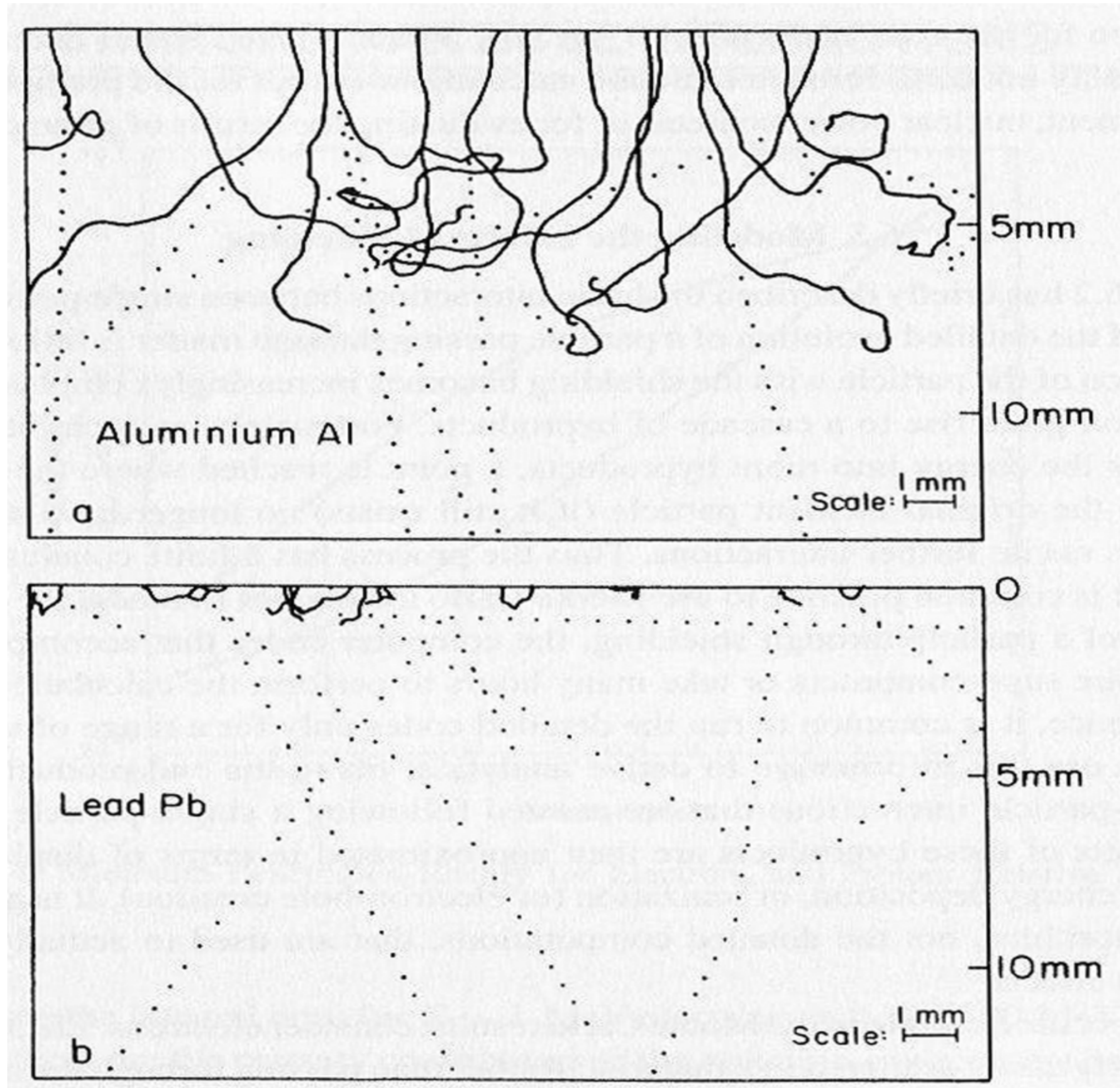
The change in kinetic energy per unit mass, dT/dm, is called the total ionizing dose (TID)

Range of electron penetration in a solid (mg cm^{-2})

$$R = 412E^{(1.265-0.954\ln E)}, E \approx 2.5\ \text{MeV}$$

$$= 530E - 160, E > 2.5\ \text{MeV} \qquad \textbf{(11-7)}$$

Electron-material interactions



Electron-material interactions: Aluminum example

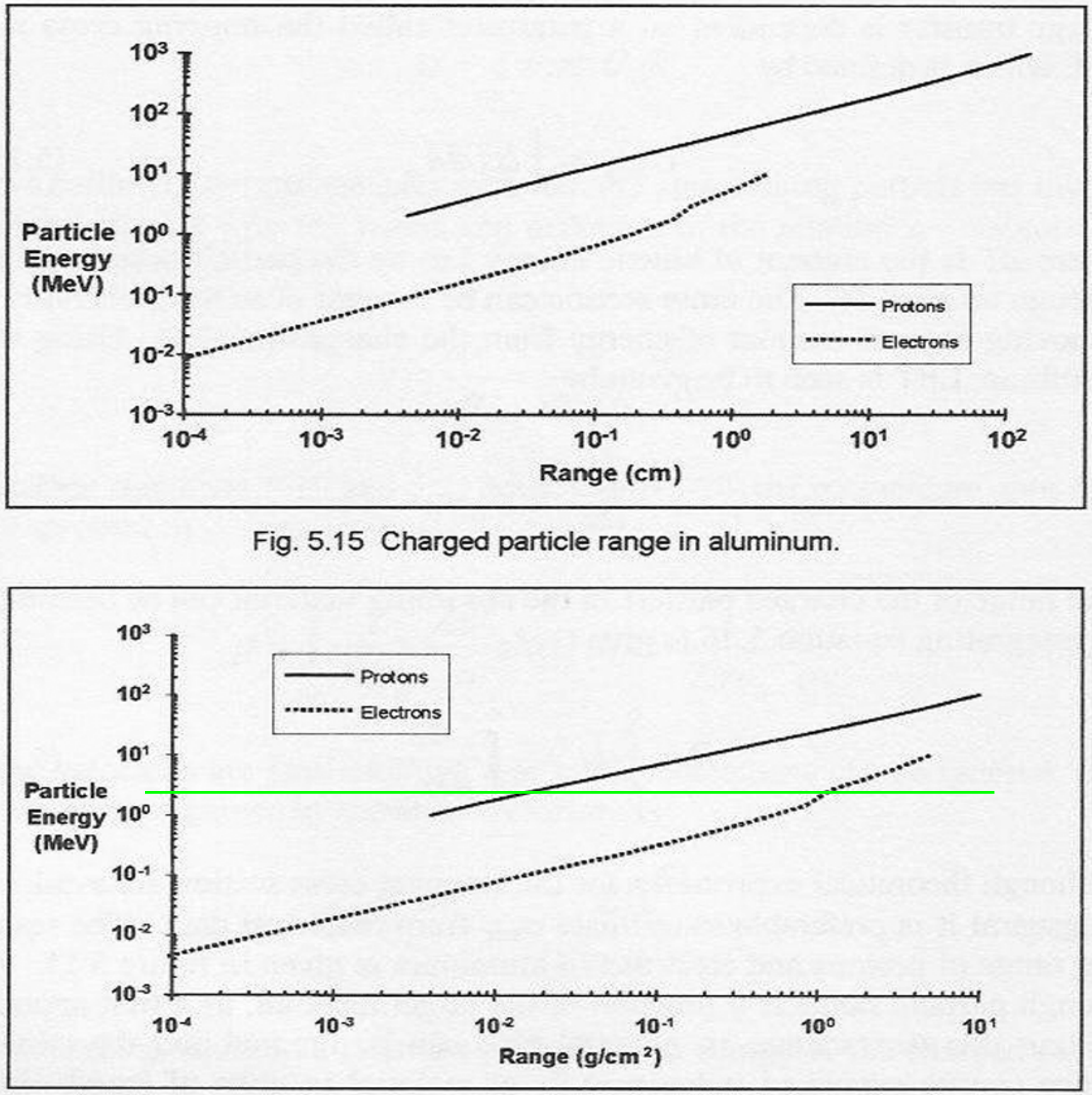


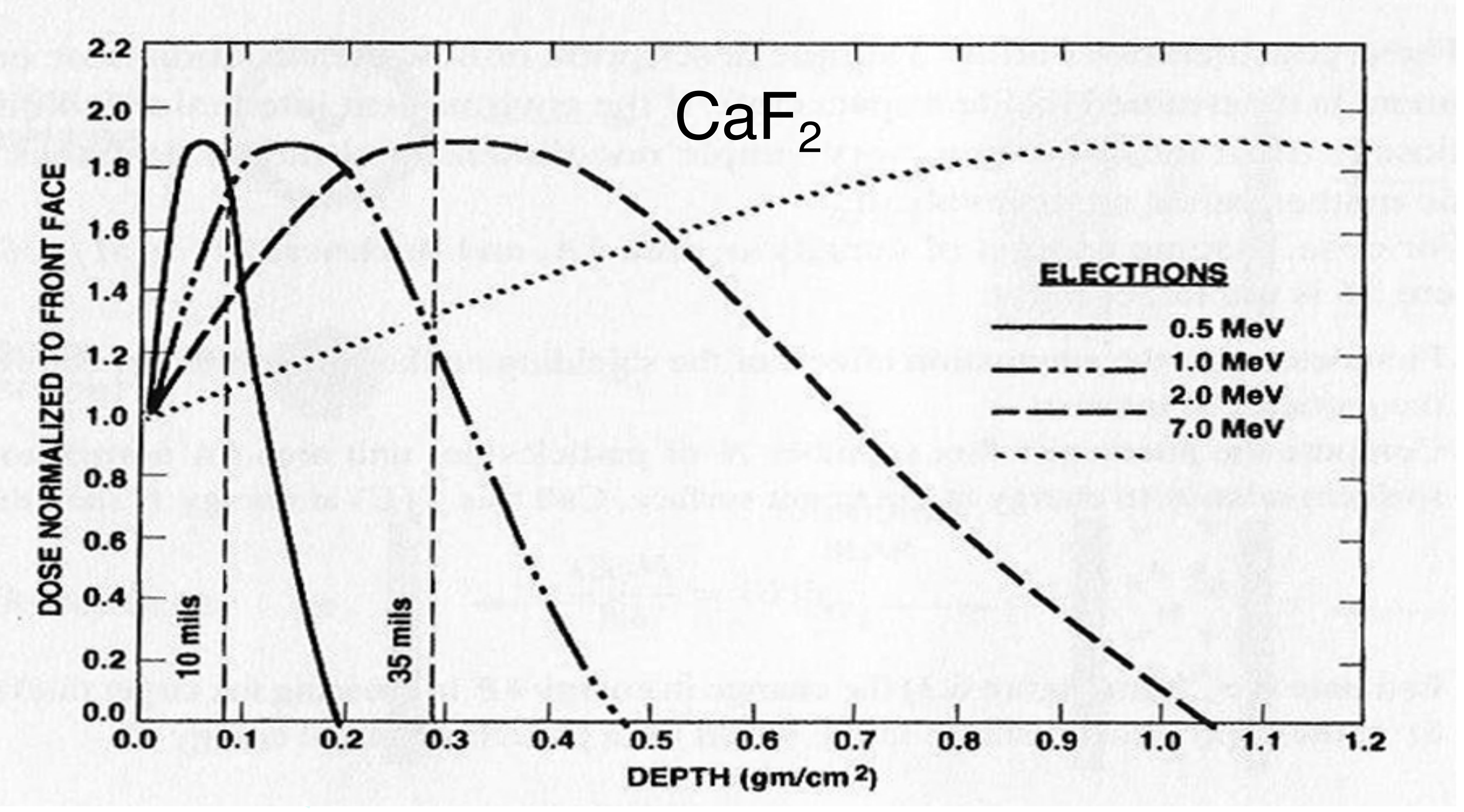
Fig. 5.15 Charged particle range in aluminum.

Fig. 5.16 Charged particle range in aluminum—normalized units.

W. Kent Tobiska <ktobiska@spacewx.com>

Credit: Ketsdever

Electron-material interactions



Ion-material interactions

Ion bombardment

Classical mechanics are appropriate for the range of ion energies involved in collisions

At some energies, the moving ion will lose some of its electrons and become multiply ionized

Primary energy loss of moving ion is through electronic excitation of solid atoms (ion transfers energy to solid atoms' electrons)

As kinetic energy decreases, the ion's degree of ionization decreases, and energy loss rate decreases

Eventually, ion gains an electron from solid material and then becomes neutral; at this point momentum transfer occurs where electron clouds play a role

For thin materials, the moving ion is not stopped but moves through the solid entirely although it still displaces electrons

Credit: Ketsdever

Ion-material interactions

Coulomb potential

At 5 to 50 MeV, the incident ion nucleus interacts directly with solid atom nuclei and electrons of both can be neglected

Interaction at this level is purely Coulombic (repulsive in this case)

The Coulomb potential between the moving ion (2) and solid atom nucleus (1) is

$$V(r) = \frac{Z_1 Z_2 e^2}{r} \qquad \textbf{(11-8)}$$

where r is the distance between the two charges, Z_1e is the stationary ion charge, Z_2e is the impacting ion charge.

Ion-material interactions

Ion kinetic energy

The ion, deflected through an angle, θ, has a kinetic energy, T, of (P is momentum)

$$T = \frac{2M_1P_2^{\;2}}{(M_2 + M_1)^2}\sin^2\frac{\theta}{2} \qquad (11\text{-}9)$$

and a *primary displacement kinetic energy*, T_m, for E_2 in units of eV

$$T_m = \frac{4M_1M_2E_2}{(M_2 + M_1)^2} \qquad (11\text{-}10)$$

and a cross section for Rutherford scattering of

$$\sigma_d = \pi\frac{M_2Z_1^2Z_2^2e^4}{M_1EE_d} \qquad (11\text{-}11)$$

Ion-material interactions

Mean free path and total number of displacements

The mean free path between collisions in which electron displacements occur and where N_0 is the solid number density is

$$\lambda = \frac{1}{N_0 \sigma_d} \quad \text{(11-12)}$$

The average total number of *electron displacements* produced in a solid by high energy ions (e.g., protons) is

$$n_d = \frac{1}{2}\left(1 + \ln\left(\frac{T_m}{E_d}\right)\right) \quad \text{(11-13)}$$

Ion-material interactions

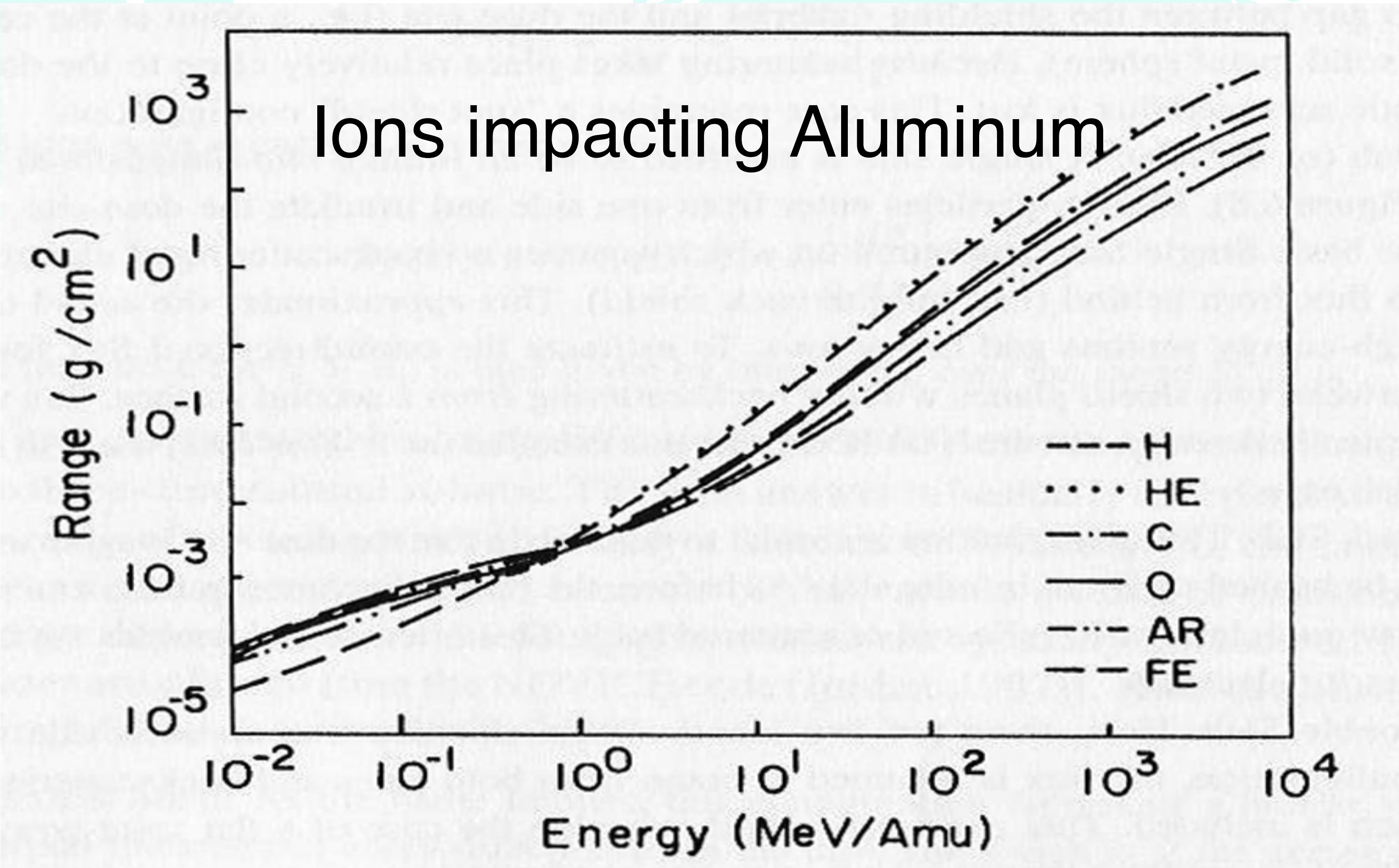
Ion range

Since the major source of ion energy loss at high energies is electron excitation of solid atoms, and the moving ion can be stripped of all its electrons, then the energy loss is through Rutherford collisions by the ion nucleus with the solid atom electrons

In these interactions, it is possible for the moving ion to capture electrons from the solid atom whereby the effective charge is decreased

The range (g cm^{-2}) of several ions in aluminum, for example, is shown in the next slide

Ion-material interactions



Neutron-material interactions

Neutron bombardment

Because neutrons have no net charge as compared with ions, they are not stopped in a material due to electrical forces exerted on them

Displacement of solid atoms occurs with two mechanisms

1. A neutron can **collide directly** with a solid nucleus and impart an energy in excess of E_d; the nucleus is unchanged in elastic or inelastic scattering but may have enough energy to produce further displacements
2. A **nuclear reaction** can occur causing atomic displacements; here the neutron is captured by the solid nucleus and the binding energy is released in the form of a gamma ray

Particle-material interactions

Radiation damage by particle and photon impacts: summary

Since E_d is near 25 eV for many materials, high energy impacts of MeV levels lose only a small fraction of their energy in a collision

There remains abundant kinetic energy for many additional displacements and the cumulative effect can be the change of material properties

There is no difference in damage to material from photons, electrons, ions, or neutrons although one incident photon generally produces one displacement while one incident ion can produce several or many displacements

Therefore, there is usually more severe damage from particle impact than from energetic photons

However, photons can generally penetrate further into a material

Radiation environment characteristics

Radiation characteristics

Units

- The **Gray** (Gy) is the SI unit of radiation and is the amount of radiation that deposits 1 J kg^{-1} in a material
- The **Rad** is the amount of radiation that deposits 0.01 J per kg of material (100 ergs g^{-1}) (100 Rads = 1 Gy)
- The **Dose** is the amount of radiation energy deposited in a material as a function of time; the radiation dose is dependent upon the integrated effects of the radiation energy and the material composition
- The **total dose** deposited over the life of the material and the rate at which the radiation is deposited (dose rate) are two of the most important factors in determining radiation damage

Radiation characteristics

Dose and dose rate prediction

A knowledge of the ambient high energy (solar) photon, electron, ion, neutron, and (galactic) cosmic ray environment is a first prerequisite (see lecture 10)

Galactic cosmic rays and solar energetic protons penetrate into the troposphere causing radiation in aircraft

Van Allen belts (inner, outer, and new) are generally the regions in which Earth-orbiting spacecraft encounter the trapped particles while energetic photons can be encountered in any environment

Interplanetary and outer planets (e.g., Jupiter, Saturn) environments have their own radiation environments composed of the same particles/photons

Radiation characteristics

Human-produced radiation can achieve high energies of 10^4-10^8 eV.

Solar energetic photons (hard X-rays and gamma rays) are generated during powerful solar flares. The energy of photons during solar events can achieve 10^4-10^8 eV.

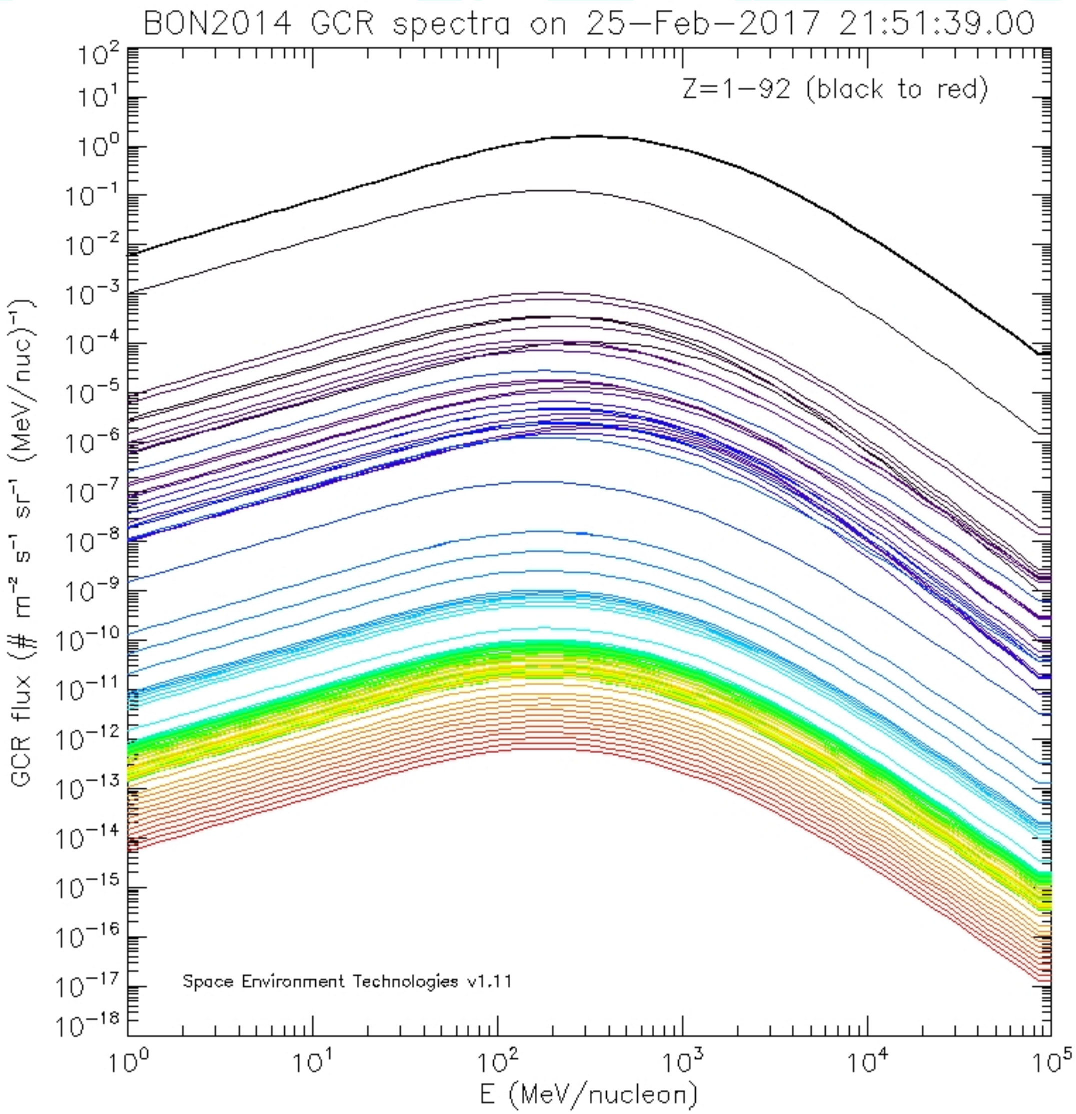
Radiation belts (RB), the regions populated with high-energy charged particle fluxes, are located within the dipole structure region of the magnetic field of the Earth and giant-planets. Particle energies can be as high as 10^9 eV for protons and 10^7 eV for electrons for extreme conditions.

Solar energetic particles (SEPs) are generated during coronal mass ejections and in IMF acceleration shocks. The frequency of such events varies with the solar activity cycle: there are more during the maximum and decline of the solar cycle. The energy of protons and nuclei during solar events can achieve 10^9-10^{11} eV.

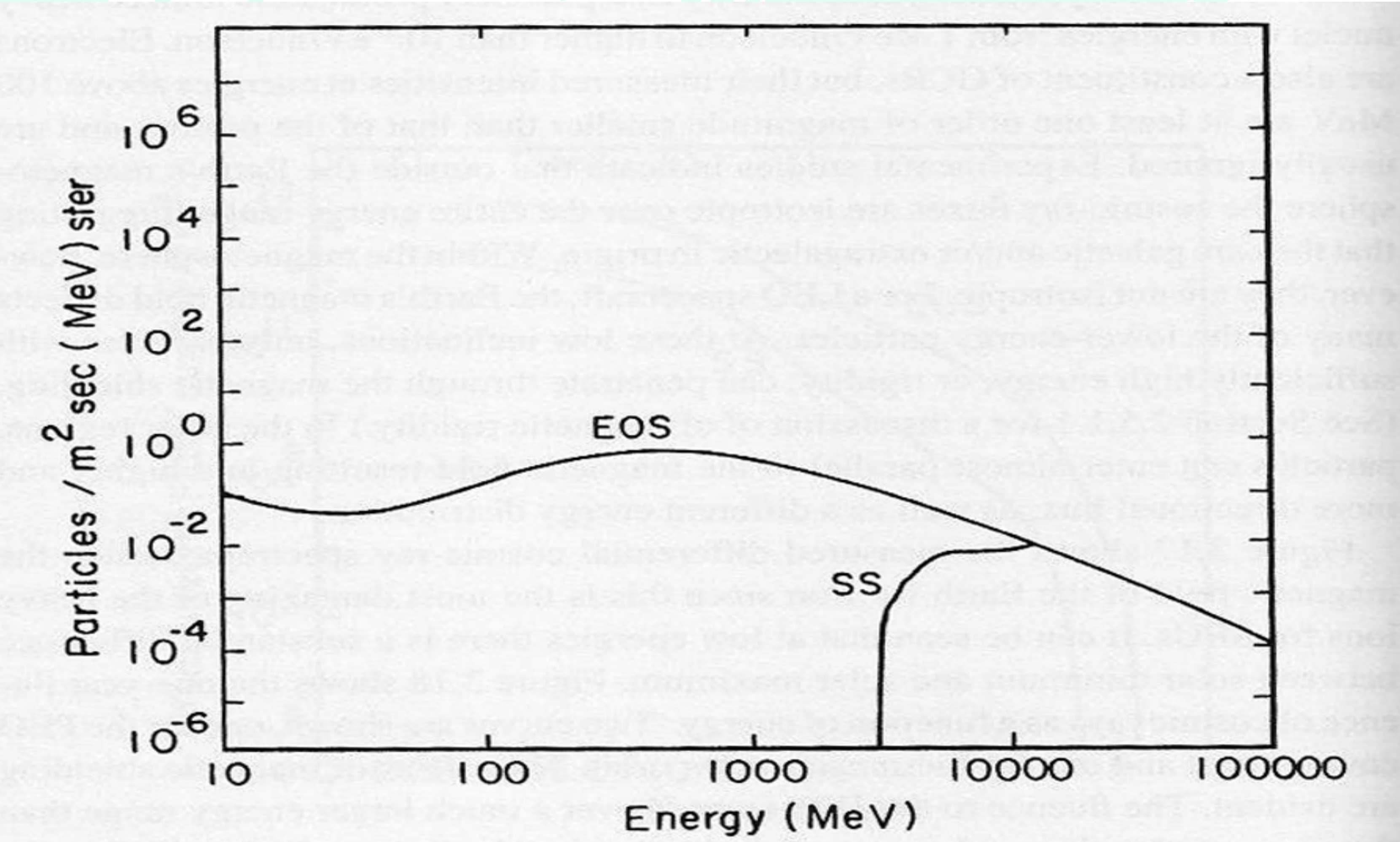
Galactic cosmic rays can achieve even higher energies - as high as 10^{21} eV with an abruptly falling energy spectrum.

