Why Space is Unique?

The Basic Environment Challenges for EEE Parts

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Note: This is not intended to cover ALL issues, but just a sampling of some of the more typical.

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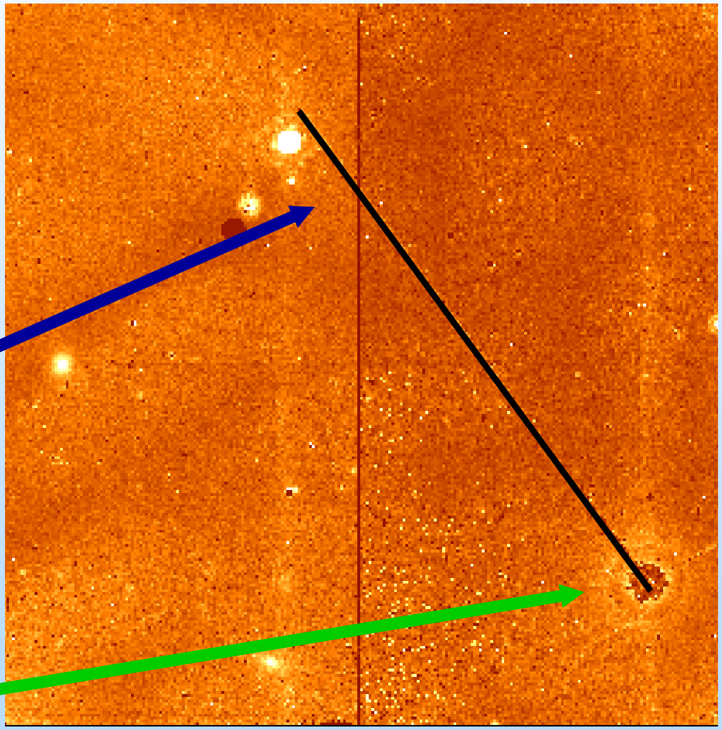
Acronyms

APS = active pixel sensor
CCDs = charge coupled devices
CMEs = coronal mass ejections
CMOS = complementary metal oxide semiconductor
COTS = commercial off the shelf
DD = displacement damage
FOD = foreign object debris
GCRs = galactic cosmic rays
IC = integrated circuit
LET = linear energy transfer
NIEL = non-ionizing energy loss
RTGs = radioisotope thermal generators
SAA = south atlantic anomaly
SEB = single event burnout
SEE = single event effects
SEGR = single event gate rupture
SEL = single event latchup
SETs = single event transients
SEUs = single event upsets
SRAM = static random access memory
TID = total ionizing dose

Outline

- Intro
  - A Unique Place to Operate Electronics
- The Space Radiation Environment
  - The Effects on Electronics
  - The Environment in Action
  - Flight Projects
    - Mission Needs
    - Radiation Hardness Assurance (RHA)
- Final Thoughts



http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html

Atomic Interactions
- Direct Ionization

Interaction with Nucleus
- Indirect Ionization
- Nucleus is Displaced