Credit: Panasyuk

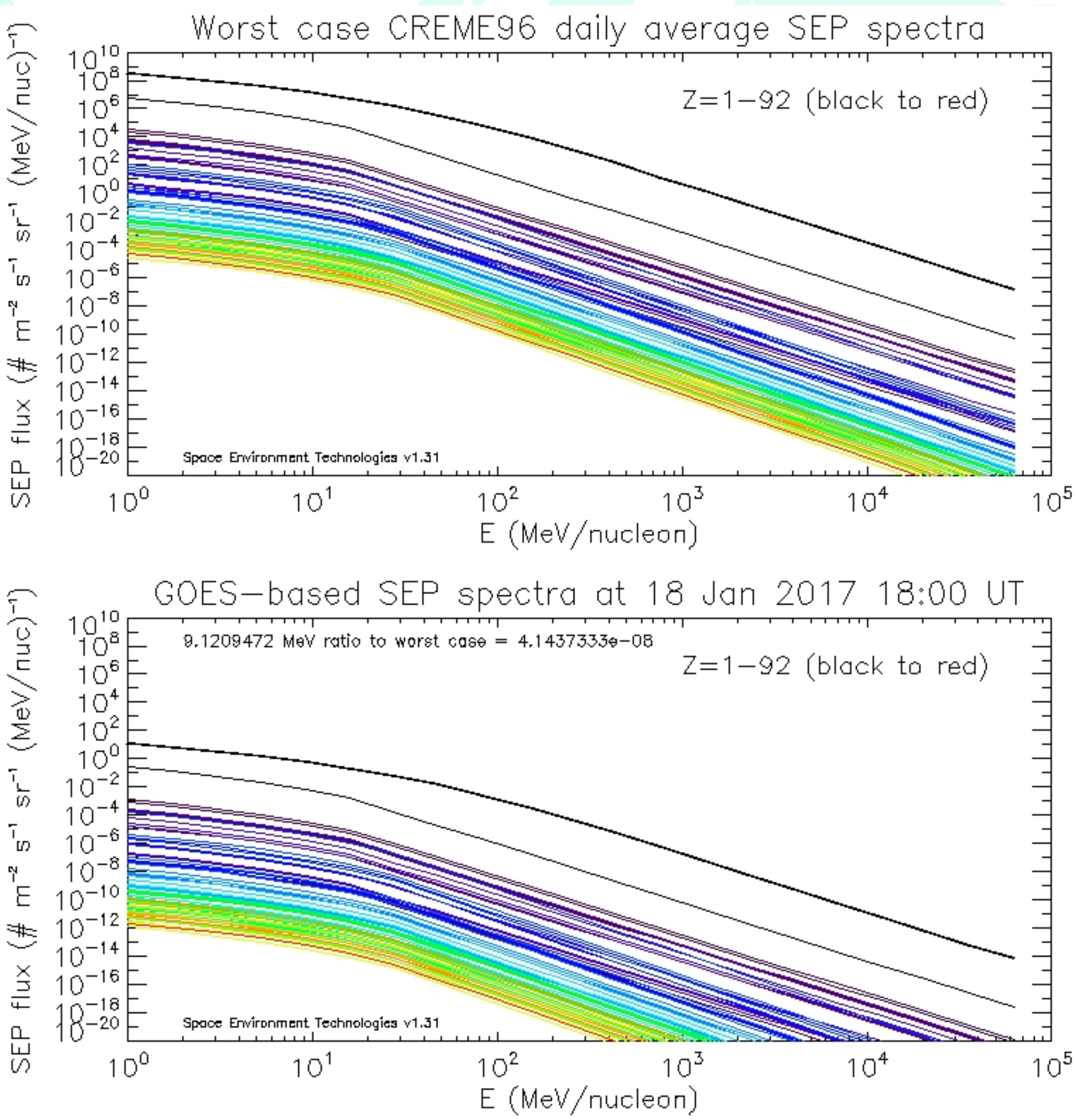
GCR spectra


BON2014 GCR spectra on 25–Feb–2017 21:51:39.00
Z=1–92 (black to red)
GCR flux (# m⁻² s⁻¹ sr⁻¹ (MeV/nuc)⁻¹)
E (MeV/nucleon)
Space Environment Technologies v1.11

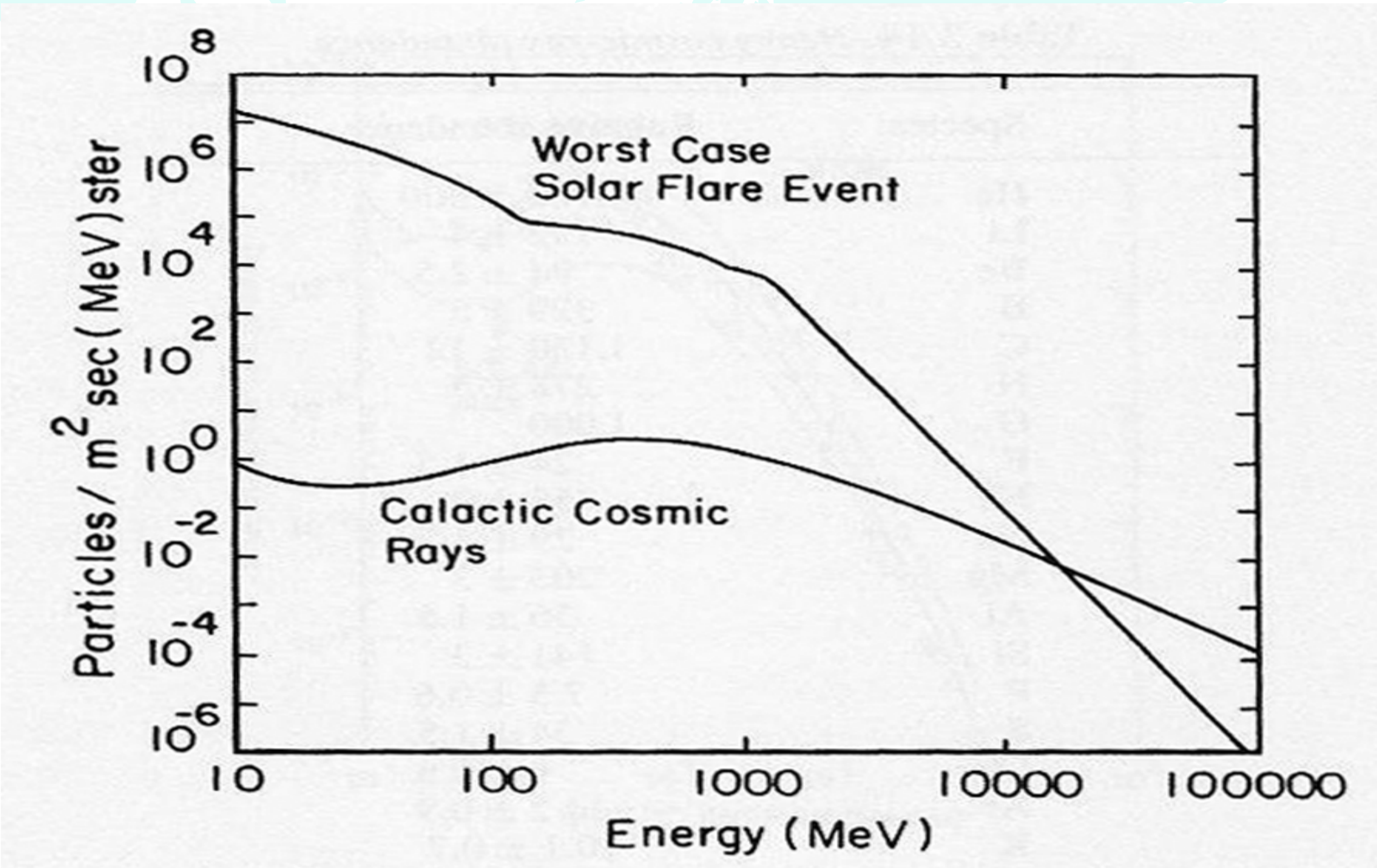
Galactic Cosmic Ray fluences



SEP spectra

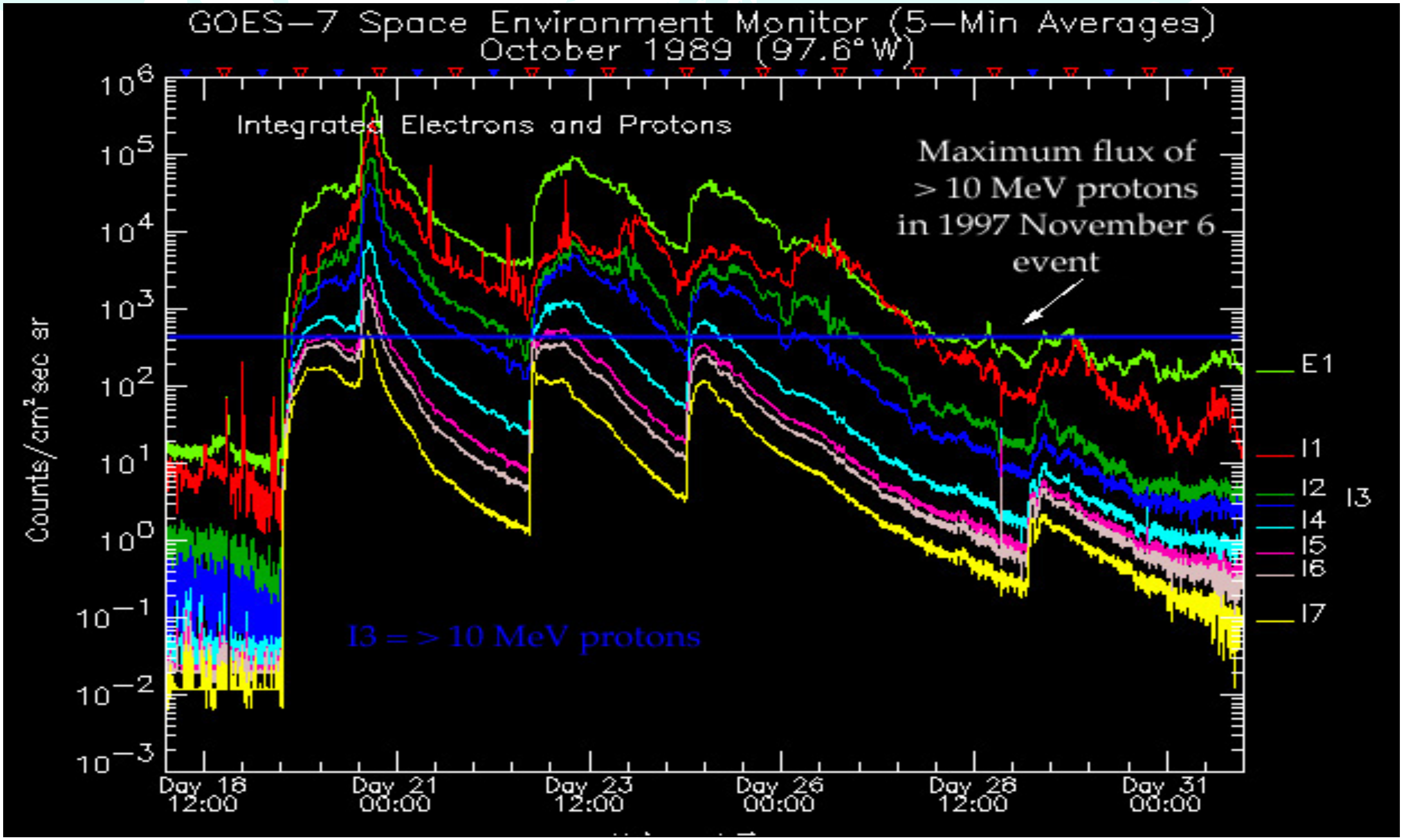

Worst case CREME96 daily average SEP spectra
Z=1–92 (black to red)
Space Environment Technologies v1.31
SEP flux (# m⁻² s⁻¹ sr⁻¹ (MeV/nuc)⁻¹)
E (MeV/nucleon)
GOES–based SEP spectra at 18 Jan 2017 18:00 UT
9.1209472 MeV ratio to worst case = 4.1437333e-08
Z=1–92 (black to red)
Space Environment Technologies v1.31
SEP flux (# m⁻² s⁻¹ sr⁻¹ (MeV/nuc)⁻¹)
E (MeV/nucleon)

Solar energetic particle fluences



Credit: Garrett

Solar energetic particle fluences



Solar energetic particle fluences

From: <secproducts@noaa.gov>
Date: November 14, 2006 5:06:23 AM GMT+00:00
To: <ktobiska@spacenvironment.net>
Subject: ALERT: Electron 2 MeV Integral Flux exceeded 1,000 pfu

Space Weather Message Code: ALTEF3
Serial Number: 1198
Issue Time: 2006 Nov 14 0503 UTC

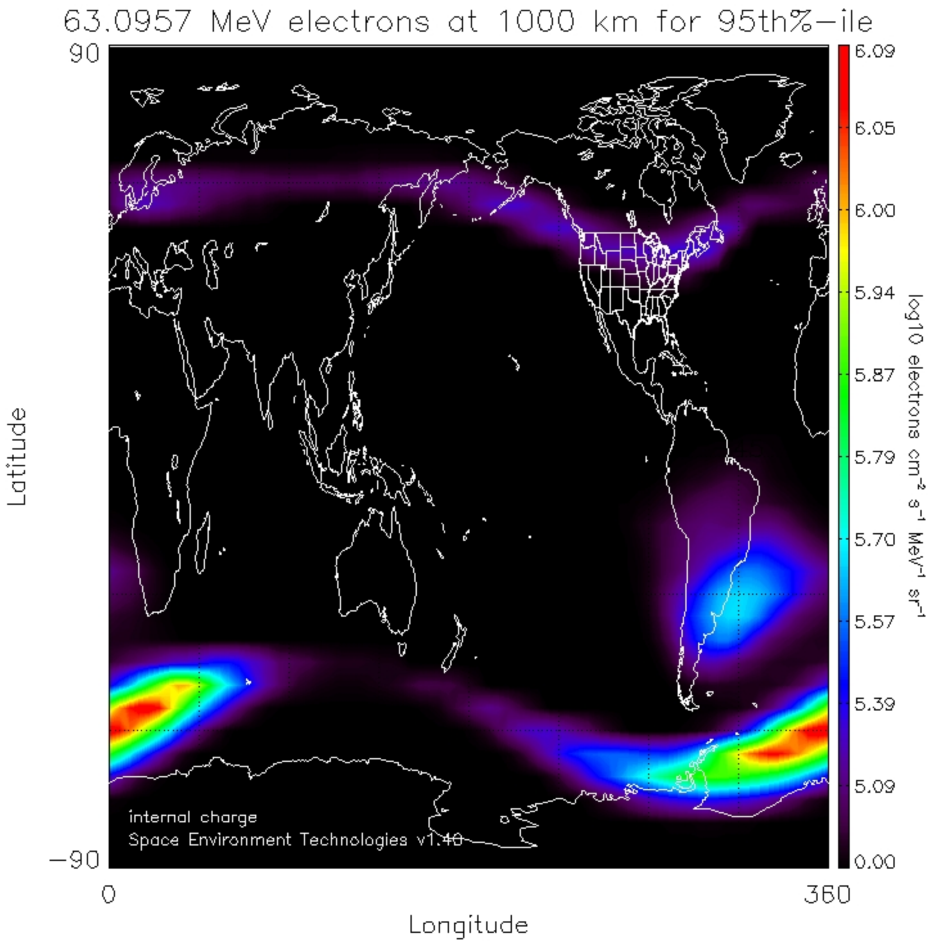
ALERT: Electron 2MeV Integral Flux exceeded 1000pfu
Threshold Reached: 2006 Nov 14 0500 UTC
Station: GOES12
Observed Yesterday: Yes
Yesterday Maximum 2MeV Flux: 13400 pfu

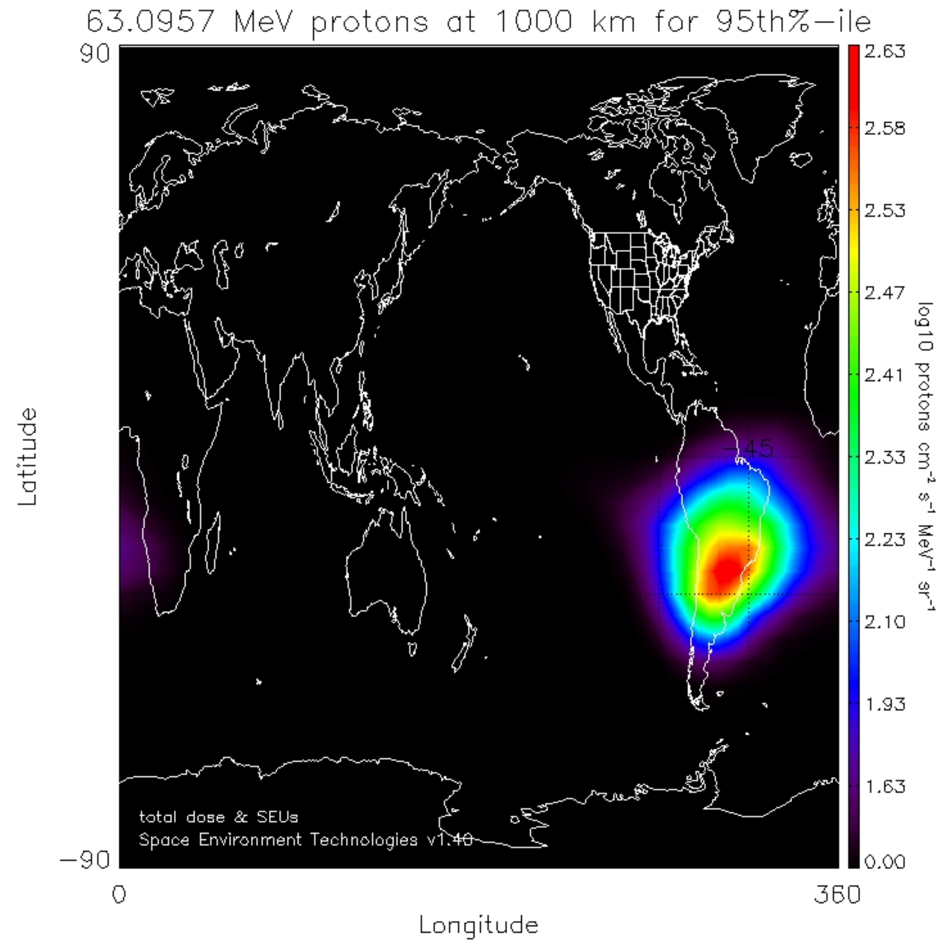
NOAA Space Weather Scale descriptions can be found at www.sec.noaa.gov/NOAAscales

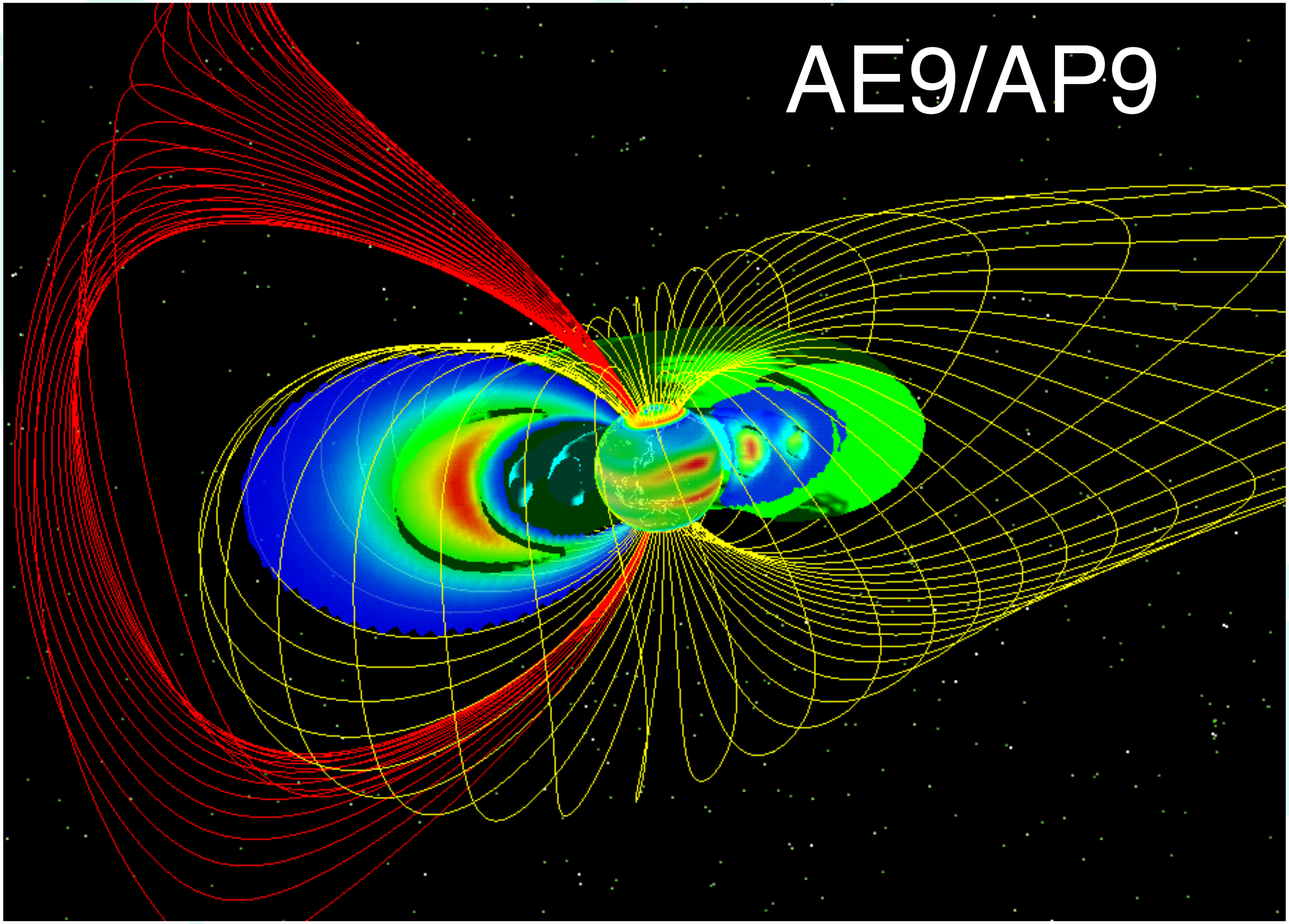
Thank you for using the SEC Product Subscription Service. If you would like to remove a product subscription or update the personal information in your account, go to: https://pss.sec.noaa.gov. For problems, contact: mailto:secproducts@noaa.gov.

Credit: NOAA

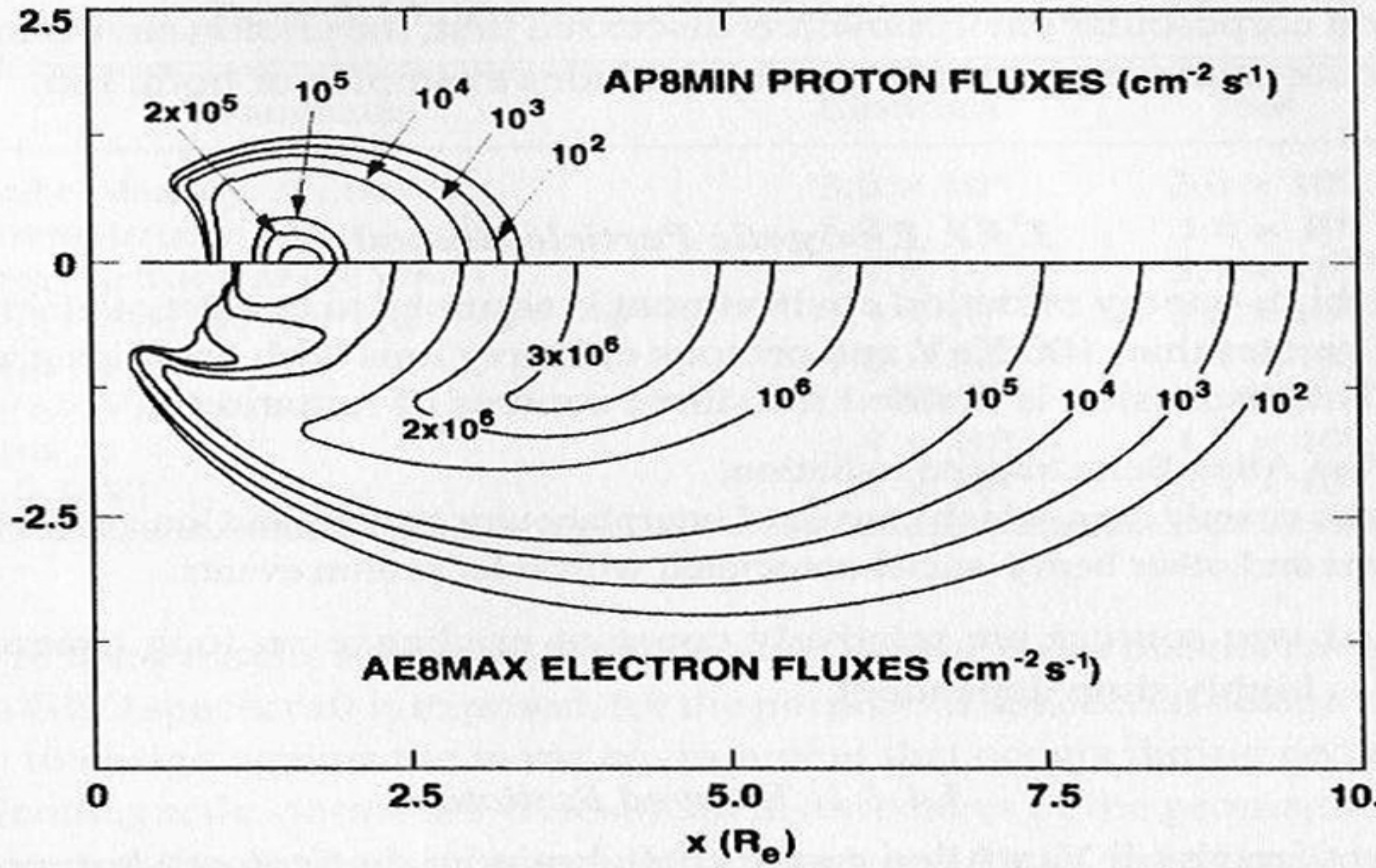
AE(P)-9 Trapped particles






AE9/AP9

Van Allen belt fluences

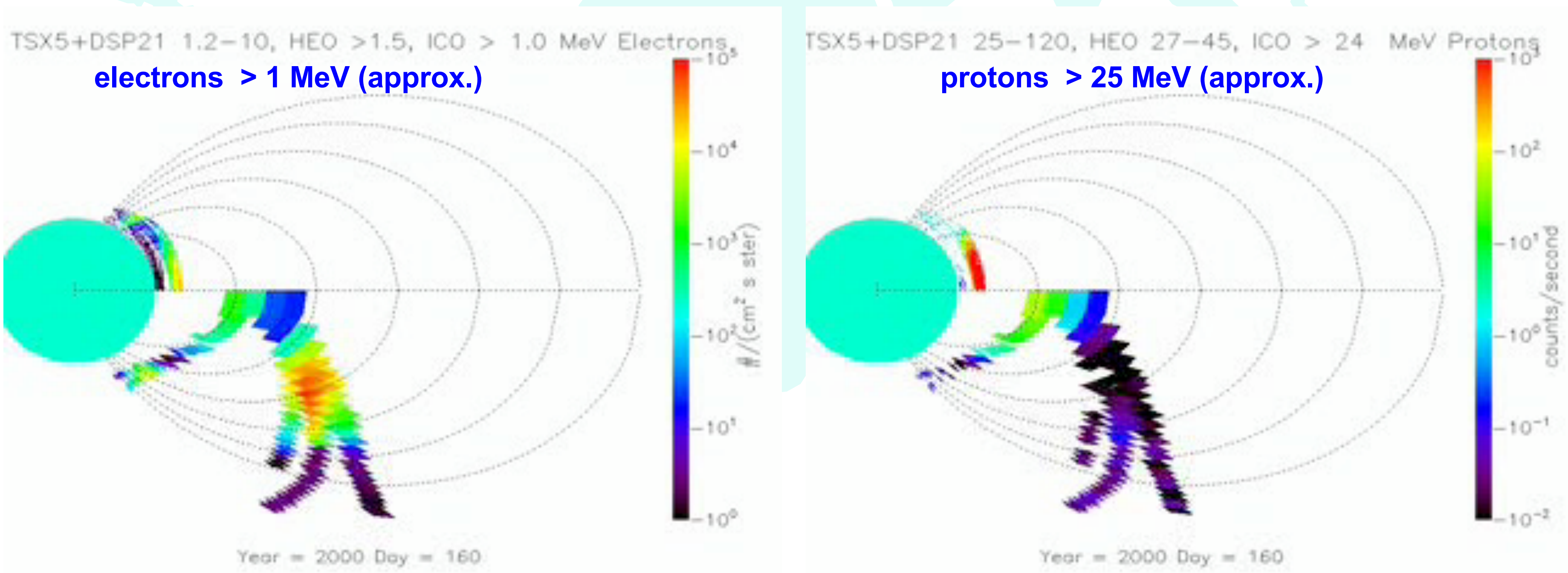


AE(P)-9 Summary

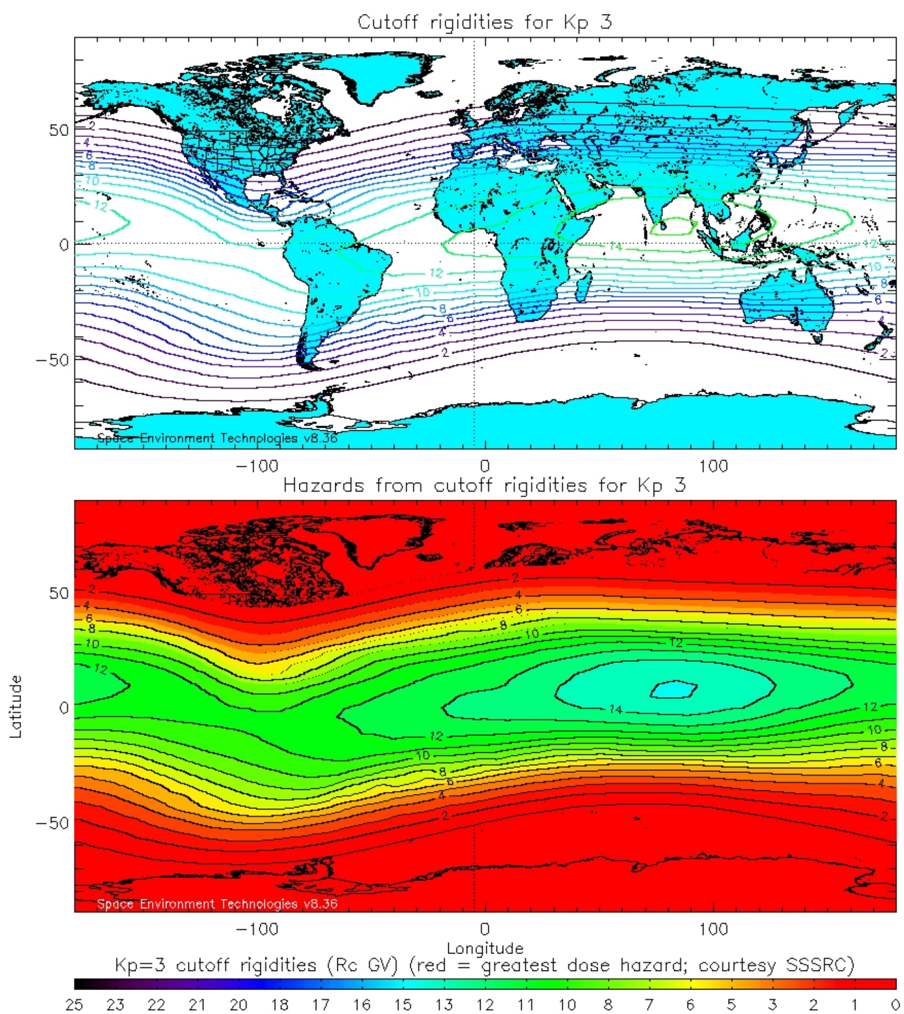
AE(P)-9 improves AE(P)-8 and addresses vital needs of space system design community

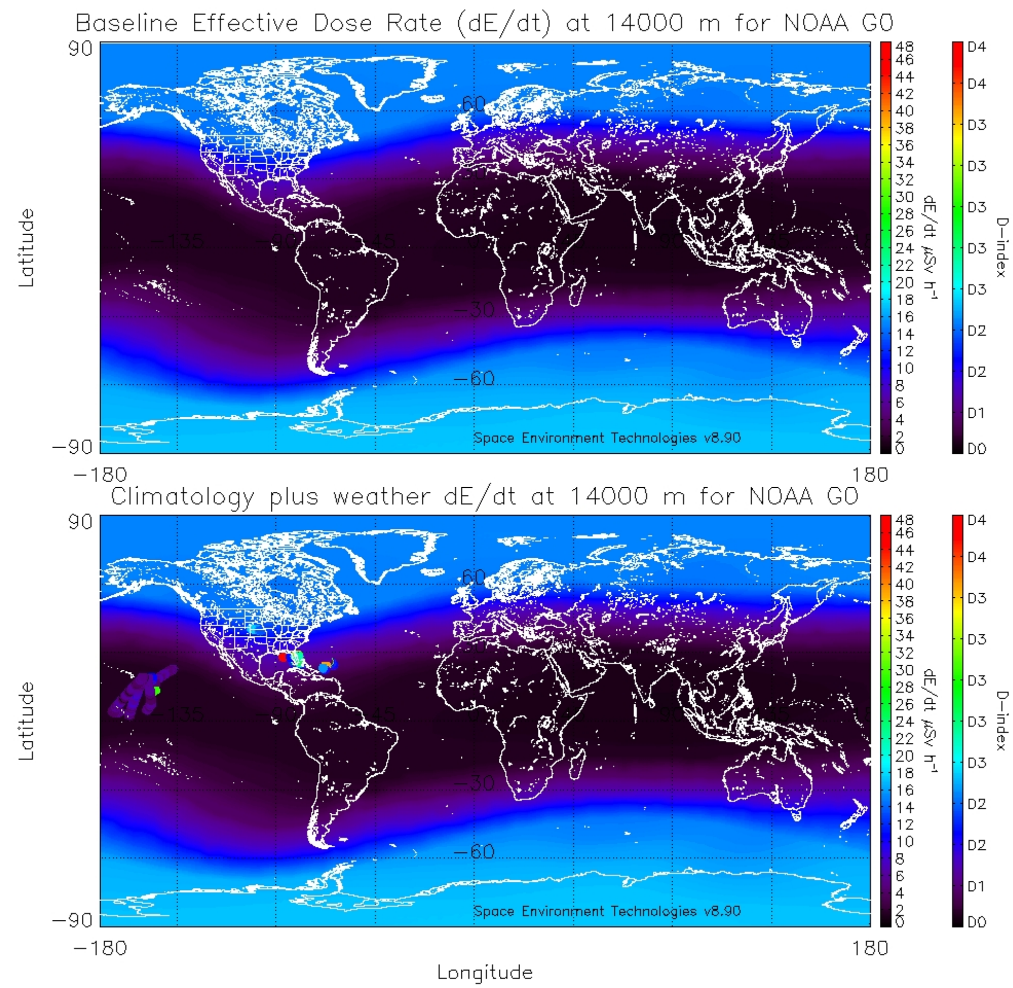
- More coverage in energy, time & location for *trapped* energetic particles & plasma
- Instrument error & space weather statistical fluctuations are captured
- Two component approach provides
  - Empirical model with statistics but no time correlation
  - “Standard Solar Cycle” through which notional missions can be flown to provide temporal correlation

◆ Final version available September 2012

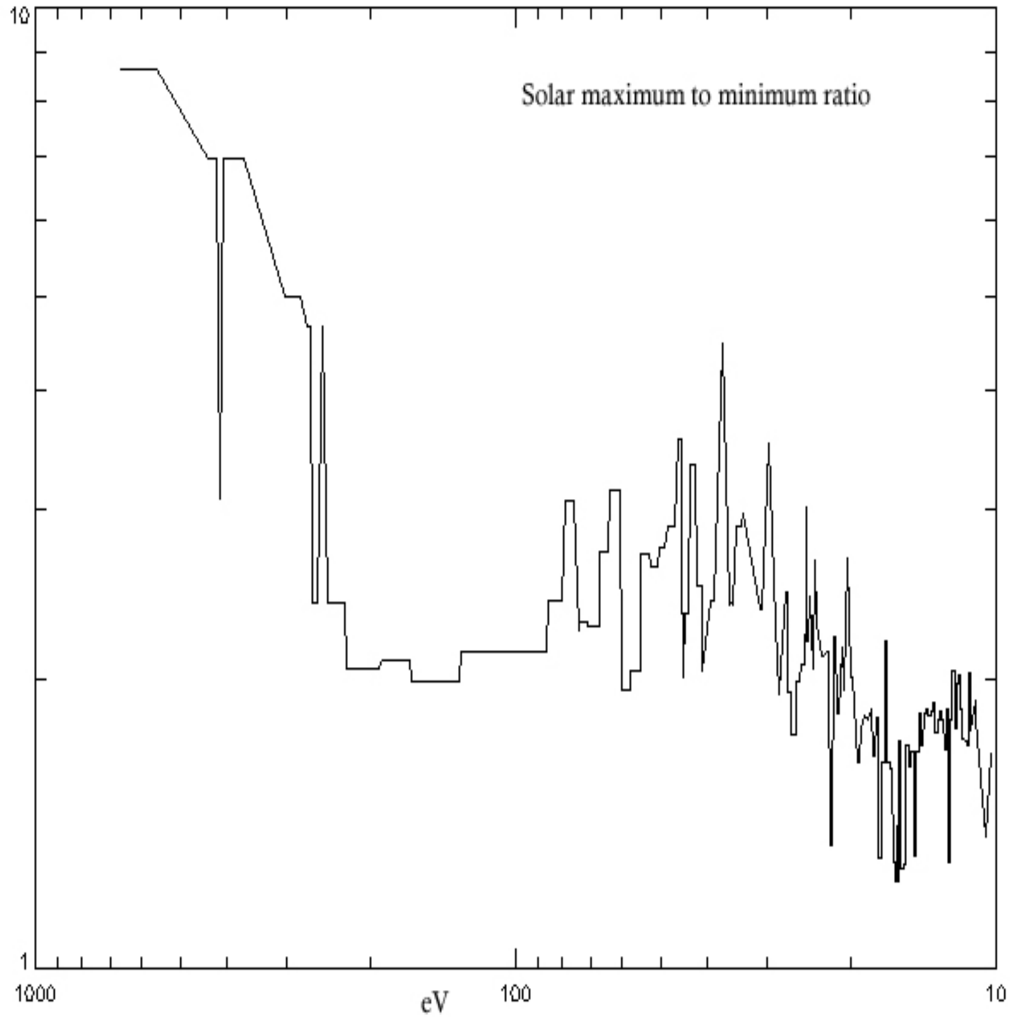


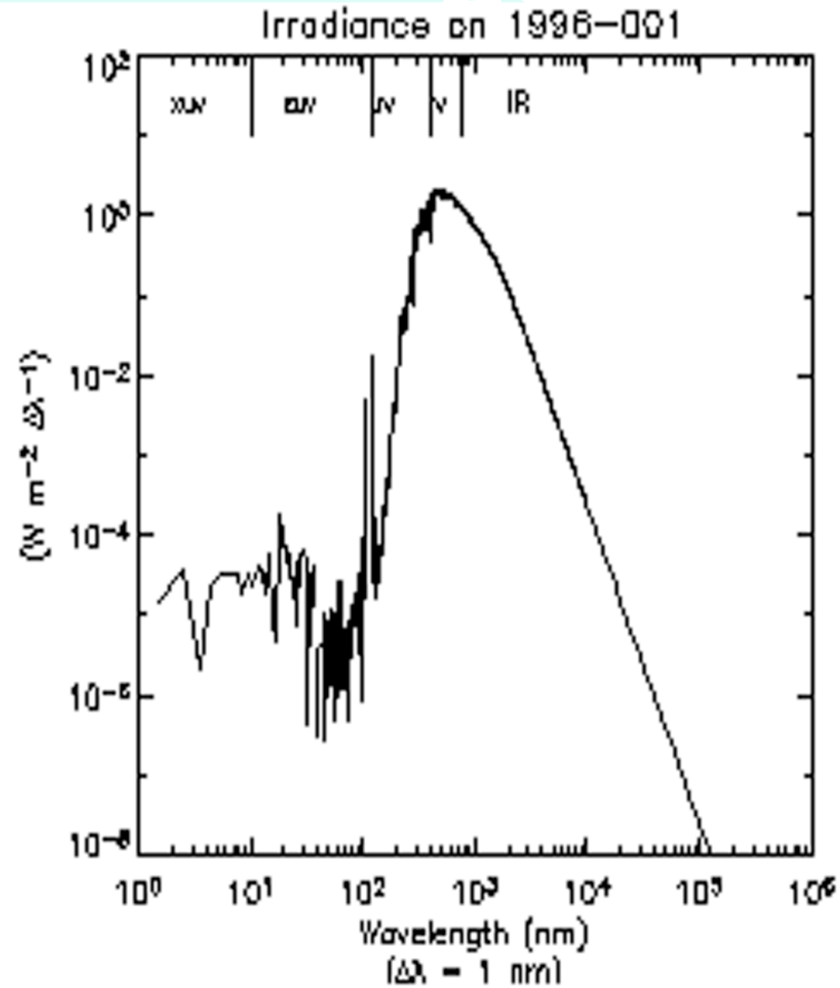
Cutoff rigidities





Solar energetic photons

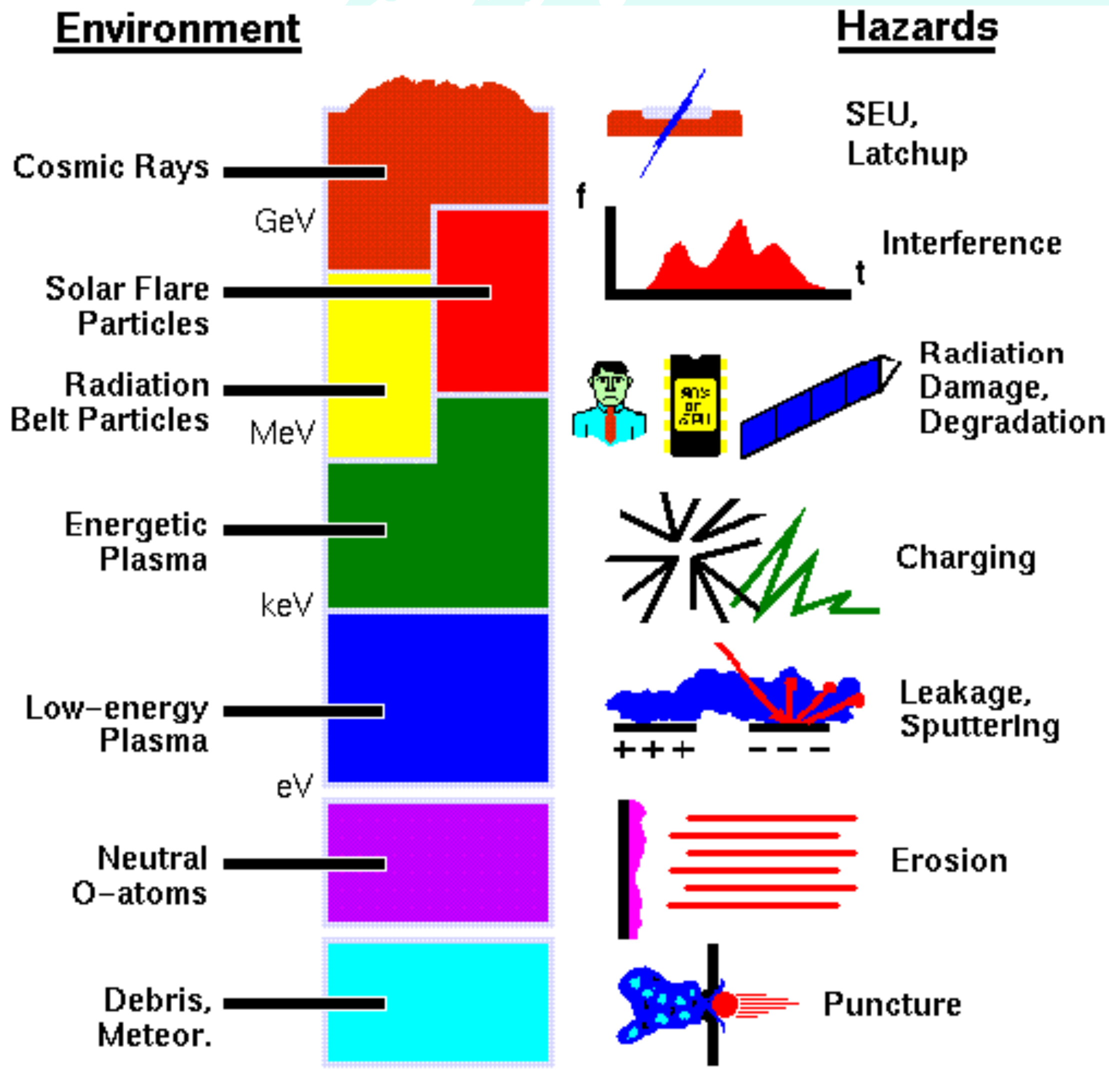




BREAK

Radiation (charged particle) effects

Particle radiation effects



Radiation effects

Space environment radiation can be gathered into two groups according to their localization:

1) **surface impacting effects** which are a hazard for unshielded equipment elements and outer surfaces of the SC (for example, hot and cold plasma particles, solar ultraviolet emissions, and microparticles);

2) **penetrating effects** impacting deep layers of materials and system elements in the interior modules of the SC (for example, RB particles, SEP, GCR).

Radiation effects

Surface impacting effects

- **Conducting materials** (thermal paints and coatings as well as electrical resistive coatings) can degrade from impacts
- Materials include Kapton insulation, Teflon, chemglaze paints, and fused silica
- Results can cascade to premature end-of-life (EOL) for s/c
- High temp superconducting materials generally offer improved s/c performance, e.g., low surface resistance at high frequencies results in reduced RF losses in superconducting waveguides, bandpass filters, and antennas. When these radiators are located on shaded side of s/c to radiate direct to space, they can get high radiation dosages.
- Thin coats of YBCO superconducting films resist radiation degradation effects.

Radiation effects

Surface impacting effects

Solar arrays can suffer irreversible losses in output due to radiation damage. An example was the 1989 solar proton events (SPEs).

An important factor is how much radiation has the array received prior to the SPE and this is based on the integrated radiation dose from the trapped electrons and protons, the solar cell cover glass thickness, and the amount of time the s/c has been in orbit.

Solar cells do not degrade linearly with time but obey an approximate exponential loss of output with total radiation dose.

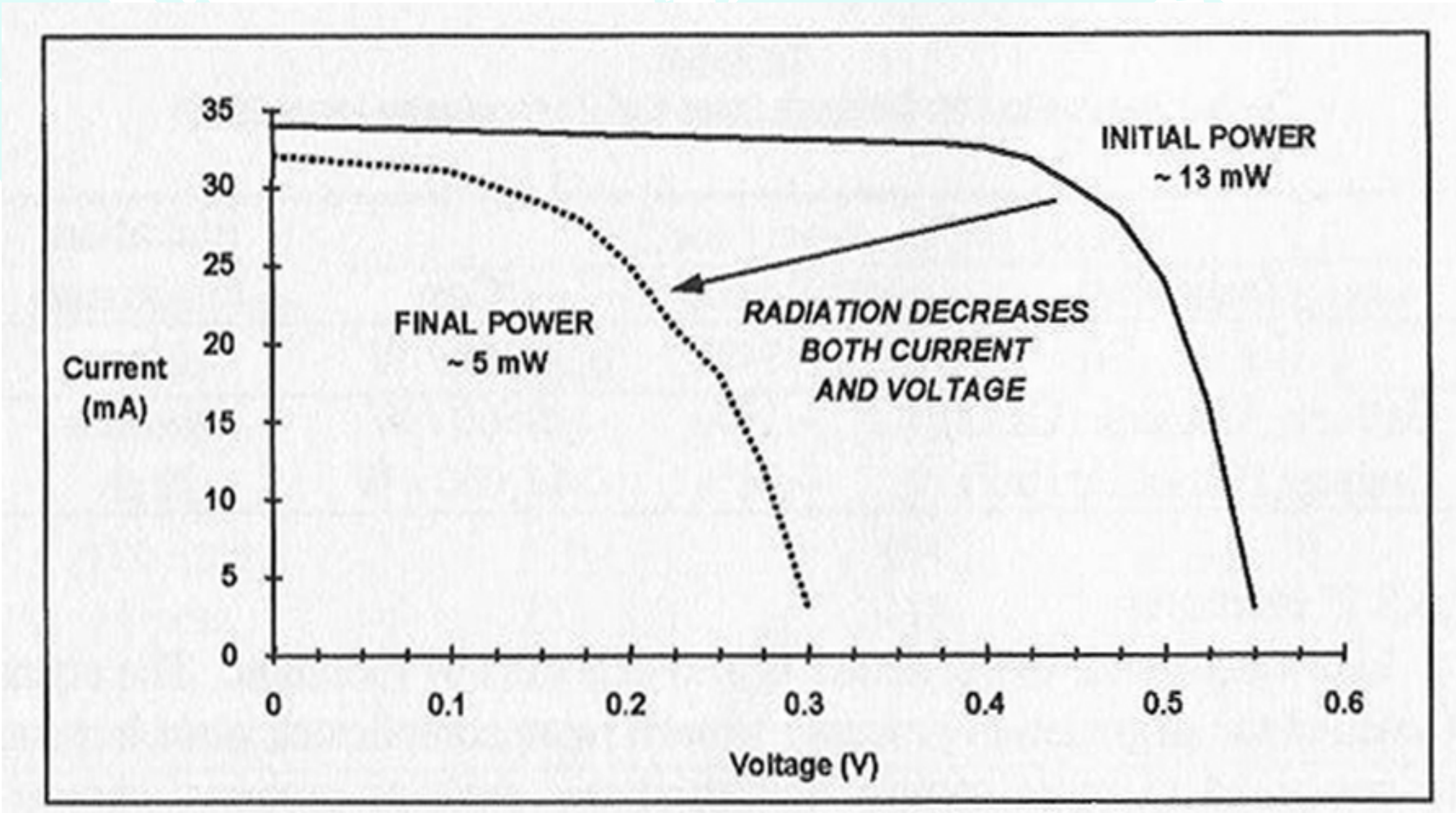
Thus, incremental fluences late in life result in smaller output decreases compared to fluences early in solar cell life (first 2 years).

Degradation mostly results from atomic displacement and formation of color centers in the cover glass and underlying solar cell.

Si cells degrade faster than GaAs.

 Credit: Panasyuk

Solar array power



Radiation effects

Surface impacting effects

Optical surfaces can be damaged at the surface or in bulk.

Surface optical damages result in reduced reflectance of metallic surfaces or overcoatings, for example, and tend to come from low energy fluxes as well as XUV-UV irradiances

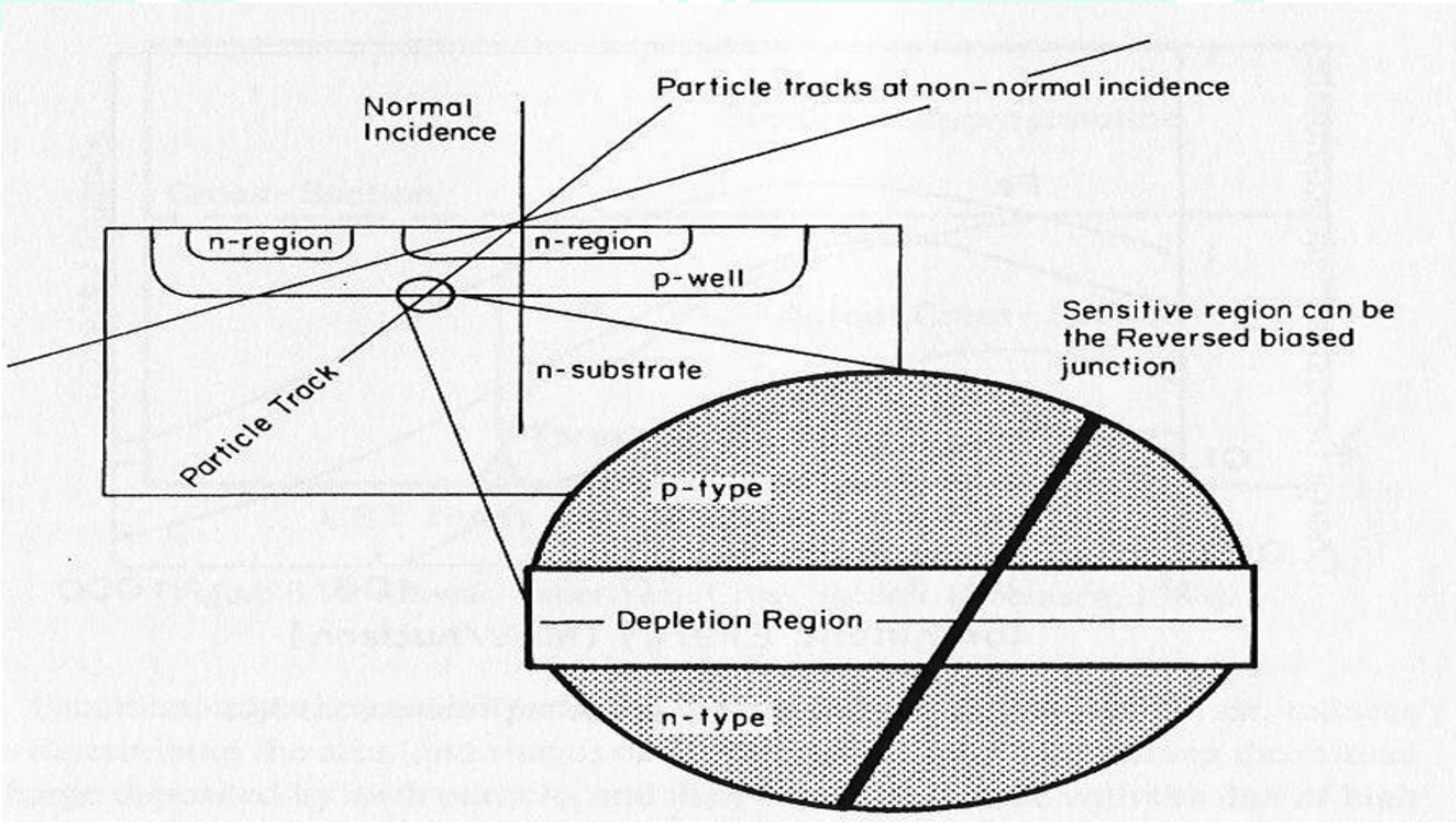
Bulk optical damages result in damages within the material and polymers such as Teflon and Kapton are examples. Higher energy particles and photons penetrate the material and cause depth dose effects.

Radiation effects

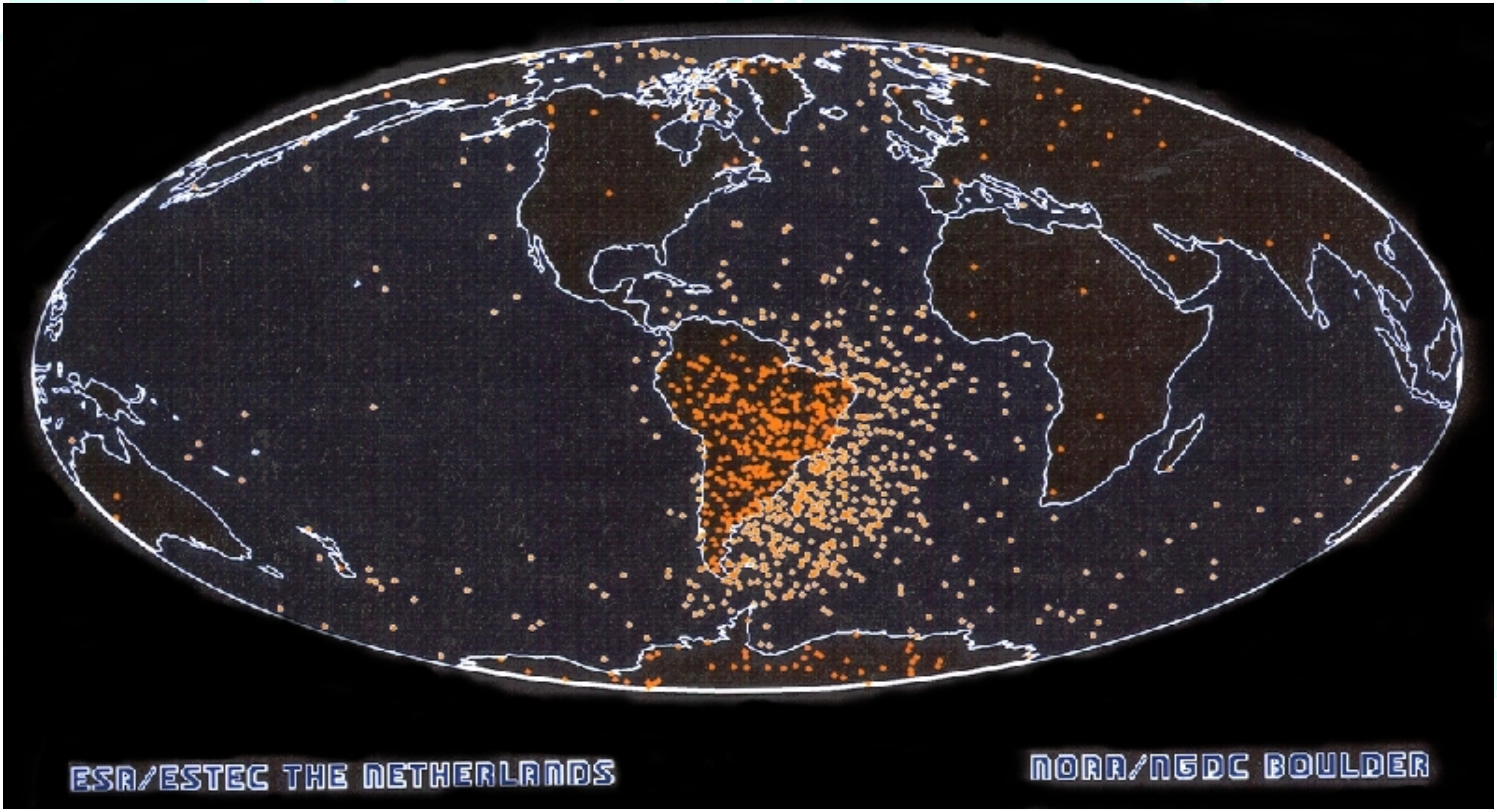
Penetrating effects

- **Single Event Upsets (SEUs) or Single Event Effects (SEE)** result from a deposition of charge in an analog, digital, or power circuit caused by the interaction of a single particle or photon
- There is a long history of SEU monitoring and the South Atlantic Anomaly (SAA) has historically been a location of repeated SEUs on s/c
- The overwhelming majority of upsets is attributed to trapped radiation, specifically energetic protons

SEU diagram


Particle tracks at non-normal incidence
Normal
Incidence
n-region
n-region
p-well
Sensitive region can be
the Reversed biased
junction
n-substrate
Particle Track
p-type
Depletion Region
n-type

UOSAT-2 Memory Upsets



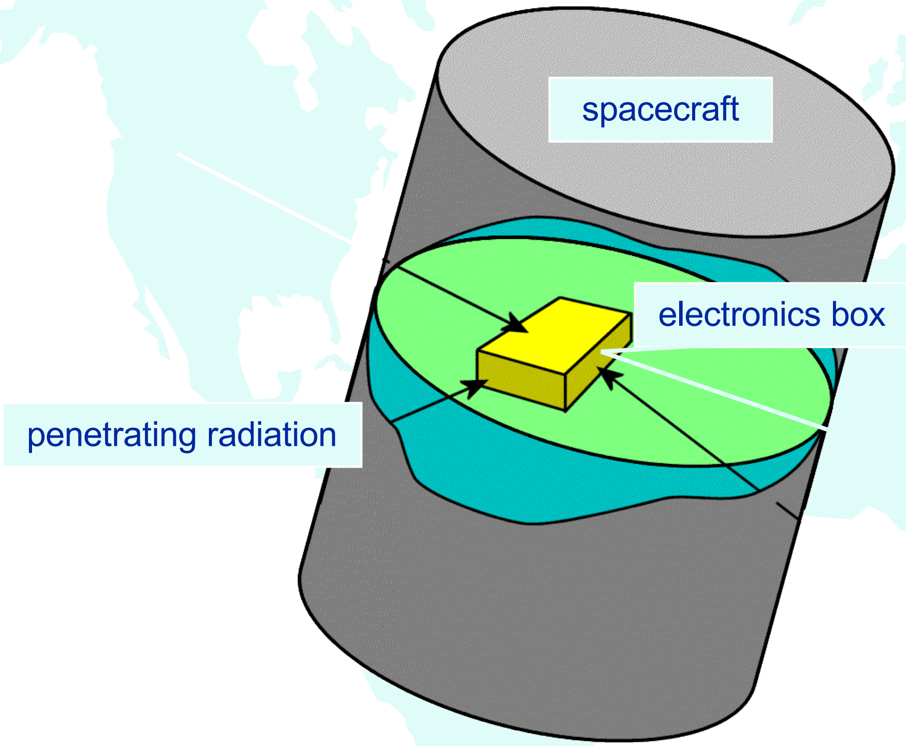
Credit: NOAA

Radiation effects

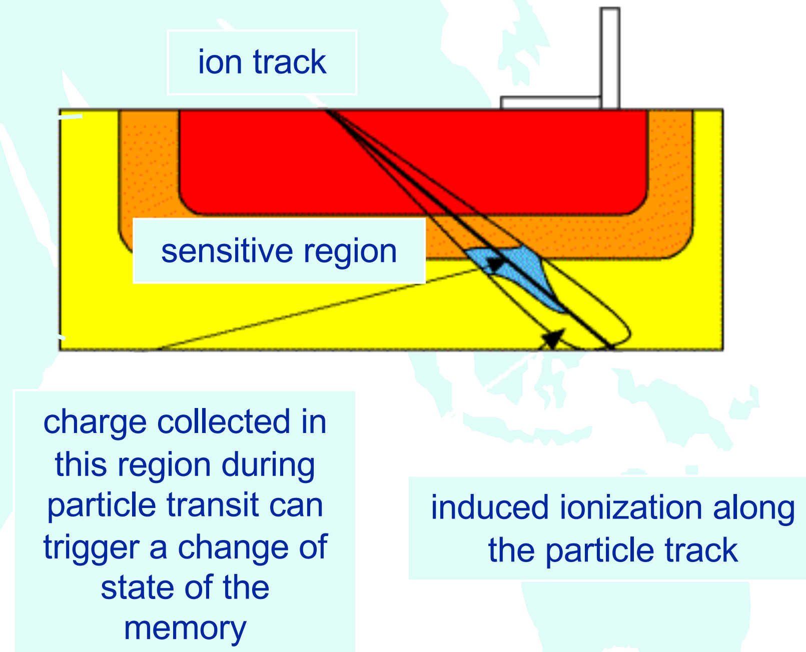
Penetrating effects

- **Latchup** is generally a high current state in which a device no longer accepts input signals and the result can be catastrophic for the system and/or spacecraft
- CMOS PROM devices may be sensitive to latchup
- **Deep dielectric charging** occurs when electrons of 2-10 MeV penetrate deep into satellite surfaces (0.6 MeV electrons can be used as an operational proxy)
  - Excess charge spreads out evenly on conducting surfaces but results in uneven potential distribution on dielectric surfaces
  - Potential differences can reach a threshold at which point discharge occurs
  - Deep dielectric charging occurs inside the surfaces of satellites and discharges can occur to circuits inside the s/c

Radiation effects

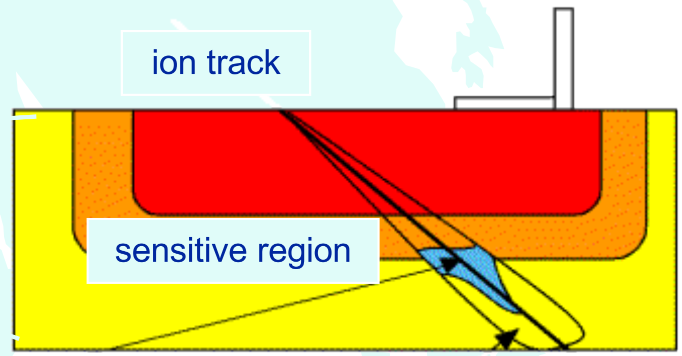


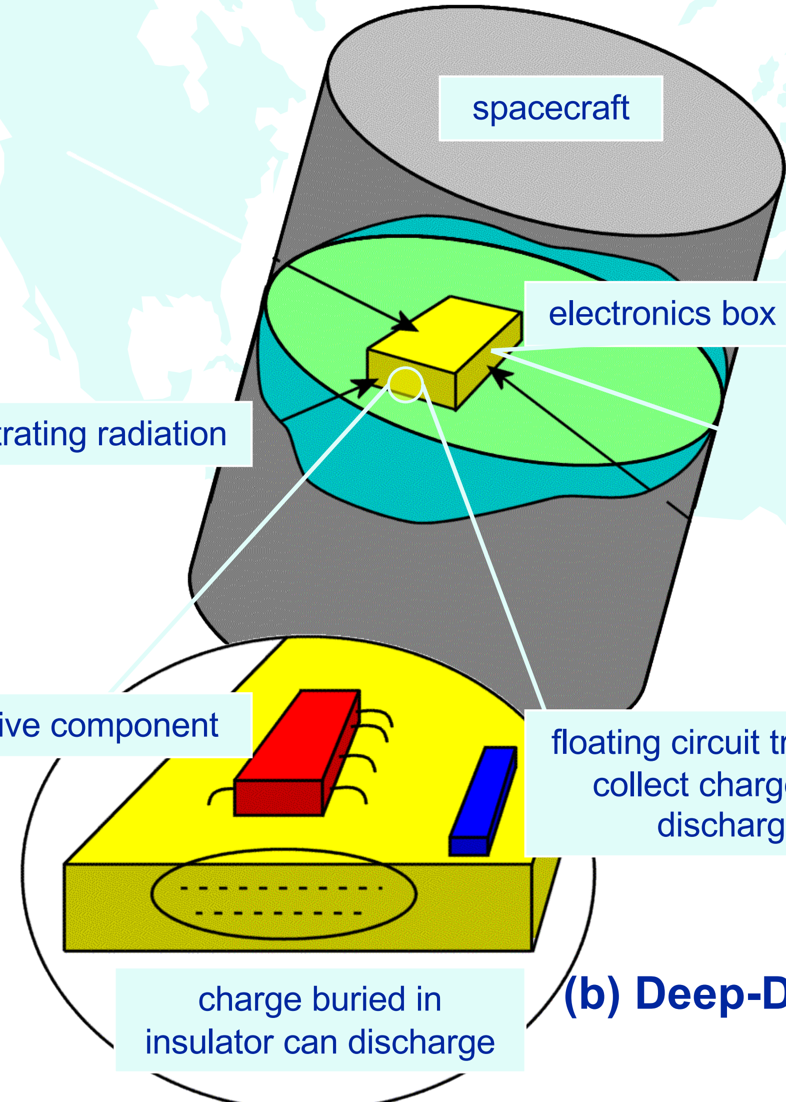
(a) Single Event Upset Mechanism Direct Ionization



Radiation effects

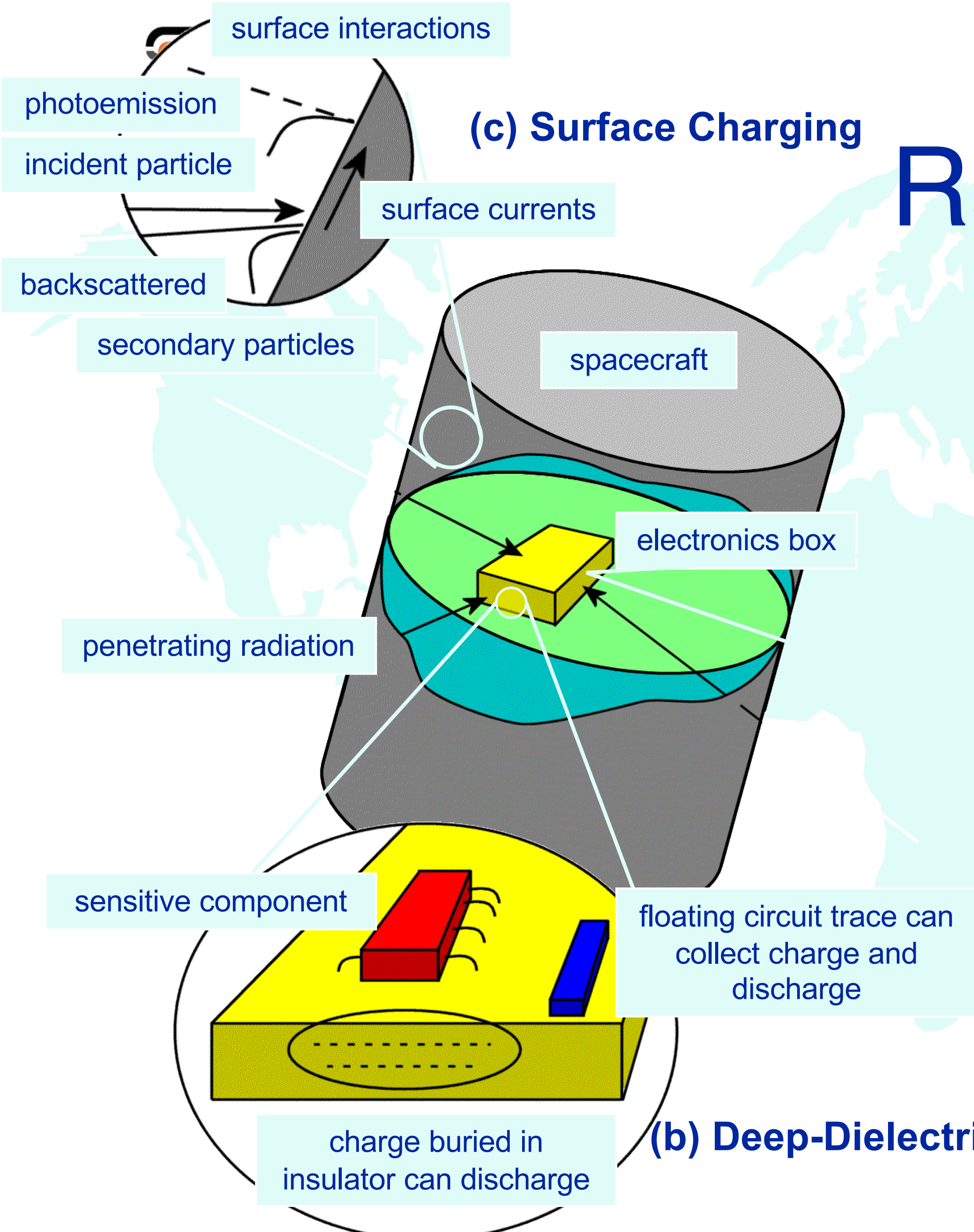
(a) Single Event Upset Mechanism Direct Ionization

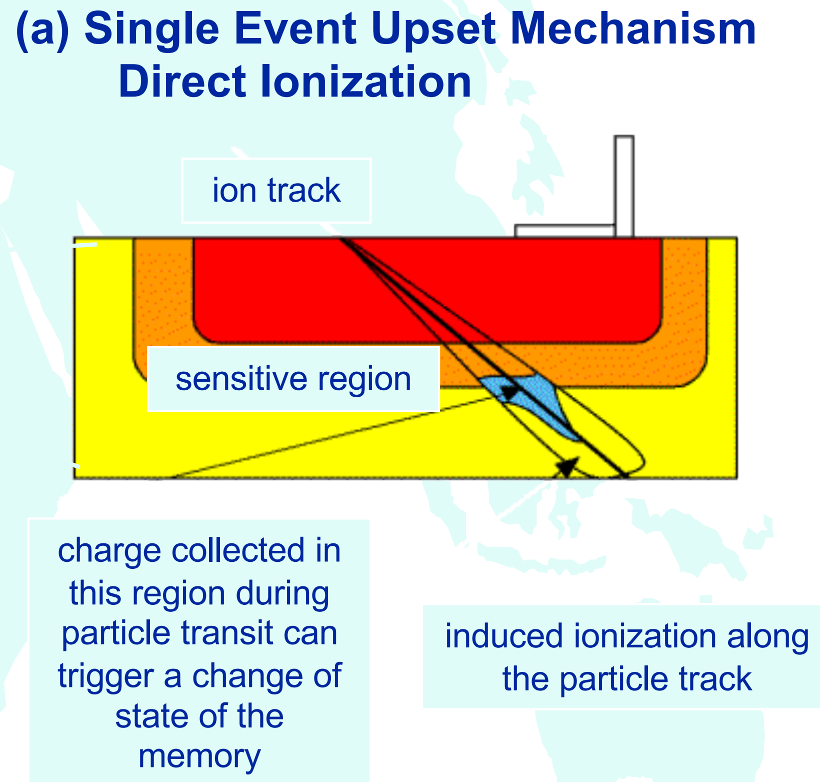




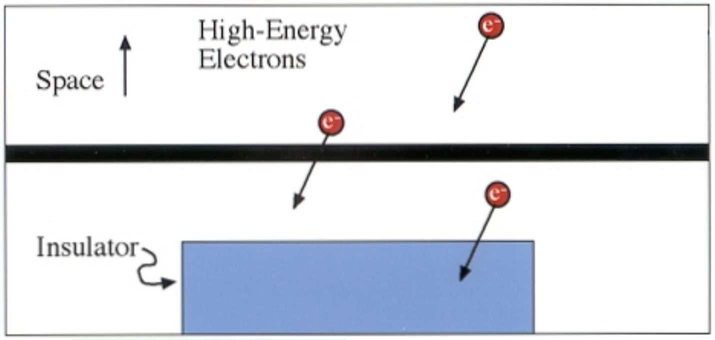
(b) Deep-Dielectric Charging

Radiation effects

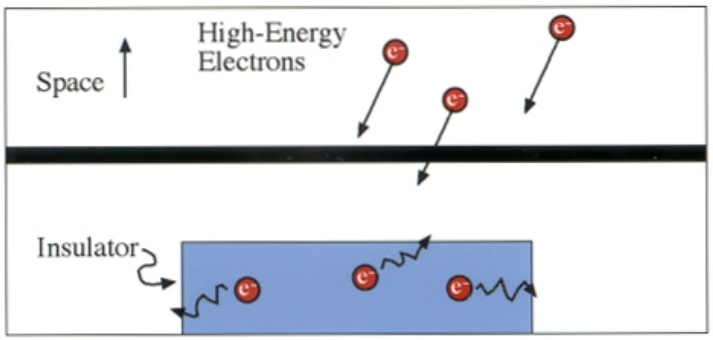




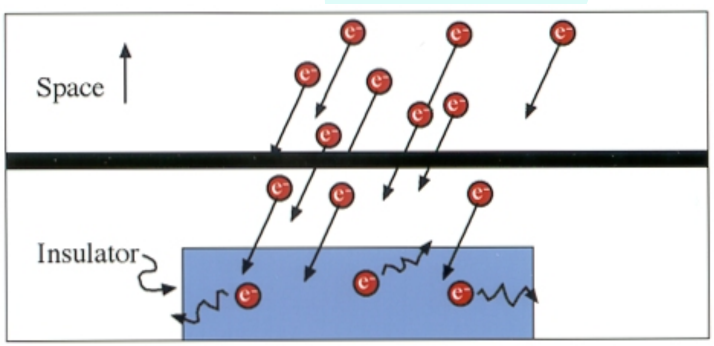
High-Energy Electrons: Deep-Dielectric Charging



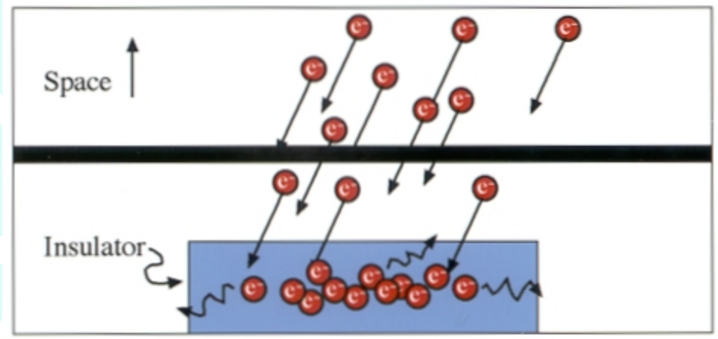
1. Electrons bury themselves in the insulator



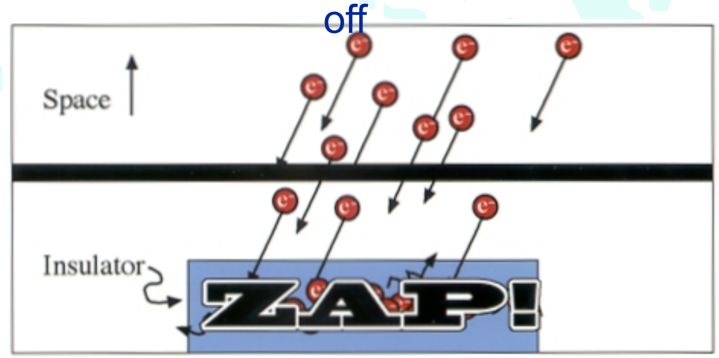
2. Electrons slowly leak out of the insulator



3. Influx of electrons increases to levels higher than the leakage rate

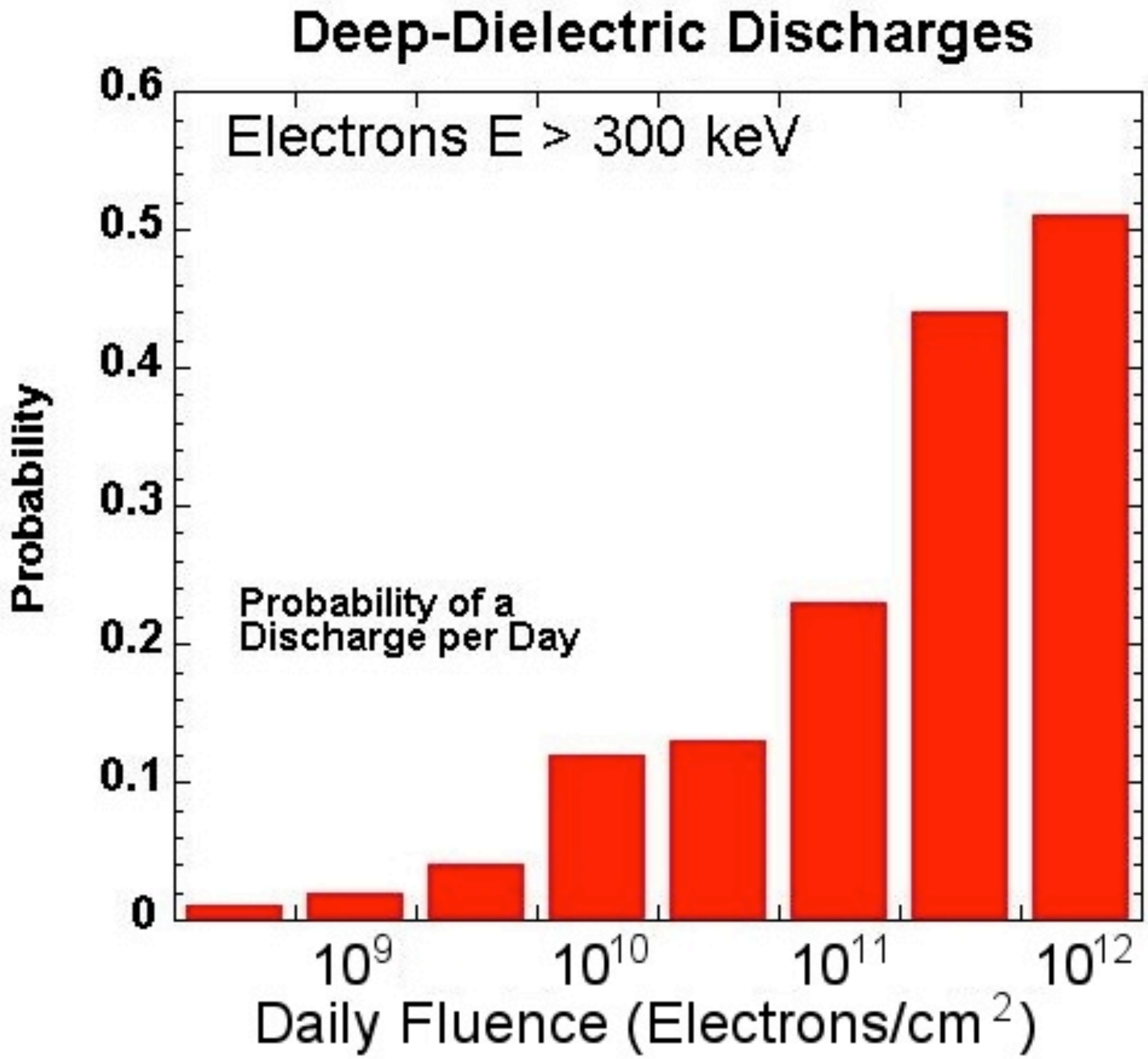


4. Electrons build up faster than they leak off



5. Discharge (electrical spark) that damages or destroys the material

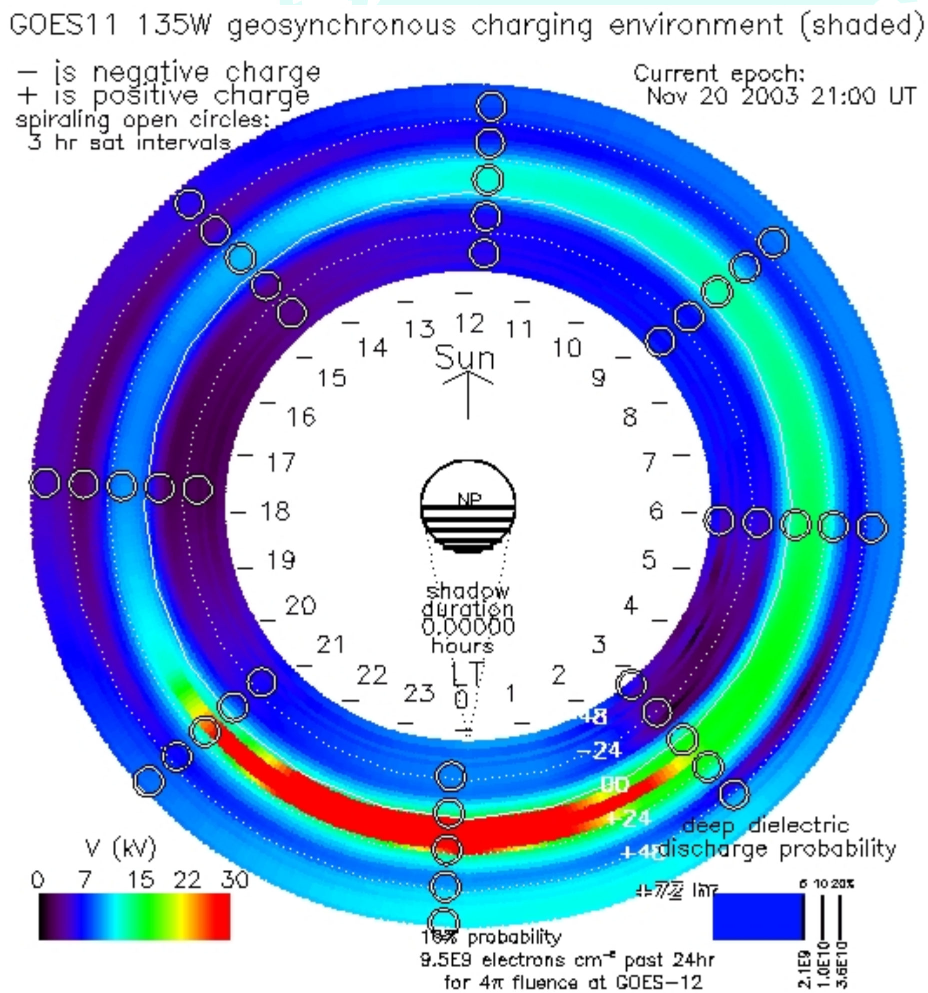
Anomalies from dielectric charging



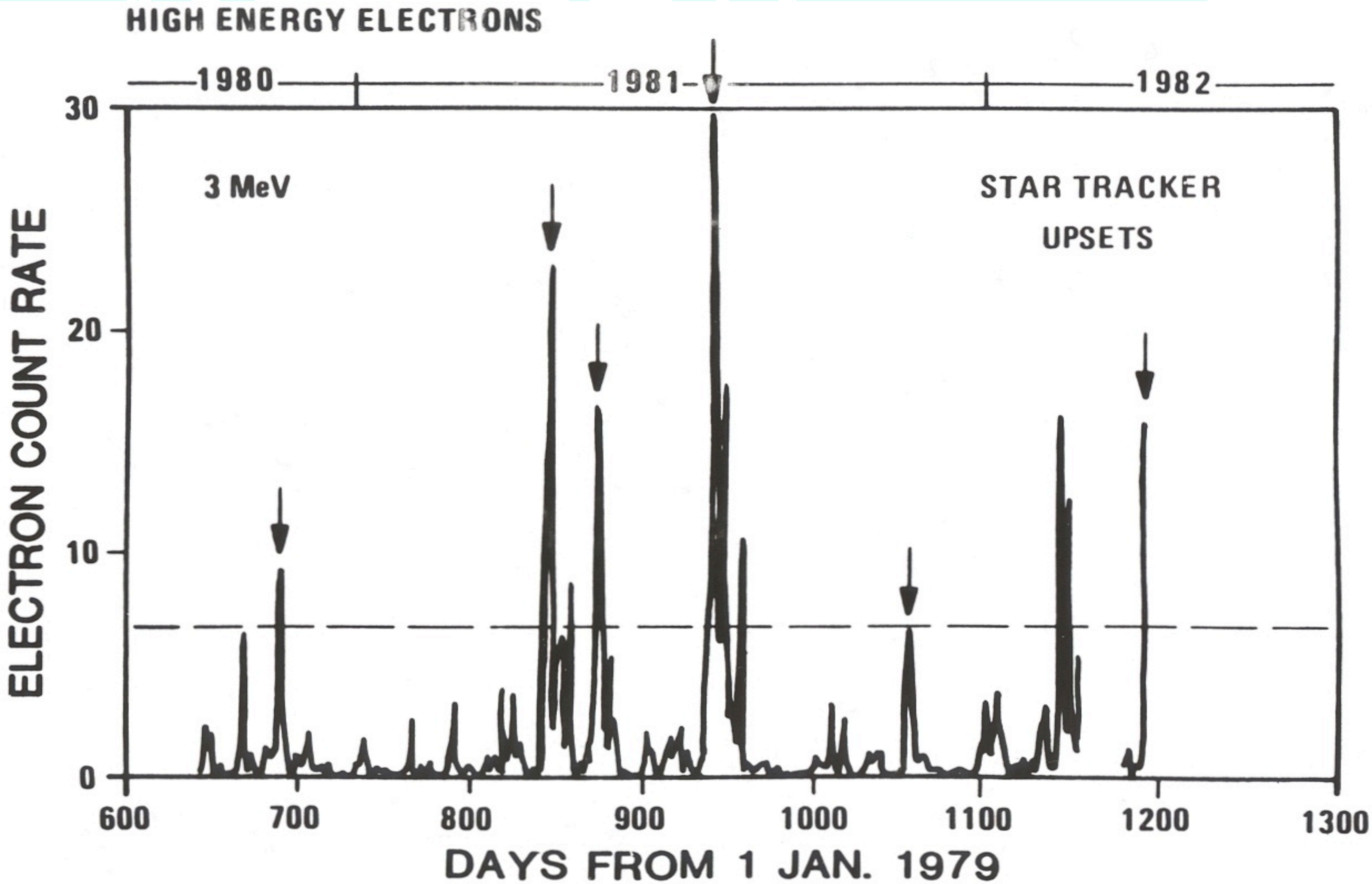
Probability of discharges goes up dramatically with increasing electron fluence.

Credit: D.N. Baker

Dielectric charging probability

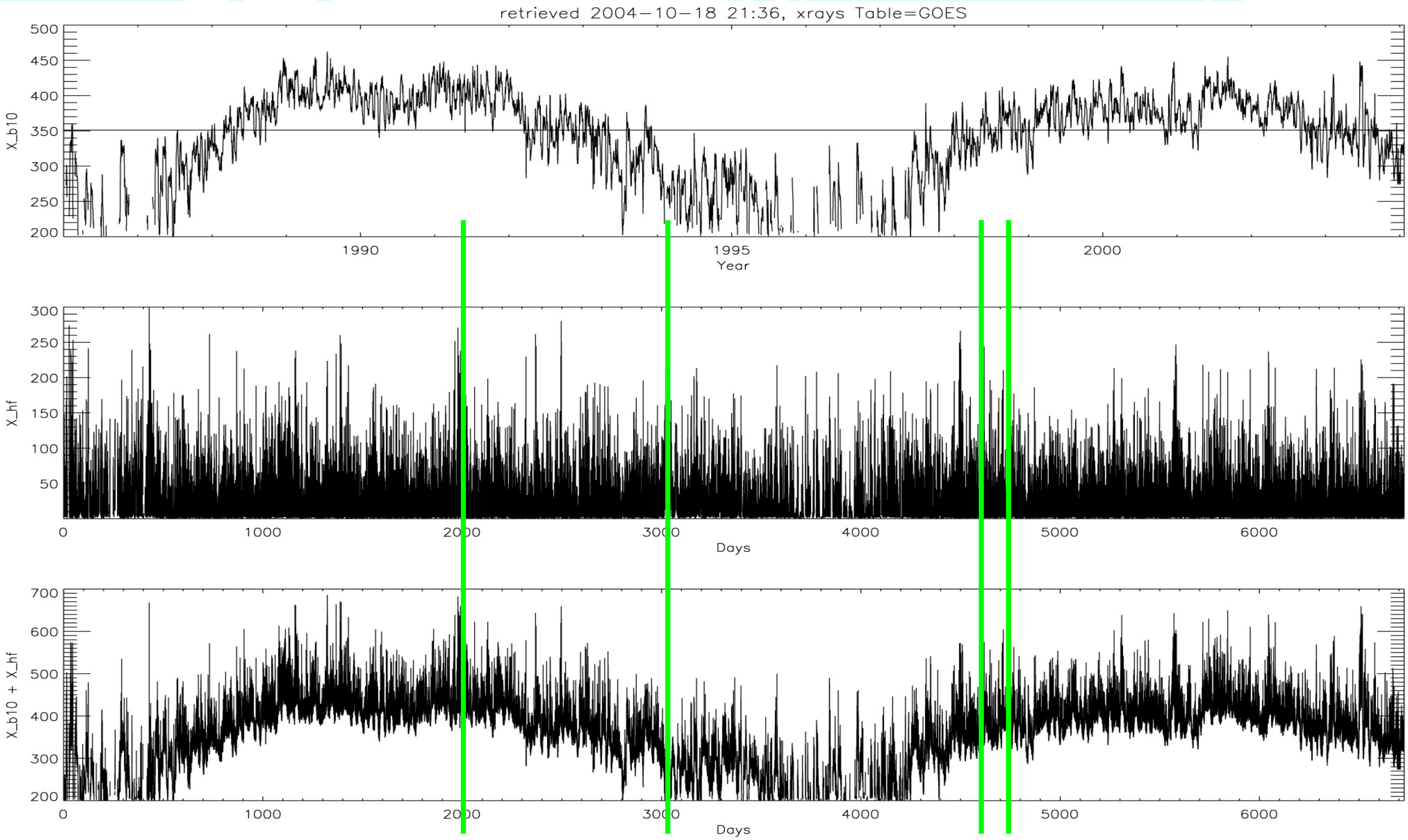


Star Tracker Anomalies at GEO



Credit: D.N. Baker

Solar Flares 1986-2004 & anomalies



Impact of Mar 1991 Solar Flares

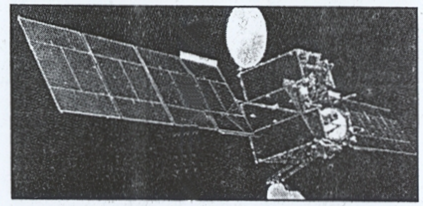
Satellite	*Effects*
MARECS-A	Satellite failure
INTELSAT 602	Permanent power degradation
GOES 7	(Decrease of satellite lifetime by 2-3 years)
TDRSS	Single Event Upsets
INTELSAT	Soft errors
CRRES	(Increase from 1 per day to 10-20 per day)
DOD	Spacecraft charging
	Deep dielectric charging
DMSP	Loss of automatic attitude control
NORAD	Satellite drag
	(Loss of 200 vehicles from catalogue)

Credit: D.N. Baker

The Hamilton Spectator

Established 1846 • Mon-Fri 47¢ + 3¢ GST

P-ANIK!



High-tech chaos as satellites spin out of control

Plug pulled on phones, TV, radio, papers

OTTAWA — Telesat Canada was facing some tough questions today as it tries to explain how its two main communication satellites tumbled out of control, interrupting TV, radio, newspaper and telephone signals across the country.

After struggling for more than eight hours to bring the wobbly Anik E-1 under control, Telesat technicians thought they had the problem licked late yesterday.

The were only half right.

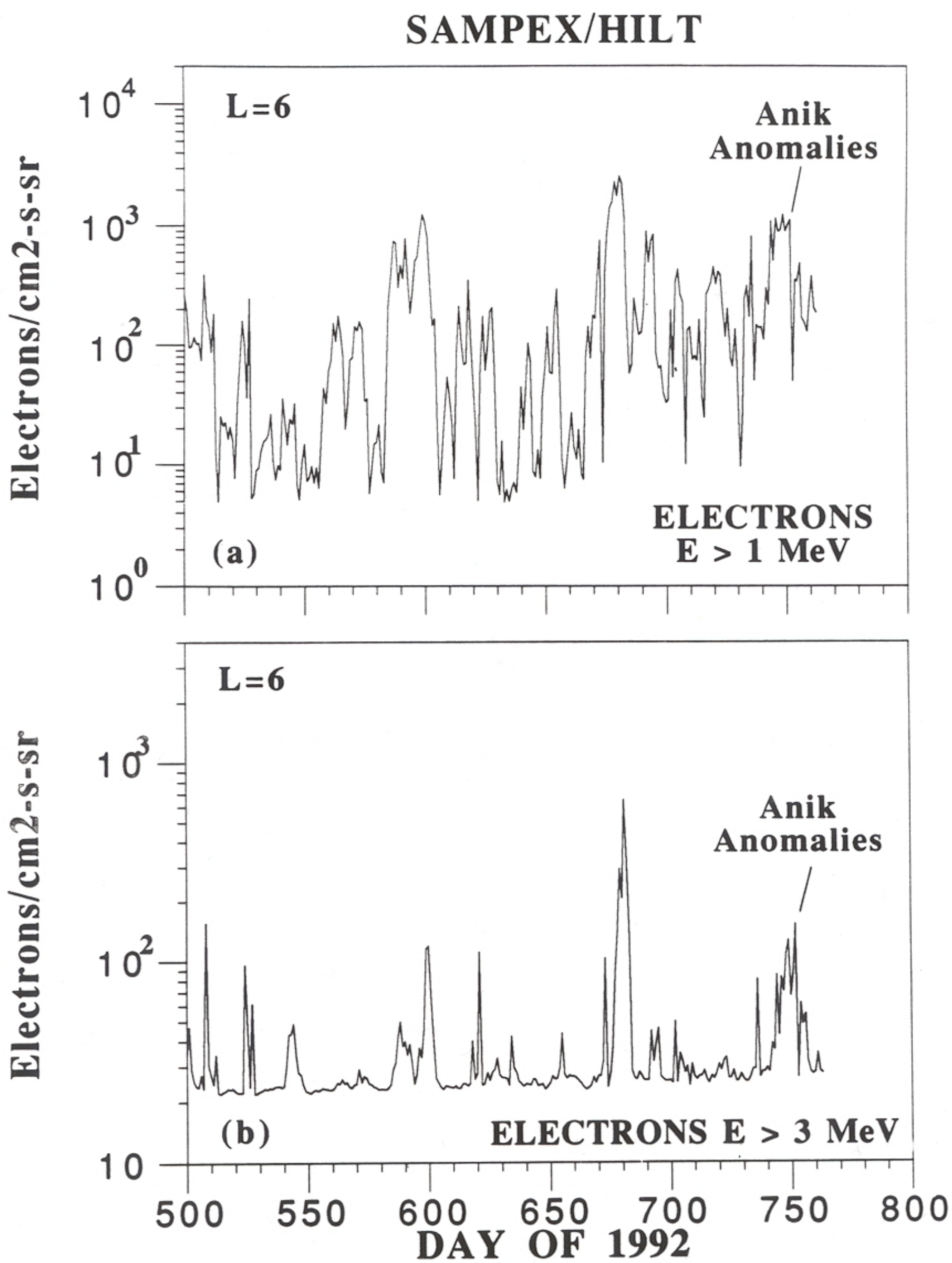
Shortly after 9 p.m. EST, as Anik E-1 settled back into position, Telesat's primary broadcasting satellite, Anik E-2, also got a bad case of the shakes.

CBC Newsworld and other national specialty cable channels, including MuchMusic, TSN, Vision and the Weather Channel, were knocked off the air. Partial service, with signals carried by fibre-optic cable, was later restored in some major centres, including Toronto.

In Hamilton local cable companies and police communications were unaffected. The Mt. Hope weather office had minor disruptions.

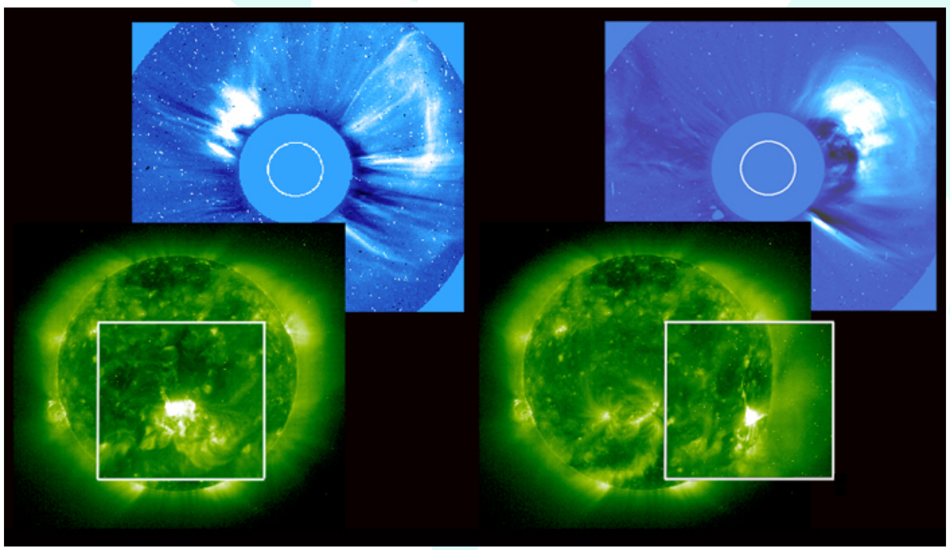
"We don't know how it was brought about," said Chris Frank, Telesat's director of public affairs.

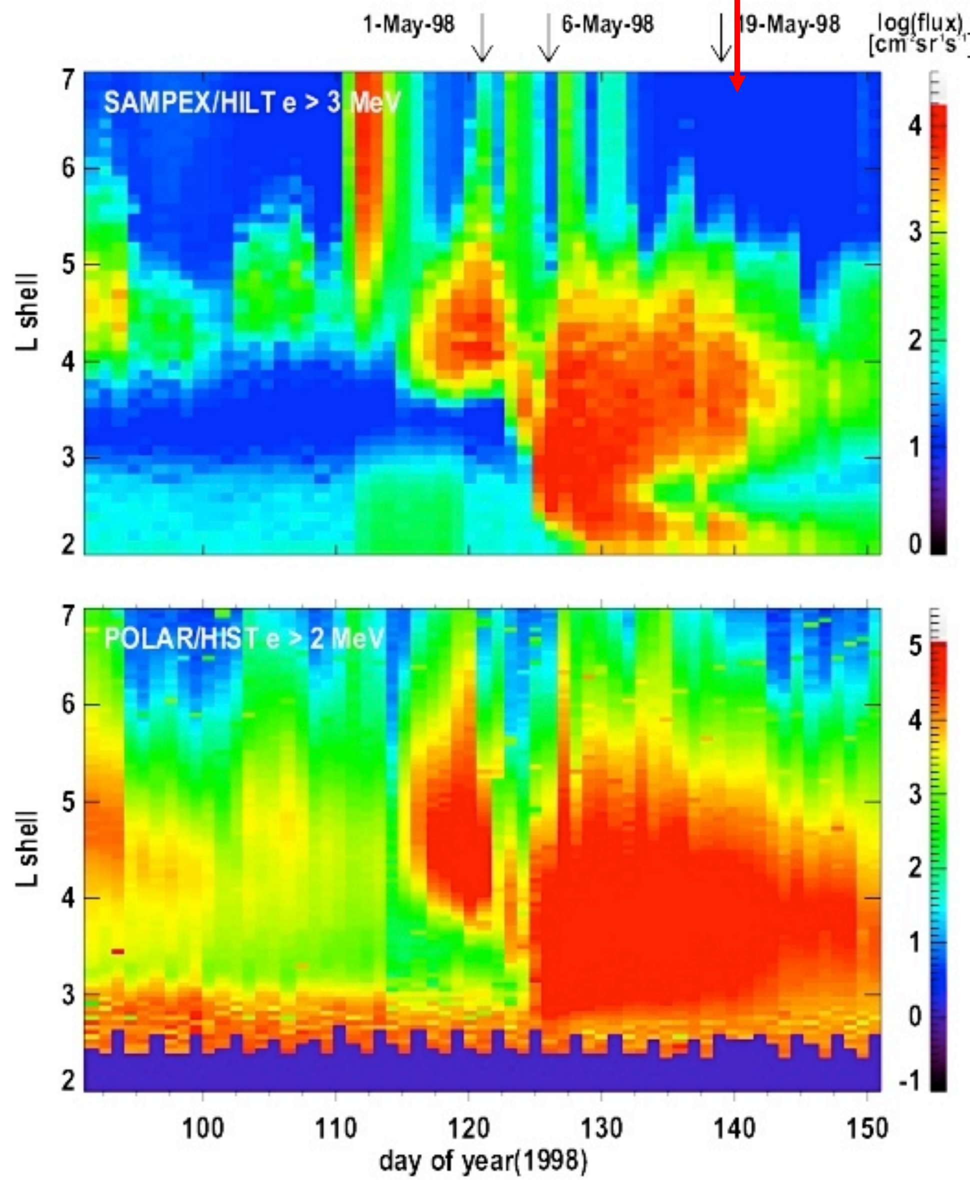
ANIK Spacecraft Failures



Galaxy-4 Satellite Failure

April-May 1998 Special Analysis Interval

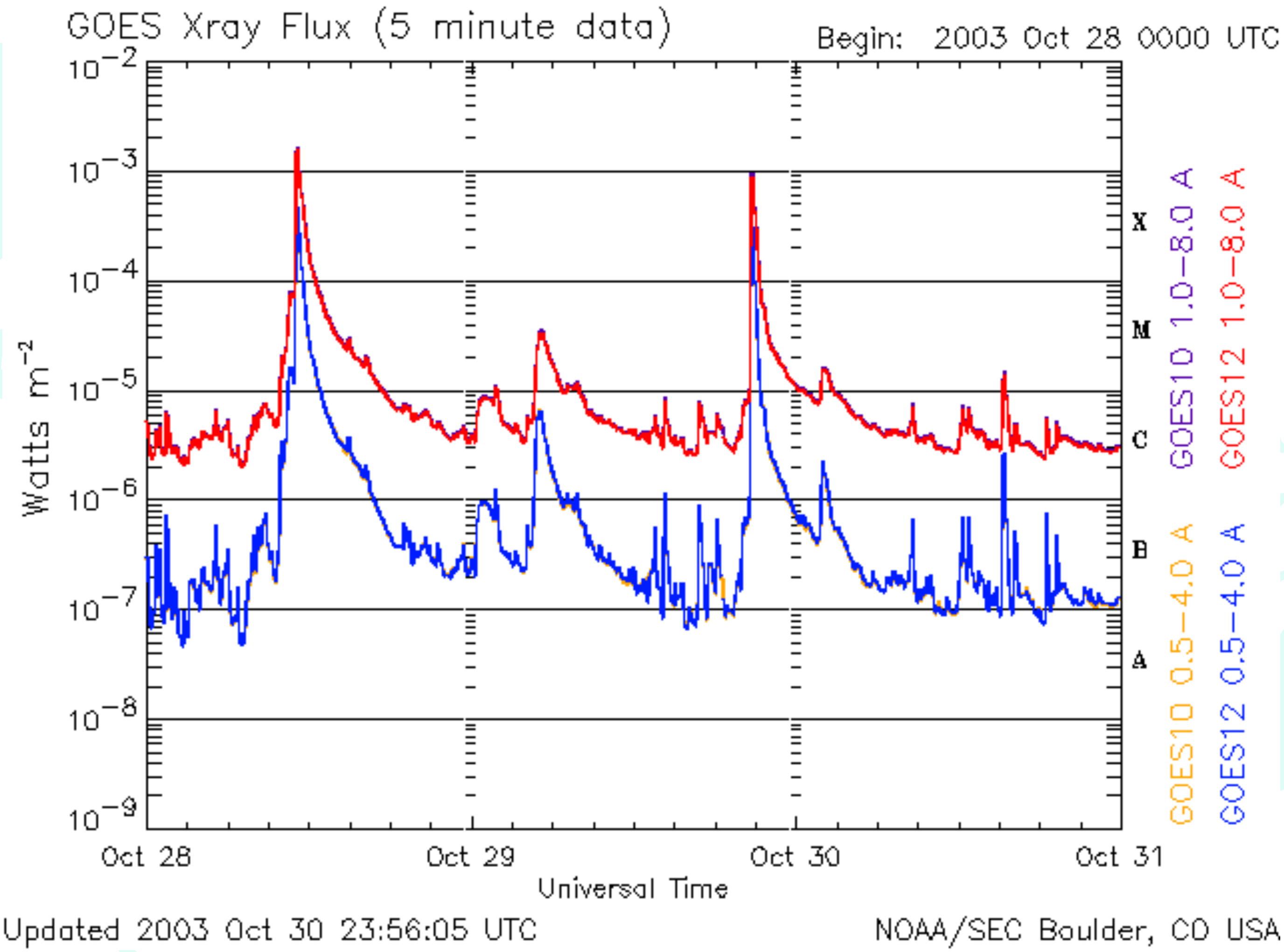




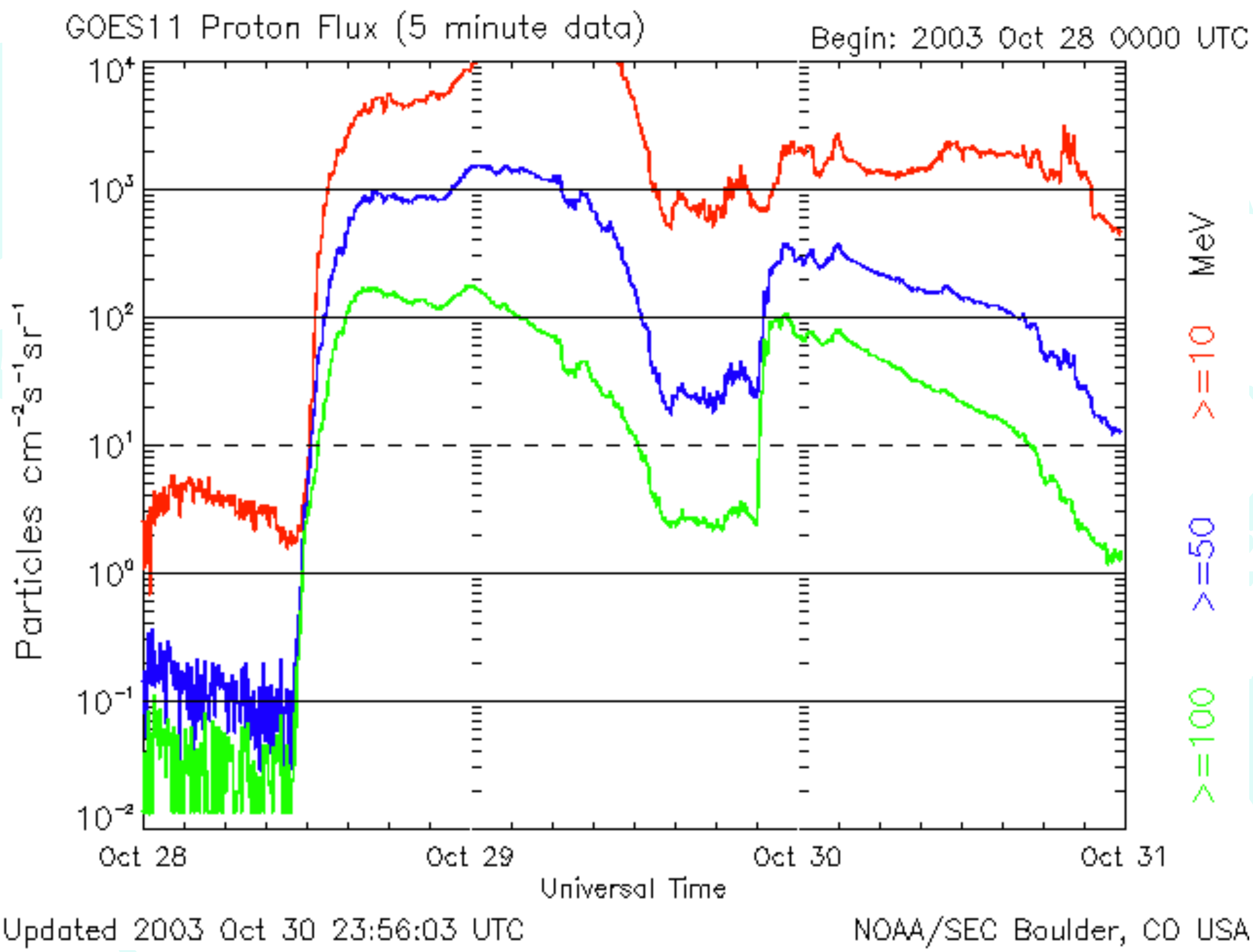
SAMPEX and POLAR

Credit: D.N. Baker

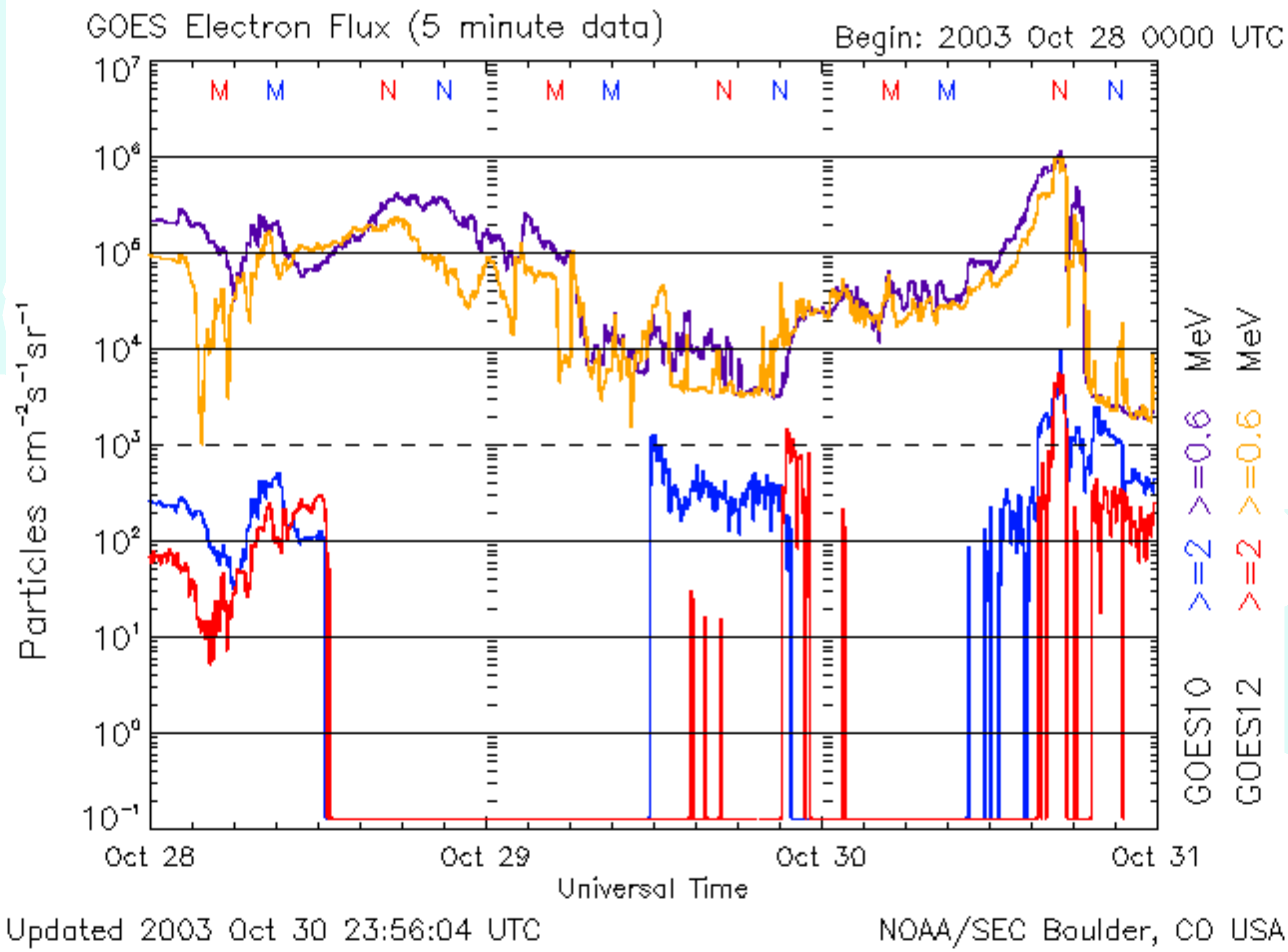
Oct 28-31 2003 X-rays



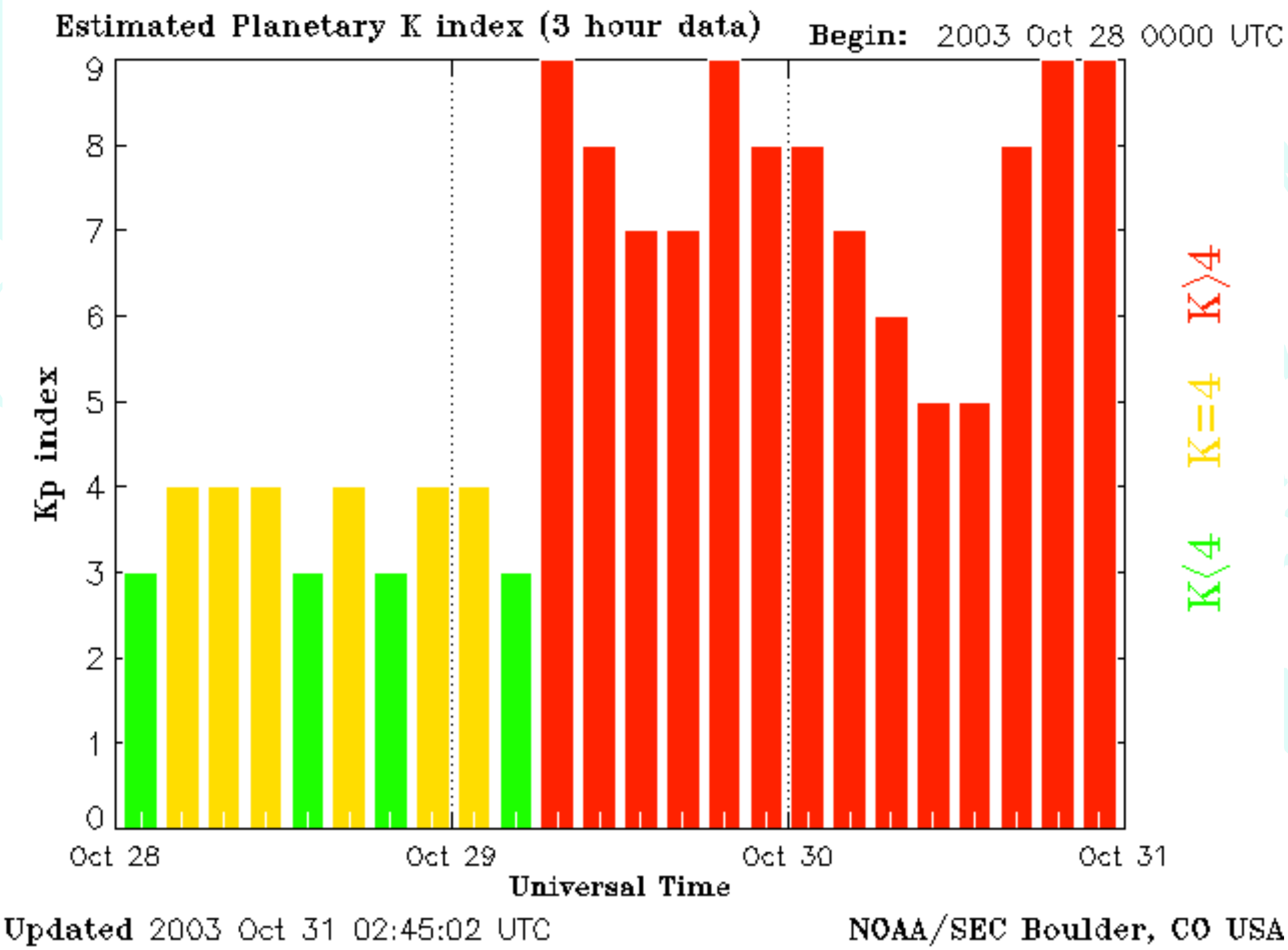
Oct 28-31 2003 protons



Oct 28-31 2003 electrons

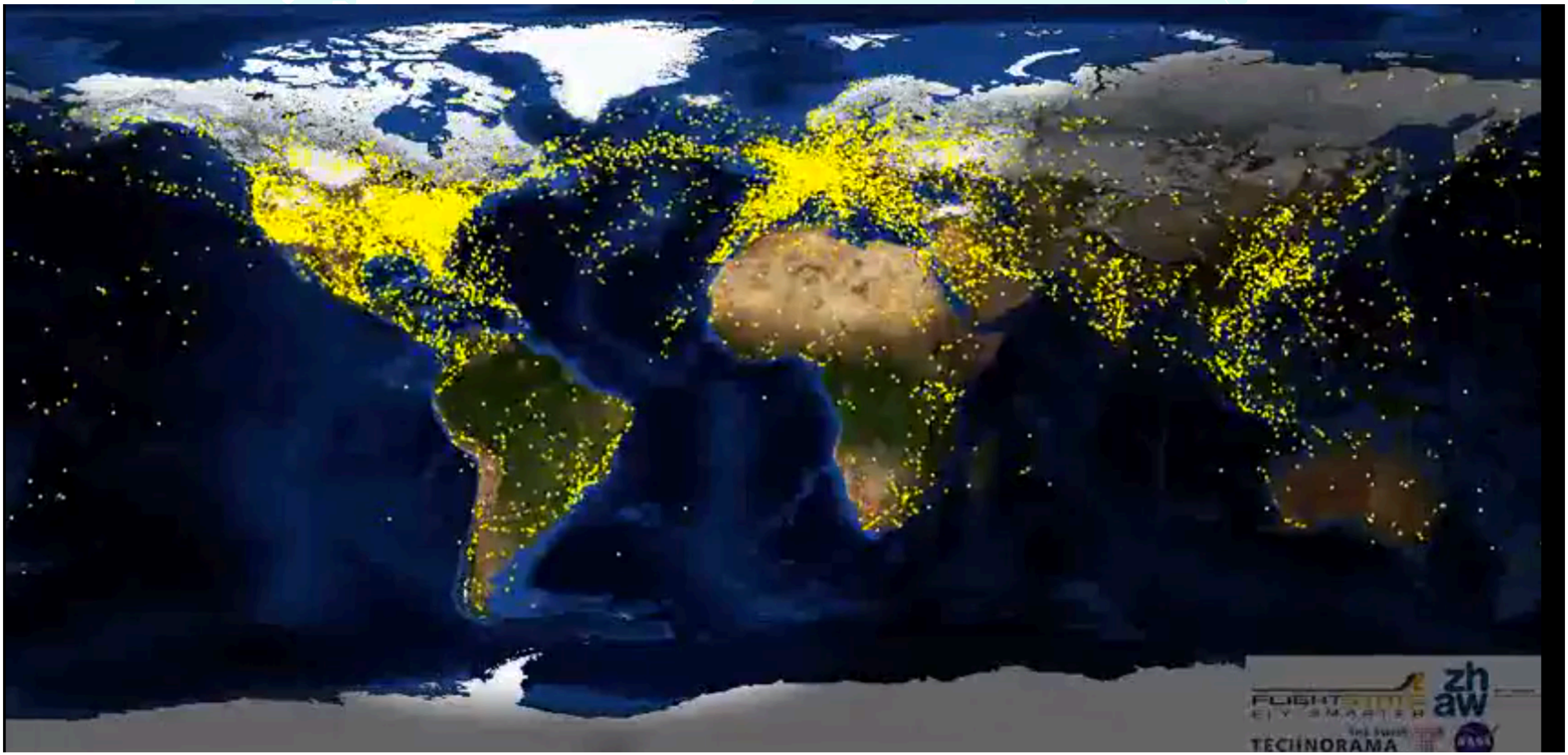


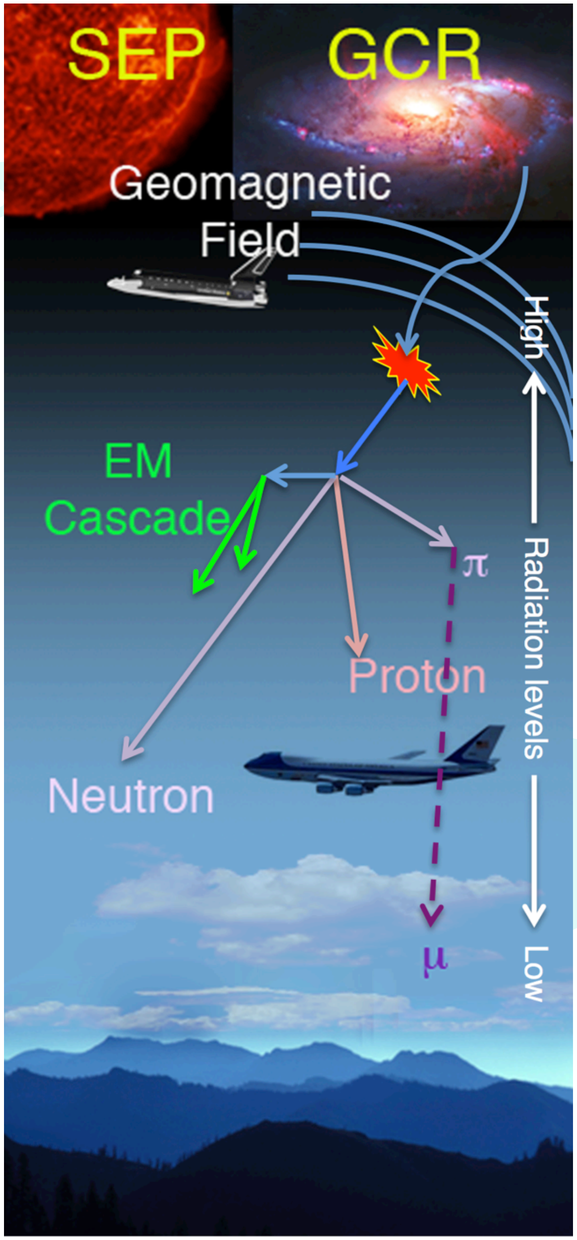
Oct 28-31 2003 Kp



Radiation effects on aviation

Typical daily snapshot of air traffic routes





Context: space weather creates a dynamic radiation environment at aviation altitudes

Aviation radiation sources

- ✓ **global phenomenon** GCRs (career health issue and avionics SEUs)
- ✓ **high latitude phenomenon**
  - ✓ **Extended major events** SEPs (fleet operations and aircrew/passenger safety issue)
  - ○ **Short-term minor events** precipitating outer radiation belt energetic electrons (career health issue)
  - ○ **Instantaneous minor events** terrestrial gamma-ray flashes (TGFs) (avionics EMI)

Steps towards aviation radiation management

1. What is the problem?

- **Radiation at aviation altitudes above FL260 can lead to elevated cancer rates, career limiting illness, or even death**
- **Crew, frequent flyers, fetuses in first trimester are the most at-risk populations**
  - GCR background can limit careers from long-term statistical exposure
  - SEP solar flare events can constrain crew schedules so they do not exceed monthly, annual dose limits from short-term *statistical* exposure; rare but historic SEP events can lead to *deterministic* radiation sickness
  - At 37,000 ft., every 10 hours ≈ 1 chest X-ray in equivalent dose rate
  - Every 6500 ft. higher doubles the dose rate (FL 430 ≈ 2 chest X-rays and FL 500 ≈ 4 chest X-rays)
  - **Every 6500 ft. lower halves the dose rate (FL 300 ≈ ½ chest X-ray)**
  - **100 km equatorward flight path in magnetic latitude may also reduce the dose rate**

Steps towards aviation radiation management

2. What can be done about it?

- **Determine the "weather" of the radiation environment**
  - SEP or EEP events can be treated like volcanic ash clouds
  - Facilitate background environment monitoring for crew career support
- **Estimate uncertainties with climatological models in ensemble runs and with data assimilation to move climatology into weather (like with hurricane tracking in tropospheric weather)**
  - Use physics-based models such as NAIRAS (NASA LaRC)
  - Use empirical such as CARI-7 (FAA CAMI)
- **Build a global system of quality real-time measurements on aircraft supplied to the ground via Iridium and WiFi for data assimilation use in radiation "weather" models**
  - Expand ARMAS and NAIRAS systems (NASA & SET) into RADIAN (SET)

Steps towards aviation radiation management

3. What is the radiation effects management path?

- **Non-pilot crew, frequent flyers and fetuses** can only monitor their personal profiles
- **Pilots** can reroute flight paths during severe radiation events in the same way a regional volcanic ash cloud is avoided
- **Air Traffic Control** can alter entire regional routes during severe radiation events in the same way a volcanic ash cloud is avoided
- **ICAO** is setting standards and guidelines for event identification
- **ATC** needs a real-time, forecast data cube to implement tools of
  - **Dropping altitude to lower the dose rate**
  - **Rerouting flight tracks equatorward to reduce the dose rate**

Steps towards aviation radiation management

4. What is currently being done?

- **CARI-7 is used for operational guidance**
- **NAIRAS (Nowcast of Atmospheric Ionizing Radiation System) is going thru operational prototype "burn-in"**
- **ARMAS (Automated Radiation Measurements for Aerospace Safety) system is in TRL 9 ops (20$^+$ FMs, 770$^+$ flights)**
  - ARMAS employs airborne micro dosimeters to collect real-time TID (total ionizing dose)
  - ARMAS transmits TID, time, and GPS location to the ground via Iridium satellite link for data comparison (eventual assimilation) with NAIRAS
  - ARMAS TID is calibrated to the "gold-standard" TEPC (tissue equivalent proportional counter) using NSRL, LANSCE, LLUMC, LLNL beam lines
  - ARMAS distributes updated dose rate information with 1–5-minute latency

Where are we today? Progress towards aviation radiation nowcast & forecast

- **DETECTORS**
  - ✓ Geiger counters
  - ✓ Bubble detectors
  - ✓ TEPC
  - ✓ Liulin
  - ✓ RaySure

1950-1990

Step 1: Discovery

- **DETECTORS**
  - ✓ Bubble
  - ✓ TEPC
  - ✓ Liulin
  - ✓ RaySure
  - ✓ ARMAS
- **MODELS**
  - ✓ CARI-6
  - ✓ NAIRAS
  - ✓ PANDOCA

1990-2016

Step 2: Validation

- **DETECTORS**
  - ✓ **ARMAS**
  - ✓ ATED
- **MODELS**
  - ✓ **NAIRAS v1**
  - ✓ **CARI-7**
  - ✓ PANDOCA
  - ✓ KREAM

2017-2020

Step 3: Monitoring
(occasional NAT or NoPAC flights; tech demo regional monitoring; demo data assimilation)

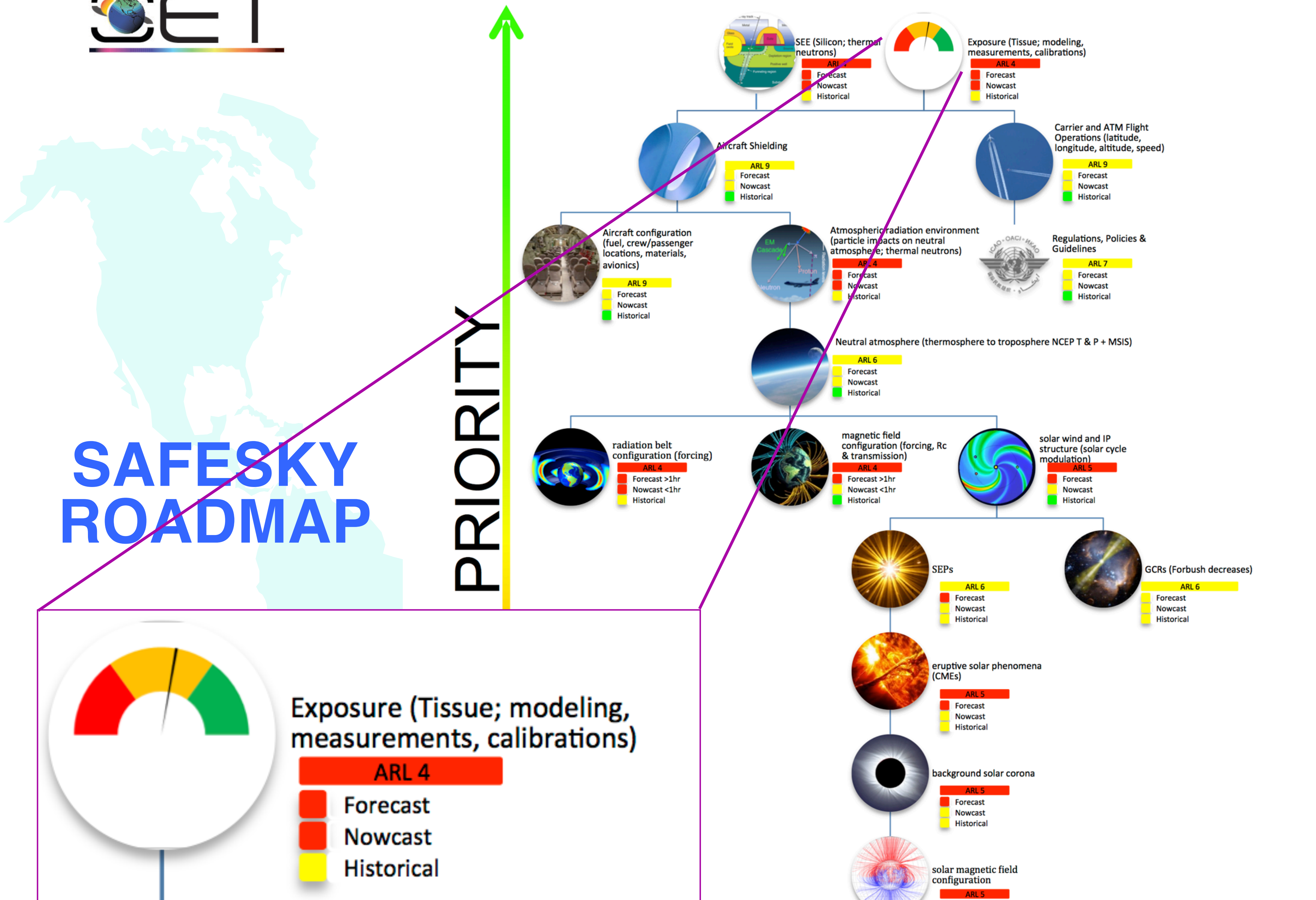
Fall 2020

- **DETECTORS**
  - ✓ **ARMAS**
  - ✓ ATED
- **MODELS**
  - ✓ **NAIRAS v2**
  - ✓ CARI-7

2021-

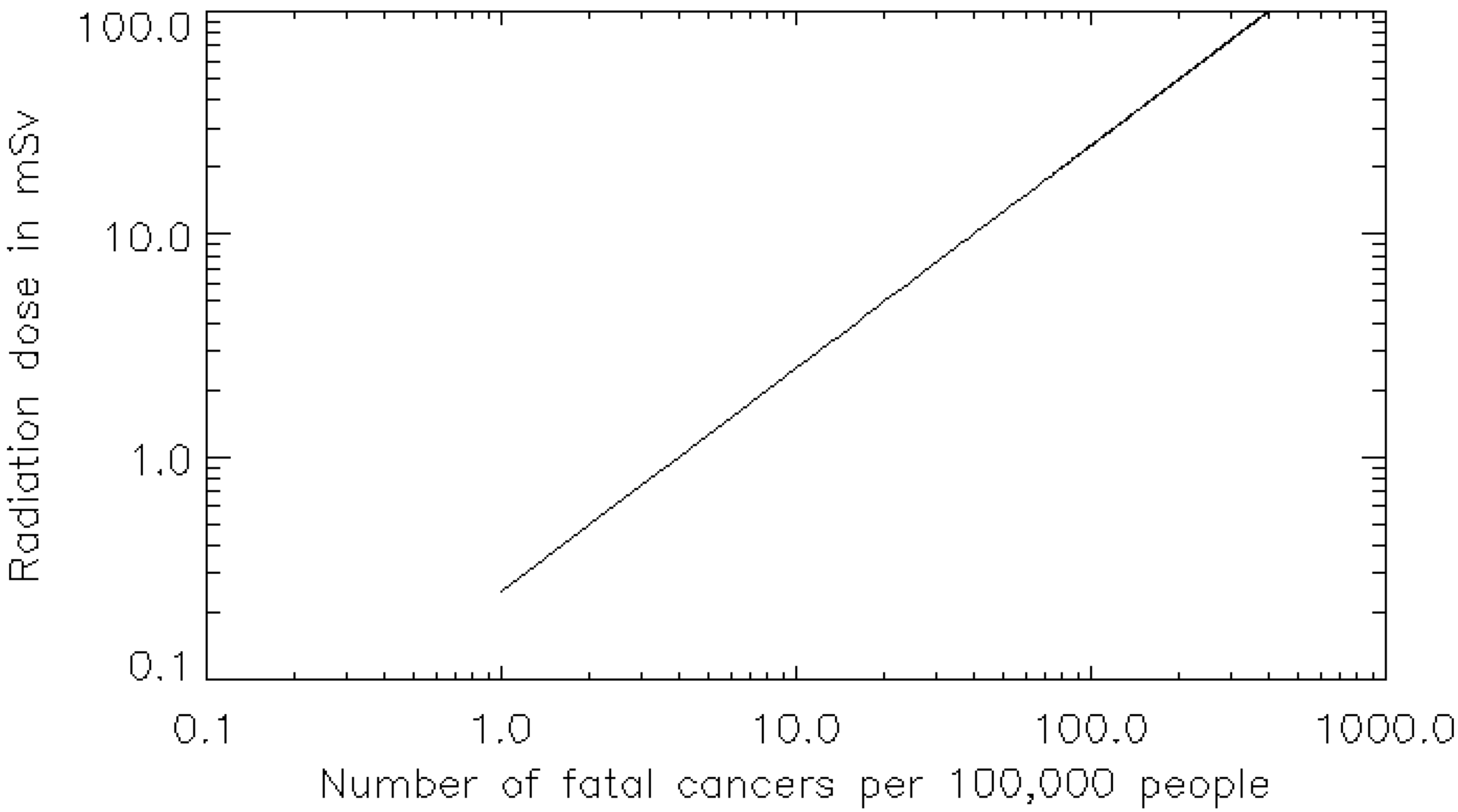
Step 4: Nowcast & forecast
(100+ daily flights for track truth, continuous balloon loiter or hi-alt/long endurance regional monitoring; operational data assimilation and demo ensemble modeling)

Roadmap for Aviation Radiation Safety



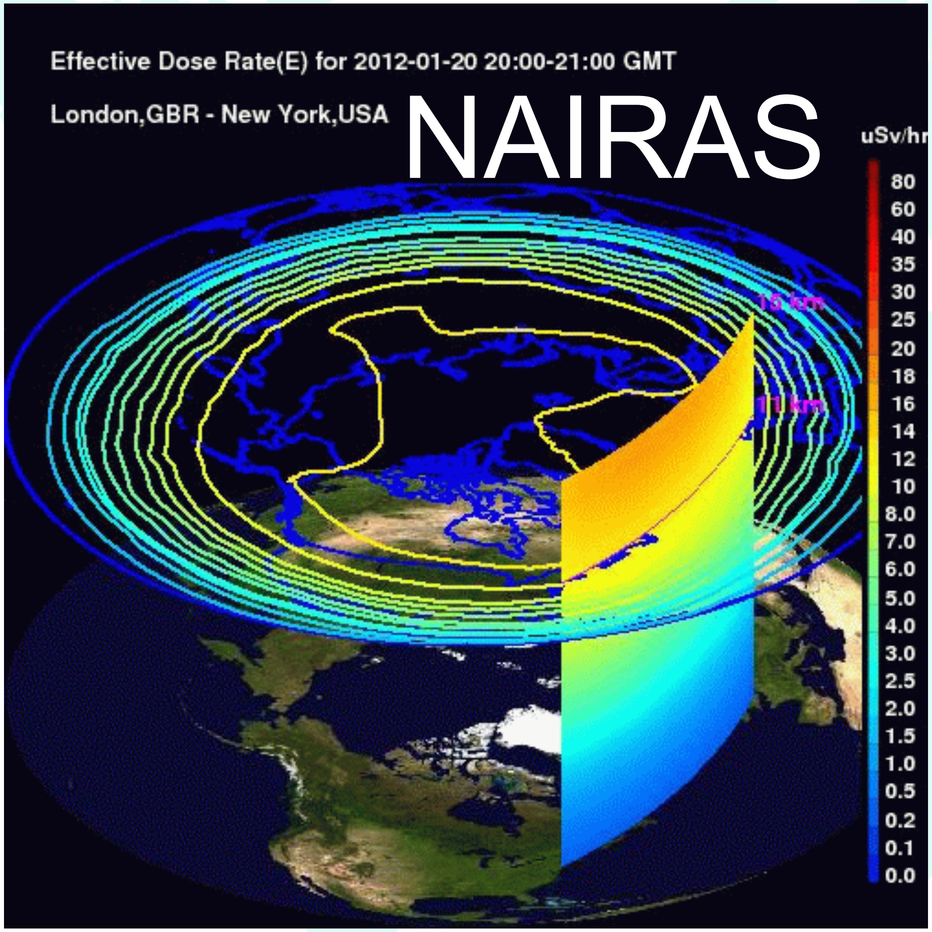
https://SpaceWx.com

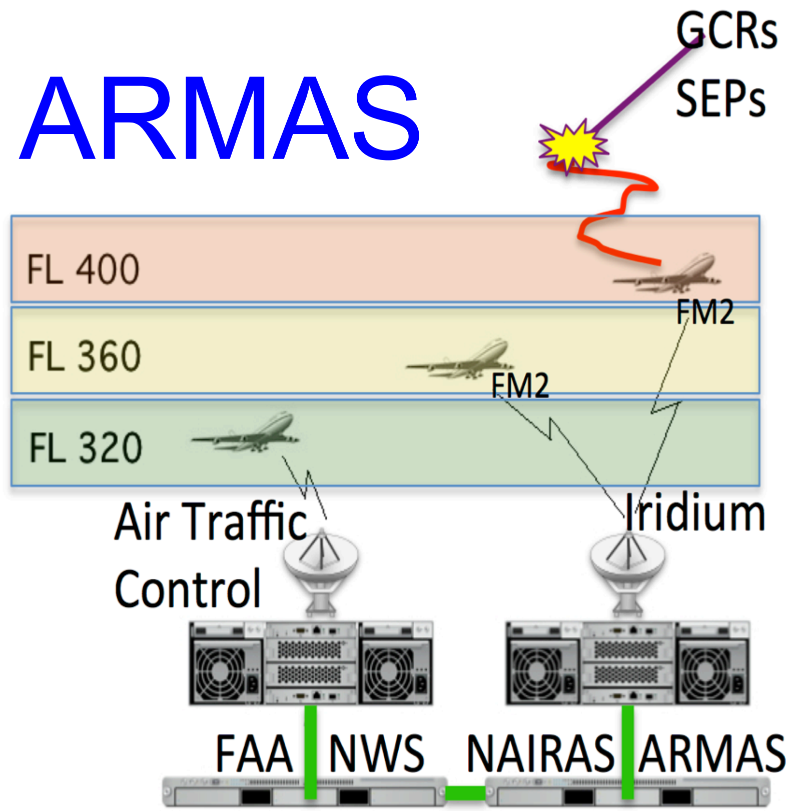
Radiation effects on aviation: Linear No-Threshold (LNT) death by cancer statistical estimate



NASA & Industry Collaboration:

NAIRAS + ARMAS = RADIAN





NAIRAS = Nowcast of Atmospheric Ionizing Radiation for Aviation Safety: real-time global aerospace radiation climatology

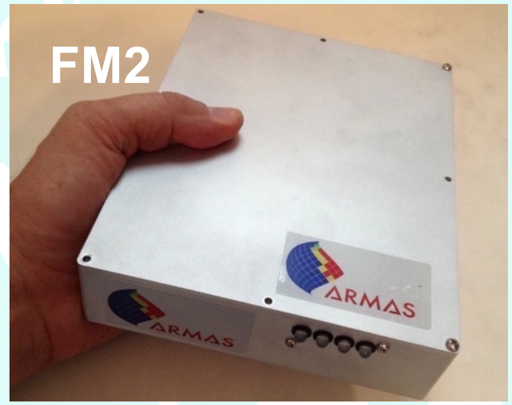
ARMAS = Automated Radiation Measurements for Aerospace Safety: real-time aerospace radiation measurements

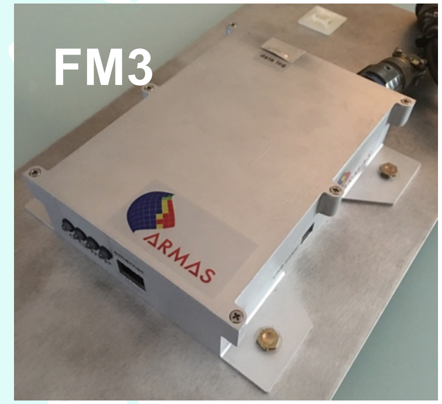
RADIAN = RADIation environment using ARMAS data in the NAIRAS model: data assimilative modeling

NAIRAS + ARMAS = RADIAN: nowcasting and forecasting of the global radiation environment

ARMAS real-time measurements demonstrated

ARMAS Flight Module 1 (FM1)
on NASA AFRC DC-8





SET

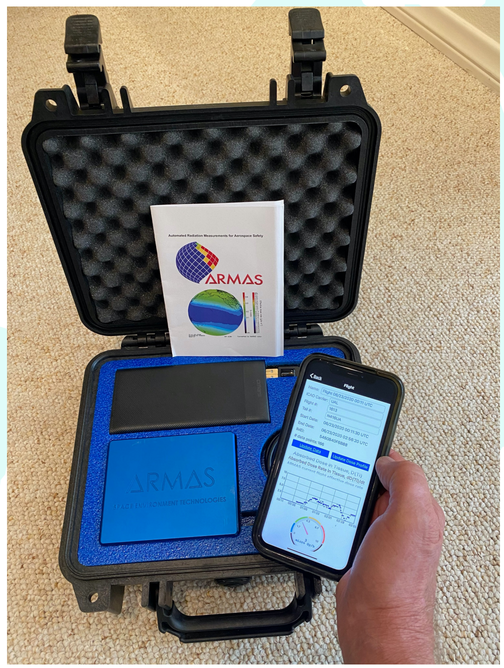
Improving state-of-the-art radiation monitoring: ARMAS Flight Module 7 (FM7) has Bluetooth paired with iOS devices using the ARMAS app

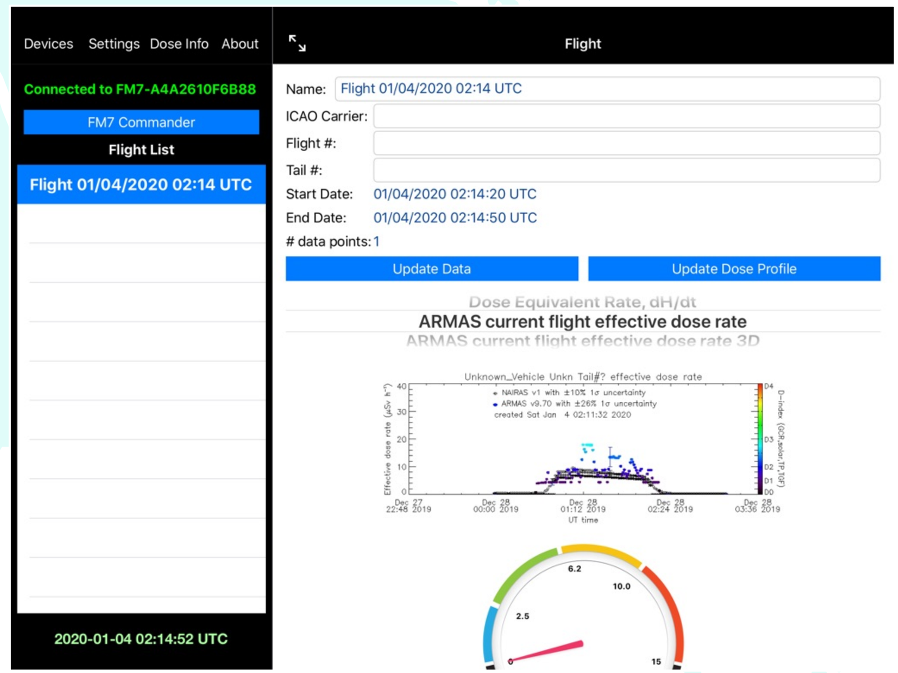
Features:

- ✓ Measures absorbed dose in silicon
- ✓ Small size, mass, and power
- ✓ Data retrieval using Bluetooth to pair with iOS ARMAS app available from Apple Store
  - Current and post-flight dose rate status displayed on app that is paired with FM7
  - Dose rate can be transmitted to ground using WiFi
- ✓ Real-time dose rates: measured absorbed (Si) and derived absorbed (Ti), dose equivalent, ambient dose equivalent, and effective

Availability:

- ✓ 12 units delivered 2018-2020
- ✓ 4^{th} production run Aug 2020





Improving measurement domains:
750⁺ ARMAS Flights from 0-106 km in 2013–2020

- ✓ **Agency and Commercial Aircraft flying ARMAS**
  - ✓ **AFRC:** DC-8 (a), ER-2 (d), G-III, SOFIA (B747)
  - ✓ **NOAA**: G-IV (b)
  - ✓ **NSF**: G-V (c)
  - ✓ **FAA**: Bombardier Global 5000
  - ✓ **Commercial**:
    - Boeing 737, 747, 757, and 777
    - Airbus 319 and 320
    - Bombardier Q200
    - CRJ 200, 700; Embraer 175
- ✓ **Balloons**
  - ✓ **World View Enterprises:** Stratollite (f)
- ✓ **NASA space stations**
  - • ISS (Low Earth Orbit)
  - ○ Gateway (Lunar Orbit)
- ✓ **Proprietary vehicles**
  - ✓ **Perlan** Stratospheric glider (e)
  - ✓ **Virgin Galactic** SS2 and WK2 (g)
  - ✓ **Blue Origin** New Shepard (h)
  - • Cubesat
  - ○ Lunar lander

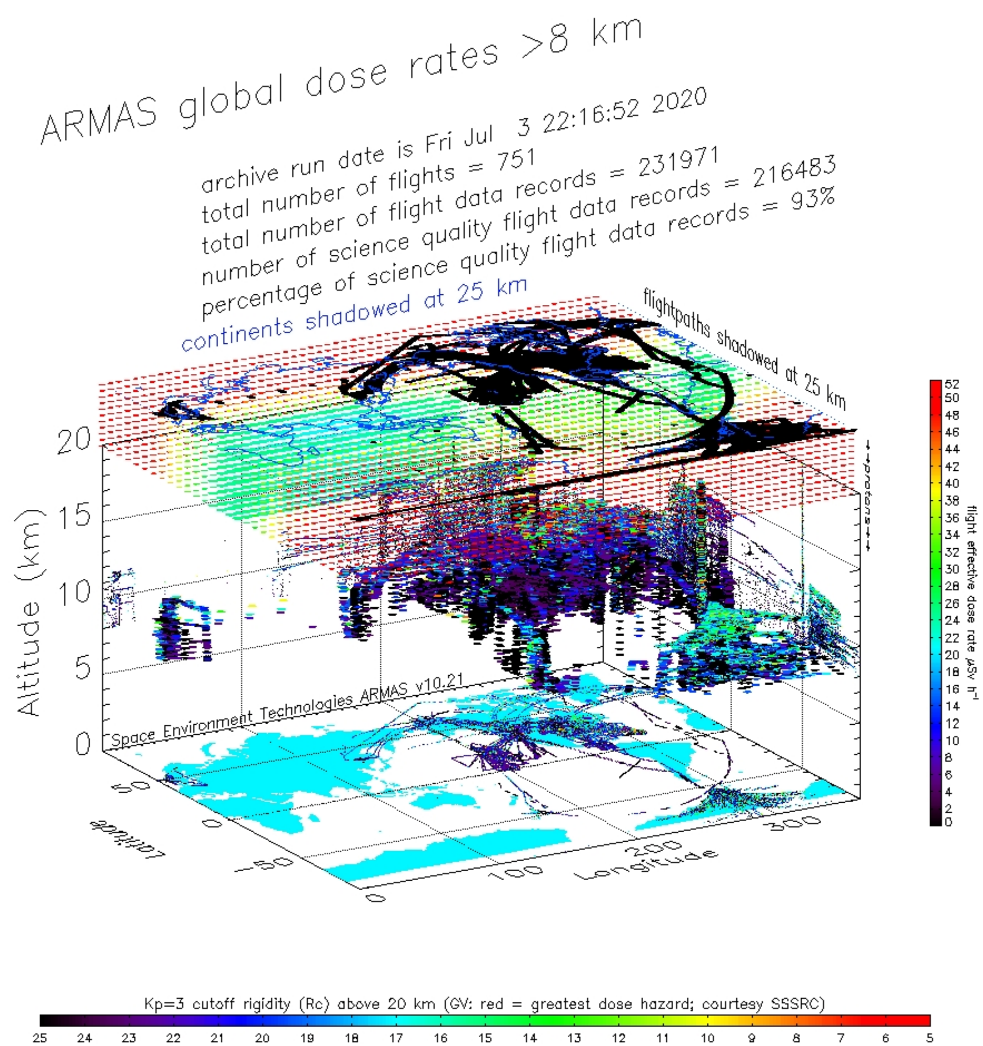
✓ Flown
• In progress
○ Potential

(h
)

W. Kent Tobiska <ktobiska@spacewx.com>

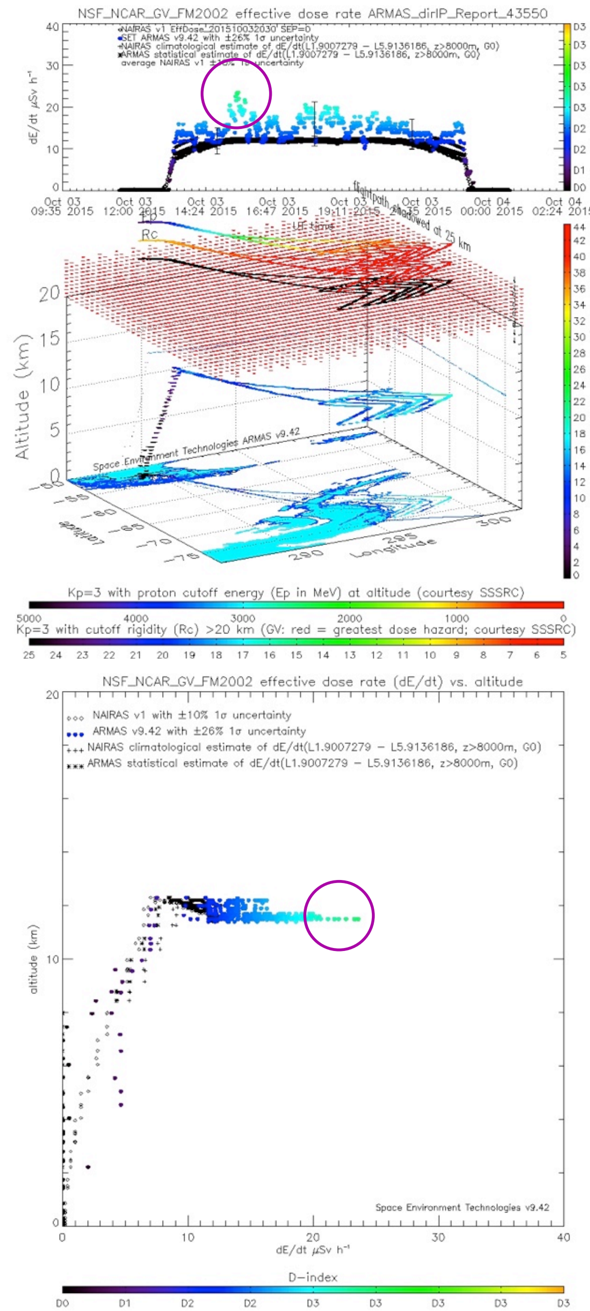
ARMAS results:

- new radiation process identified (EEP)
- global statistical database now exists for dE/dt
- can create dE/dt for any location and geomagnetic conditions
- compares extremely well with NAIRAS
- D-index now created for flights
- forecasts to 72 hours



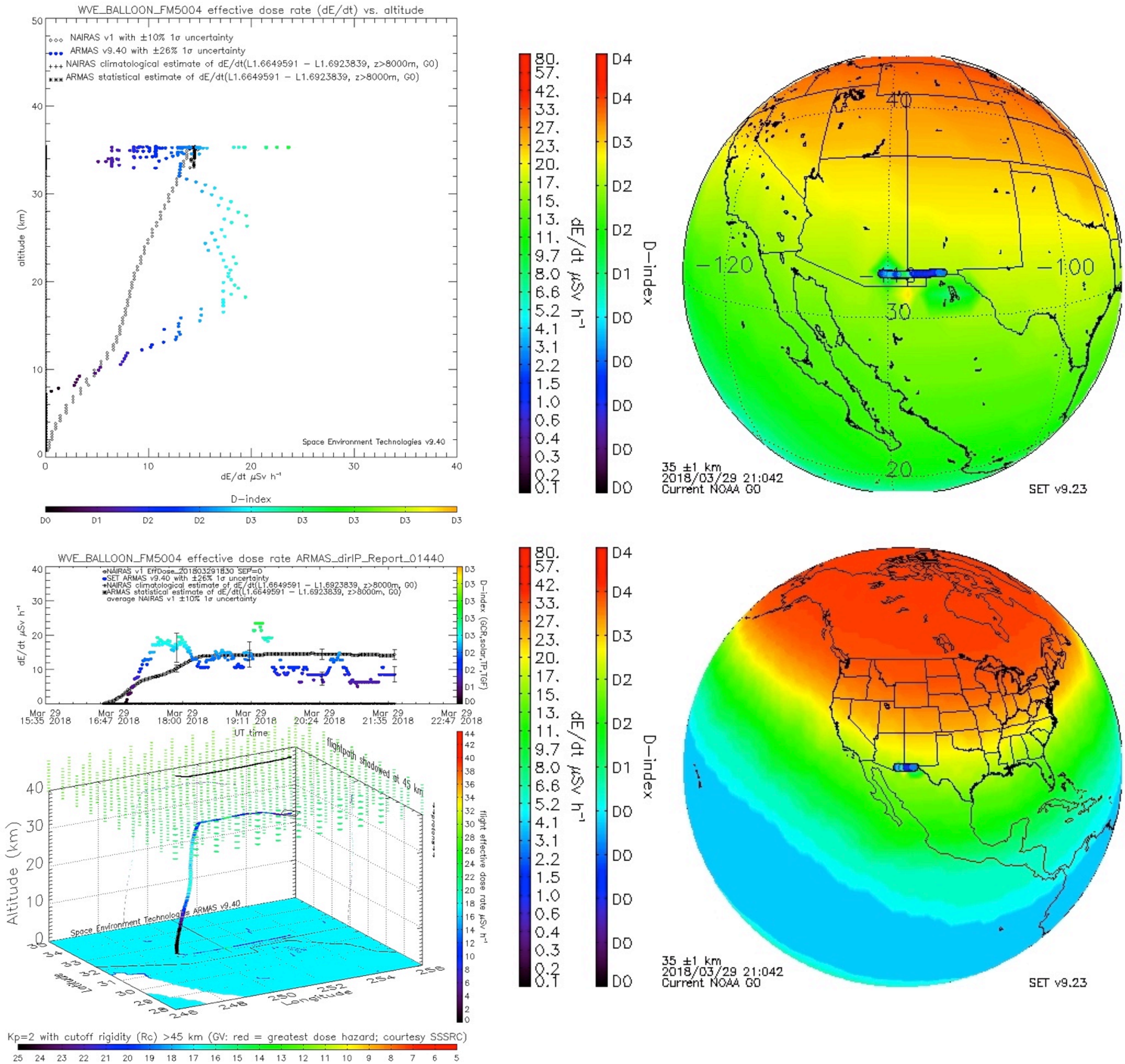
Example: flight on October 3, 2015 over Antarctica ice shelf

- ✓ NSF/NCAR G-V mission studied the Antarctic ice shelf thickness at high altitudes (11–12 km)
  - ✓ **Duration:** 13.1 h
  - ✓ **Dst**: -24 nT
  - ✓ **Observations**:
    1. Baseline for the flight altitude at 11-12 km was the same as shown by NAIRAS climatology and by ARMAS statistical database (**GCR component**)
    2. **Doubled effective dose** rate for ½ hour at L = 4.8 and 62.8° magnetic latitude – **Van Allen Belt radiation source – evidence points to relativistic electrons?**
    3. No other artifacts in dataset (EMI, TGFs, dropouts)
    4. This event was a moderate event compared with 56 similar events identified in the ARMAS database for NOAA G0 conditions and at 11 km altitudes in high latitudes



ARMAS World View

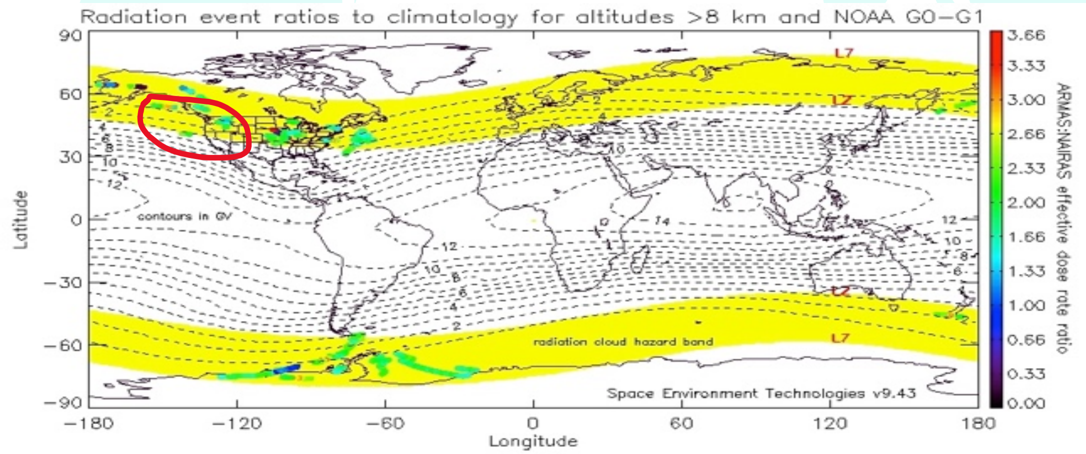
ARMAS World View Results

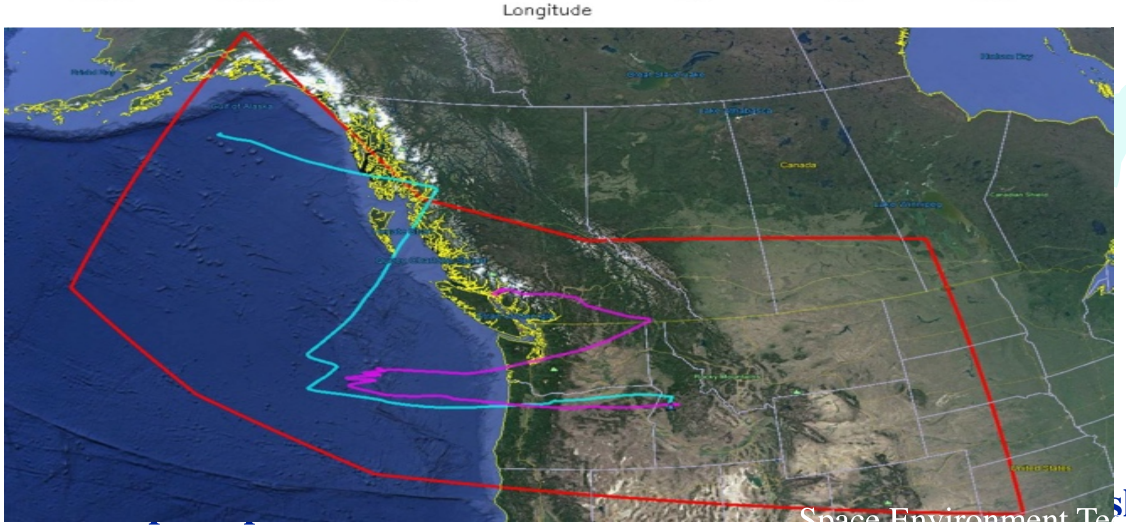


https://Space

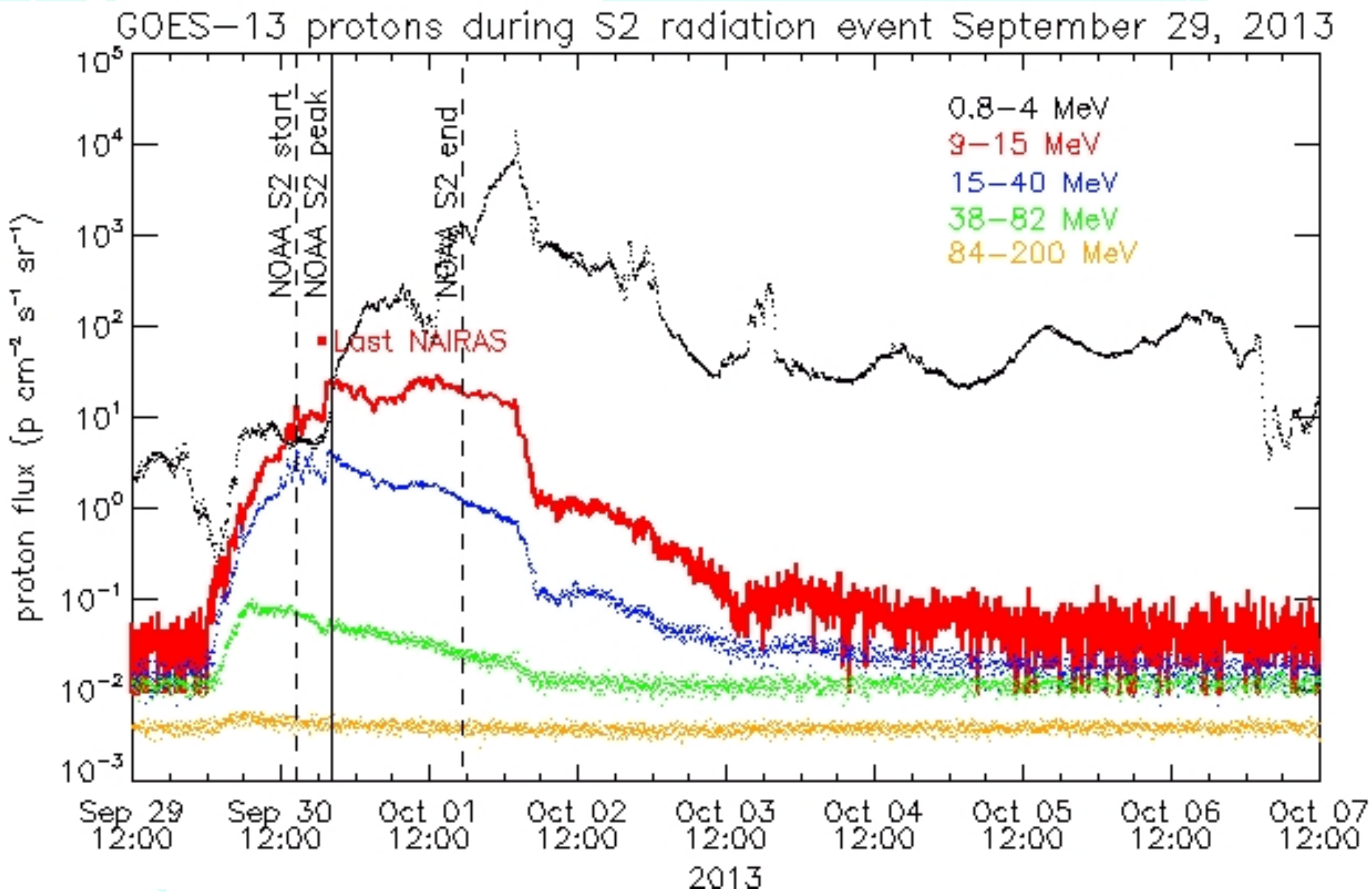
ARMAS Dual Monitor:

demonstrate operational aviation radiation monitoring

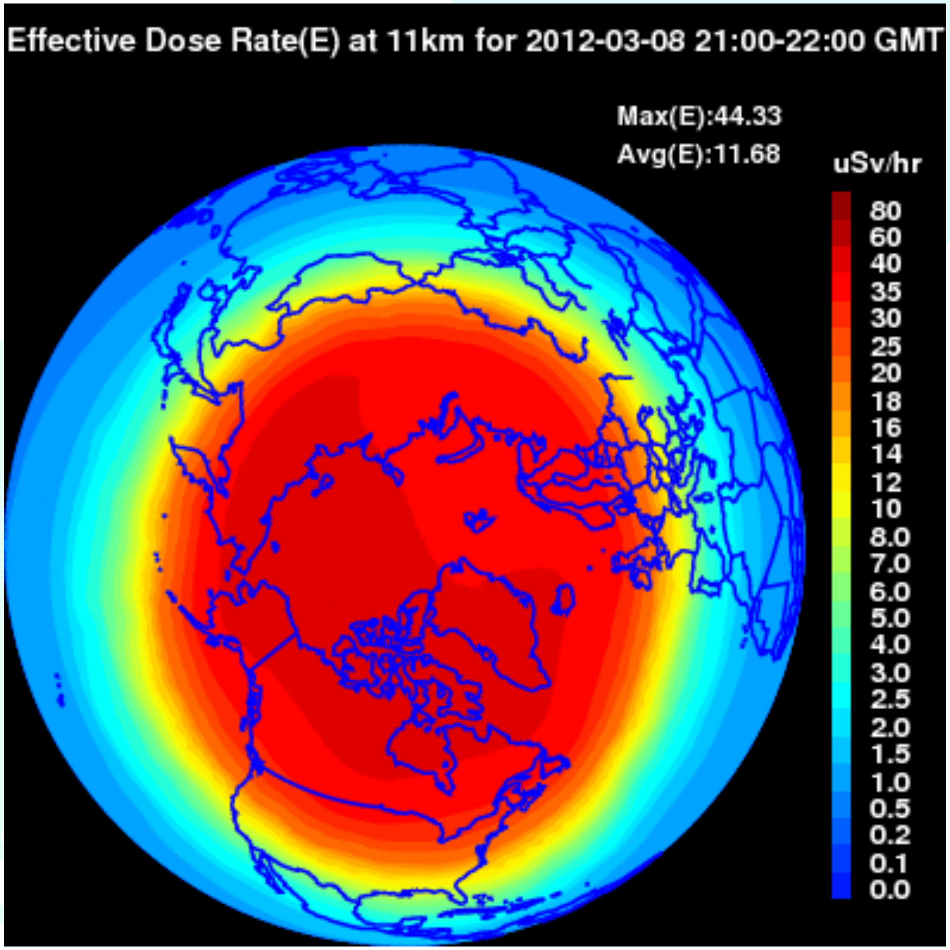




Radiation effects on aviation: ARMAS

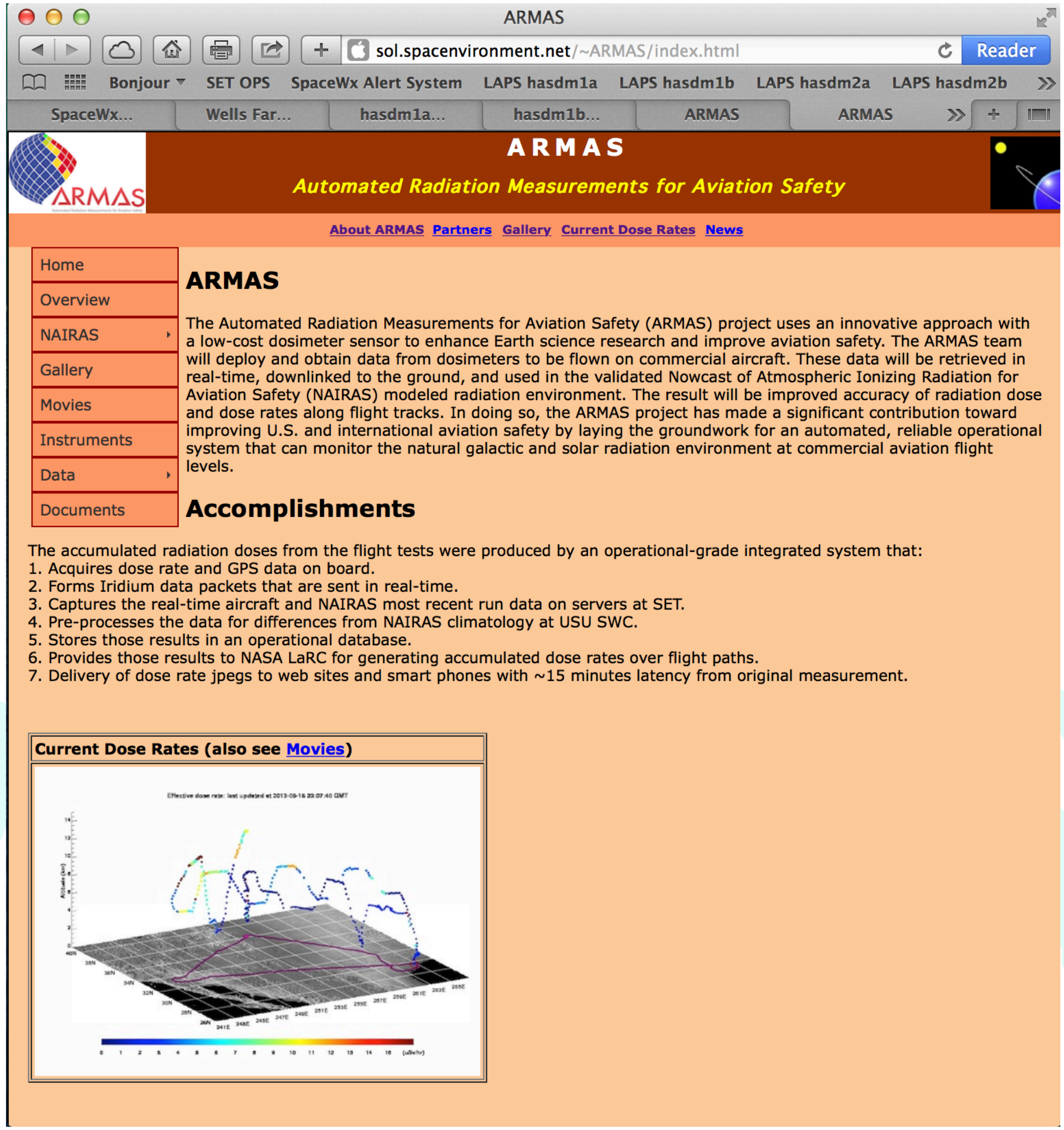


Aviation Radiation NAIRAS severe hazard example (S3)



Credit: NAIRAS & SET

Real-time Automated Radiation Measurements for Aerospace Safety (ARMAS) website



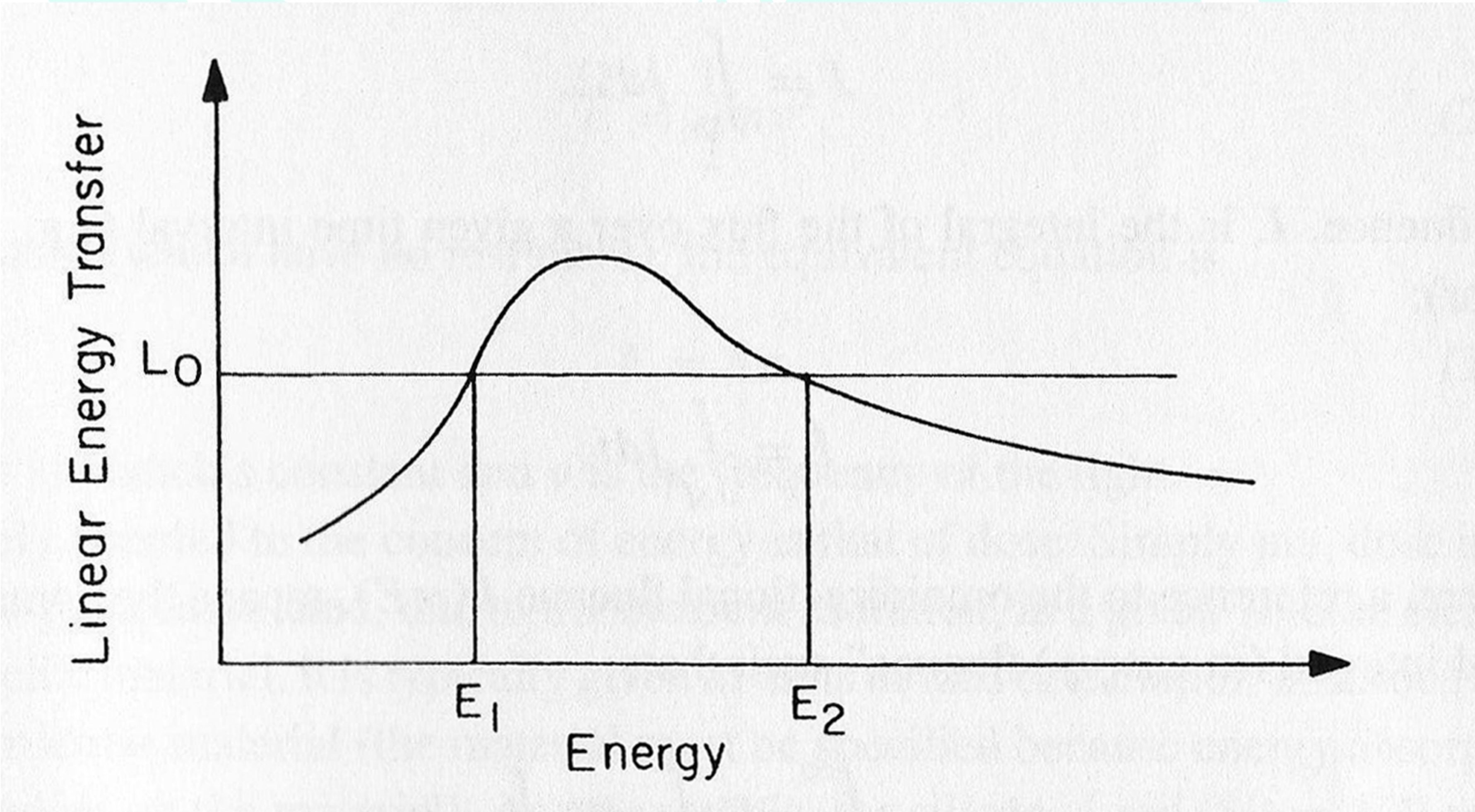
Radiation shielding

Linear energy transfer (LET)

Linear energy transfer (LET) - is the energy transferred by radiation per unit length of absorbing material

- LET = dE/dx
- Units are typically MeV/μm of the primary particle track length for ionization and excitation effects
- Or units can be MeV-cm^2/mg if the density of the material is known (values between 1 and 30)
- Important in SEU analysis since, in these cases, energy is deposited in a sensitive region and an effect occurs when a critical level is reached
- As a function of LET, SEU is a probability - any particle with a minimum LET (L_0) or greater will cause an upset

LET



Radiation doses

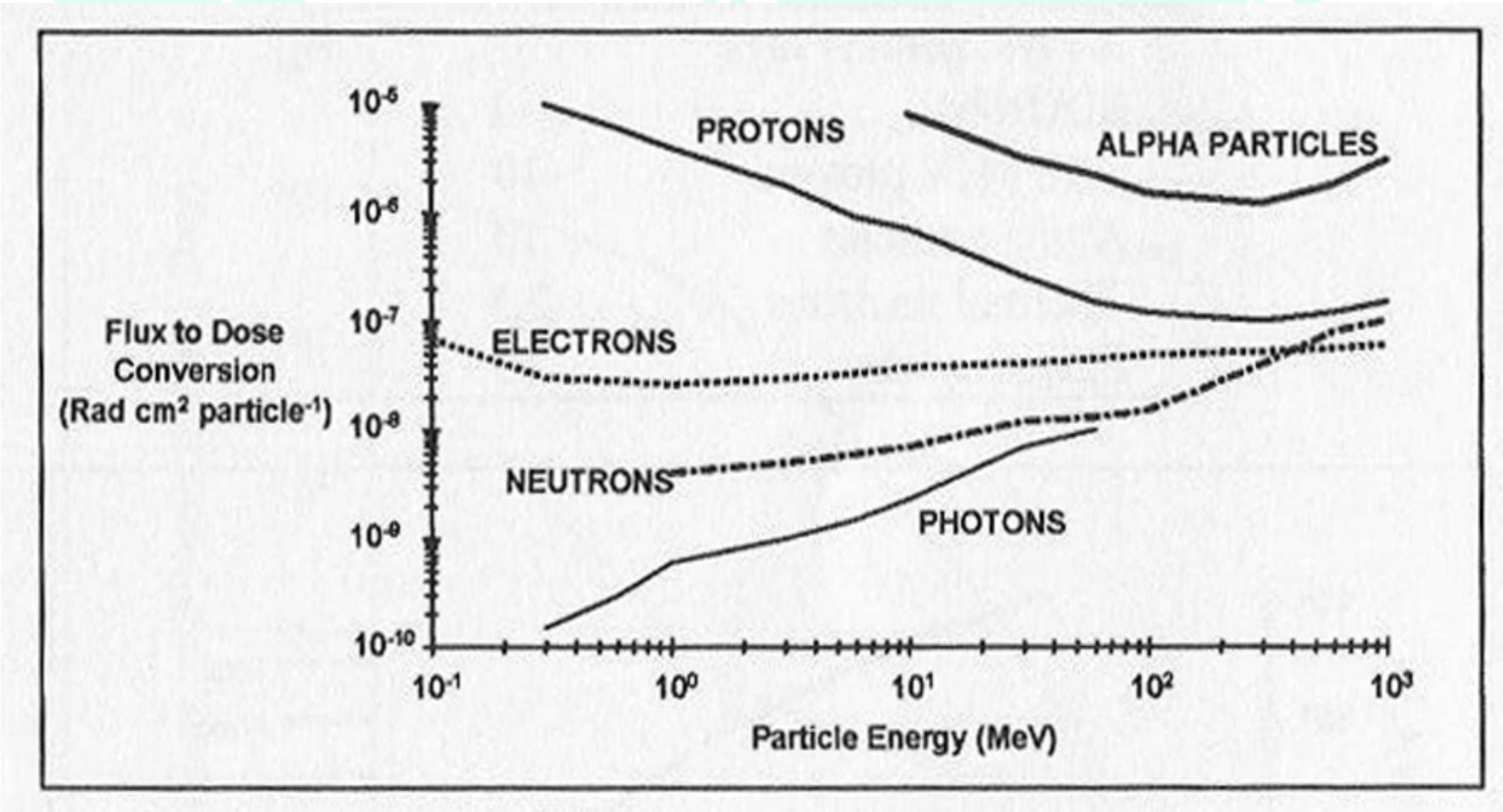
Total ionizing dose (TID) - amount of energy from any ionizing source deposited in a material that results in ionizations

Amount of radiation dose that results in displacements is called **displacement damage** (**DD**)

Rad (Si) is the radiation dose effective in silicon relevant to electronics

Rad (tissue) is the radiation dose effective for human tissue; ionizing radiation damage to tissue causes breakage of molecular bonds

Dose conversions



Radiation shielding

Shielding strategies - useful for electron environment

LEO

Orbital inclination and altitude are important considerations for total radiation dose received

Mitigation strategies for the SAA might be turning off sensitive equipment (HST example) or using radiation hardened electronics (AF satellites)

GEO

Material selection can contribute to shielding where low Z-number materials provide most effective shielding (bremsstrahlung radiation from electrons is reduced)

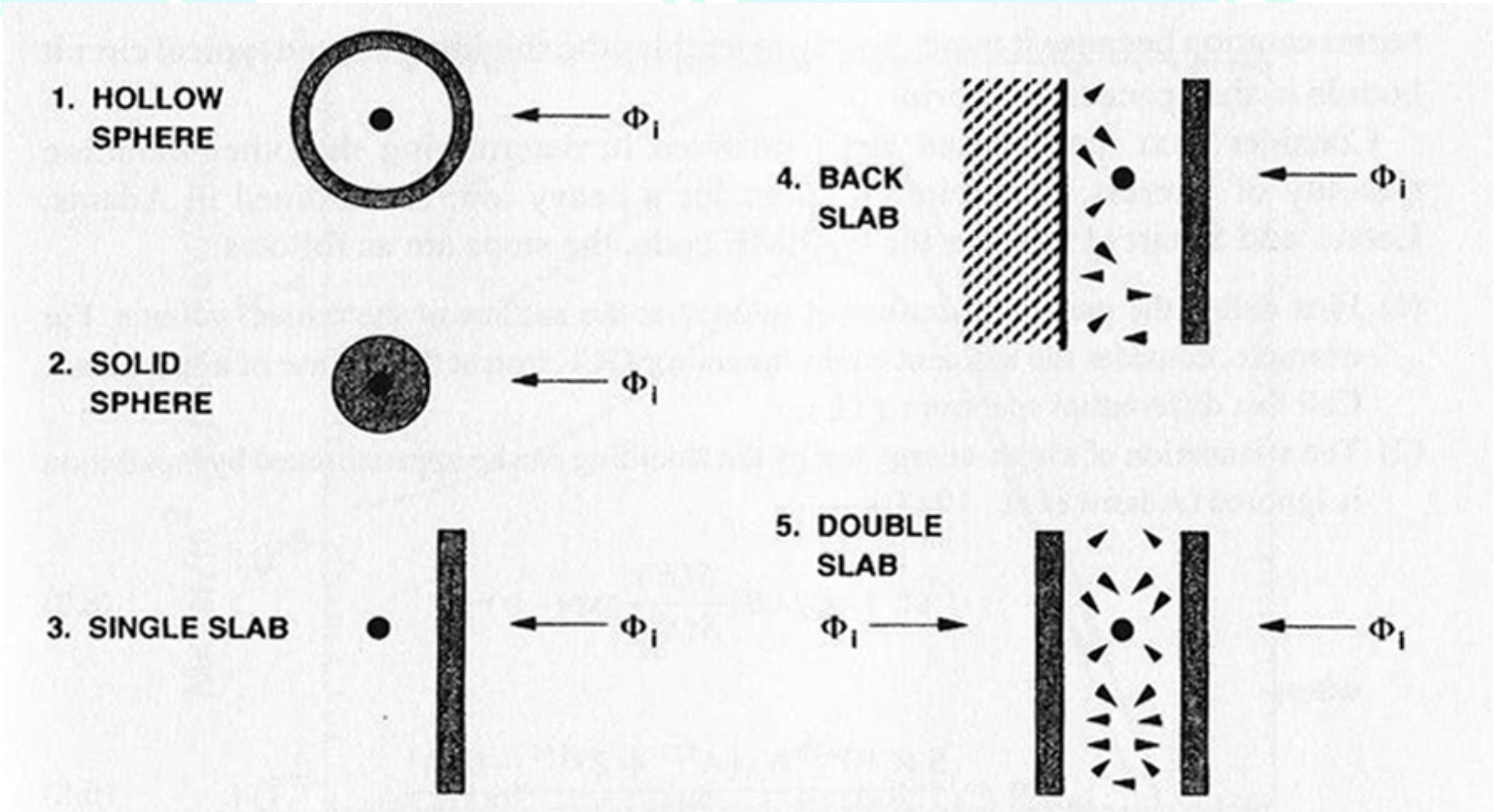
Shielding not very effective against SEUs

Shielding configurations

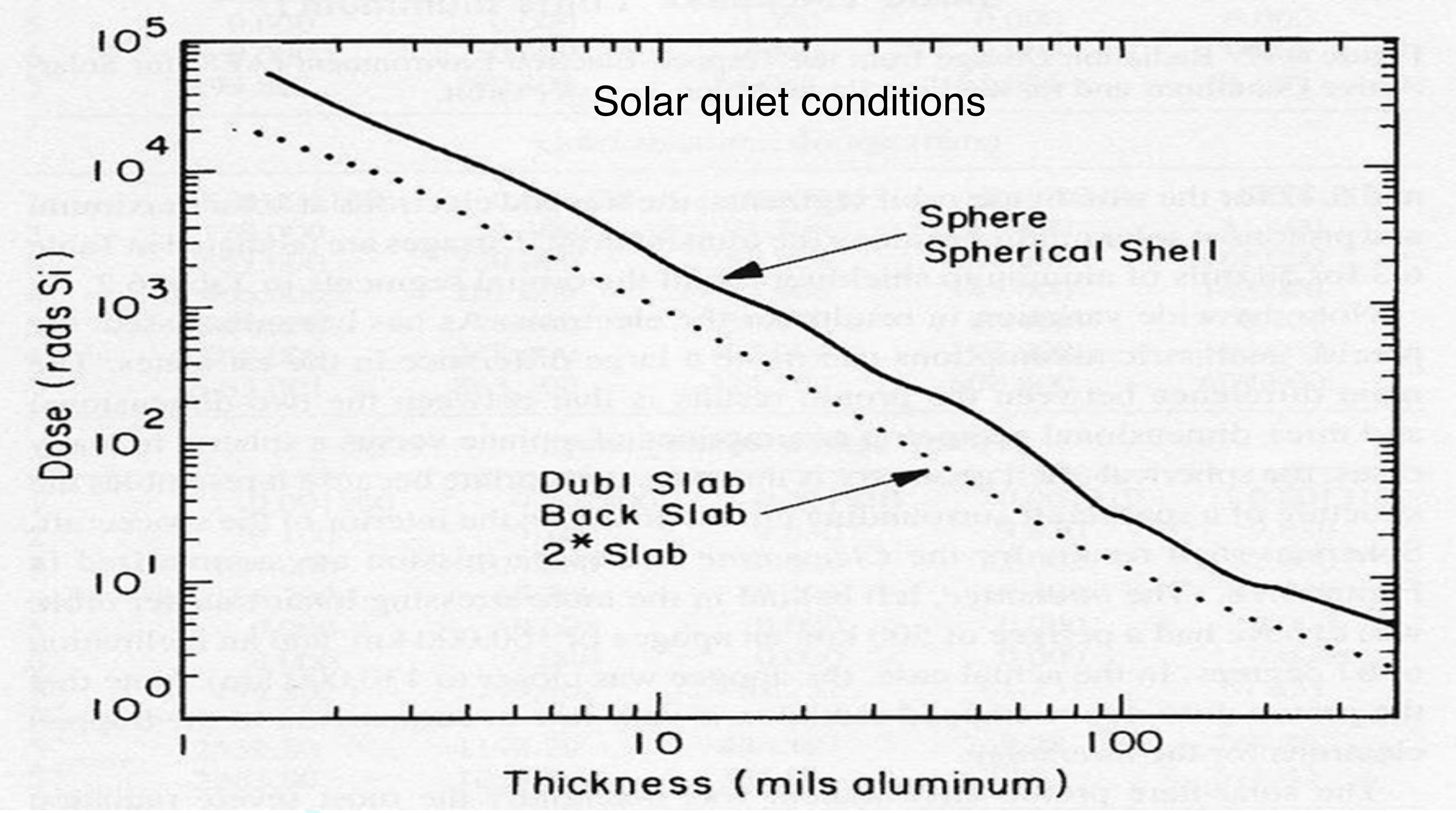
Shielding configurations used for dosage calculations

- **Spherical shell -** Hollow sphere of equal thickness in all directions for a dose point at center (hollow s/c)
- **Sphere -** Shielding material spherically distributed around dose site with no gap (spot shield)
- **Slab -** single slab assumed to be infinite 2-D surface with radiating particles coming from one direction (high energy protons and heavy ions)
- **Back slab -** dose site, as in slab, is backed up by infinite slab but now has reflected or scattered particles
- **Double slab -** two identical thin shields with one on each side where flux assumed to come from both sides (flat solar array panel extending outwards like a wing)

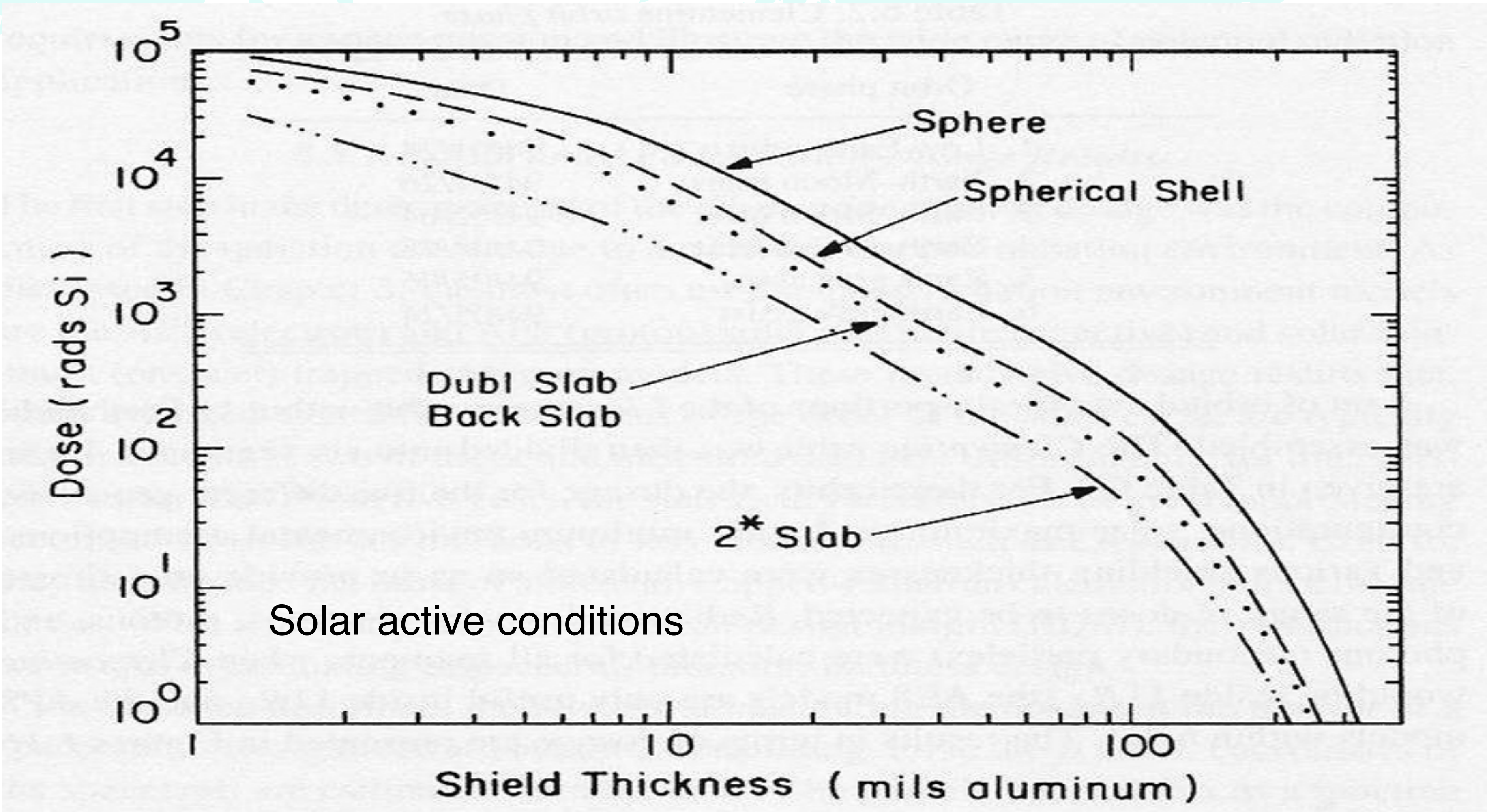
Shielding geometries



Shielding example (solar quiet)



Shielding example (solar active)



Radiation hazards for humans

Moderately high energy particles are primary danger

- Very high energy particles pass through body with little effect
- Particles which have an energy range that are stopped by human tissue pose the most serious problems (150-250 MeV protons, e.g.)
- A dose of rads can be from any radiation source since a rad represents an amount of absorbed radiation and not the source
- 100 rads of radiation (1 Gy) will cause immediate radiation sickness in humans and this dose will kill a tissue cell by creating dozens of lesions in the DNA molecules
- Relative Biological Effectiveness (RBE) is used to compare biological effectiveness from different radiation sources (rem = dose (rad) x RBE)
- Roentgen equivalent in man (REM) is used in human radiation studies and is as damaging to human body as 1 roentgen of hard x-rays
- 100 μSv (1E-4 Gy) ~ 1 chest X-ray (about 10 hours of flying at 37,000 ft. from GCRs)
- Sep 30, 2013 S2 event statistically produced 4 fatal cancers in the commercial flying population of ½ million at the time of that 1-2 mSv event

Credit: Tobiska

Standards, guidelines, models

Resources

- IS 15390 - Galactic Cosmic Rays
- IS 21348 - Solar irradiances
- IS 22009 - Earth's magnetosphere
- IS 16695 - Earth's main field
- IS 16457 - Earth's ionosphere and plasmasphere
- IS 12208 Observed Proton Fluences over long duration at GEO and Guideline for selection of confidence level in statistical model of Solar Proton Fluences
- IS 15856 – Radiation exposure for non-metallic materials
- AIAA G-083-1999 - Earth's trapped radiation
- MIL-STD-1541A section 6.7 - how to test an electronic assembly's susceptibility to ESD
- AE9/AP9 released in 2011
- Emission of Solar Proton model (*Xapsos et al*., 1999, 2000)
- Cosmic Ray Effects on Microelectronics (CREME96) galactic cosmic ray & SEP model (*Tylka et al*.,1997)
- *Spacecraft-Environment Interactions,* Hastings and Garrett, Cambridge Univ. Press, 1996
- JPL-91 solar proton model (*Feynman et al.,* 1990)

Resources

- NASA MSFC SEE program http://see.msfc.nasa.gov/dmia.htm
  - ***General*** · Lunar E-Library - knowledgebase
  - ***Electromagnetic Effects & Spacecraft Charging***
    - Electronic Propulsion Interactions Code (EPIC) - model
    - NASA/Air Force Spacecraft Charging Analyzer Program (NASCAP-2K) - model
    - Interactive Spacecraft Charging Handbook - model
    - The Charge Collector - knowledgebase
  - ***Ionizing Radiation Environment***
    - Trapped Proton Model (TPM) - model
    - Cosmic Ray Effects on Microelectronics (CREME96) - model
    - Low-Altitude Trapped Proton - model
    - Emission of Solar Protons (ESP) - model
    - Trapped Radiation Models; Uncertainties for Design - model

- ***Ionosphere and Thermosphere (Solar and Thermal Environments)***
  - Earth Global Reference Atmospheric Model (Earth-GRAM 2007) (***US Release***)
  - Mars Global Reference Atmospheric Model (Mars-GRAM 2005) (***US Release***)
  - All Global Reference Atmospheric Model ***(Intra NASA Release)***
  - All Global Reference Atmospheric Model (***Foreign Release***)
- ***Materials and Processes***
  - Spacecraft Materials Selector (SMS) Expert System - model
- ***Meteoroids and Orbital Debris***
  - Meteor Properties Database - Database
  - Meteoroid Engineering Model (MEM) - model
  - Leonid Storm Fluence Calculator - model
- ***Neutral External Contamination***
  - Satellite Contamination and Materials Outgassing Knowledgebase - knowledgebase

ISO 15390 GCR standard

- specifies a model for estimating the radiation impact of galactic cosmic rays (GCR) on hardware and on biological and other objects when in space.
- can also be used in scientific research to generalize the available experimental evidence for GCR fluxes.
- establishes the model parameters and characteristics of variations in the 101 MeV to105 MeV GCR particles (electrons, protons, and $Z = 2$ to 92 nuclei in the near-Earth space beyond the Earth's magnetosphere)

AIAA G-083-1999

- **Guide to Modeling Earth's Trapped Radiation Environment**
- Topics covered:
  - Basic concepts of the space radiation environment
  - The trapped radiation environment
  - Geomagnetic field
  - Basic particle motion
  - AE8 and AP8 models
  - Solar cycle effects
  - Magnetospheric heavy ions
  - Shielding
  - Photon and charged particle interactions
  - Recommendations
  - References

Summary

- **Environmental effects (radiation effects)**
  - Radiation physics
    - Radiation-surface interactions (photons, electrons, ions, neutrons)
  - Radiation environment characteristics
    - Radiation units (gray, Rad, dose)
    - Van Allen belts, solar energetic photons, solar energetic particles, galactic cosmic rays,
    - Radiation (charged particle) effects
    - Surface impacting effects (conducting material, solar arrays, optical surfaces)
    - Penetration effects (single event upsets, latchup, deep dielectric charging)
    - Example events (Mar1991, Jan 1994 (Anik), May 1998 (Galaxy-4), Oct 28-31 2003)
    - Linear energy transfer, doses, radiation shielding, radiation hazards
  - Standards, guidelines, models (AE8, AP8, JPL, CRÈME, L2-CPE)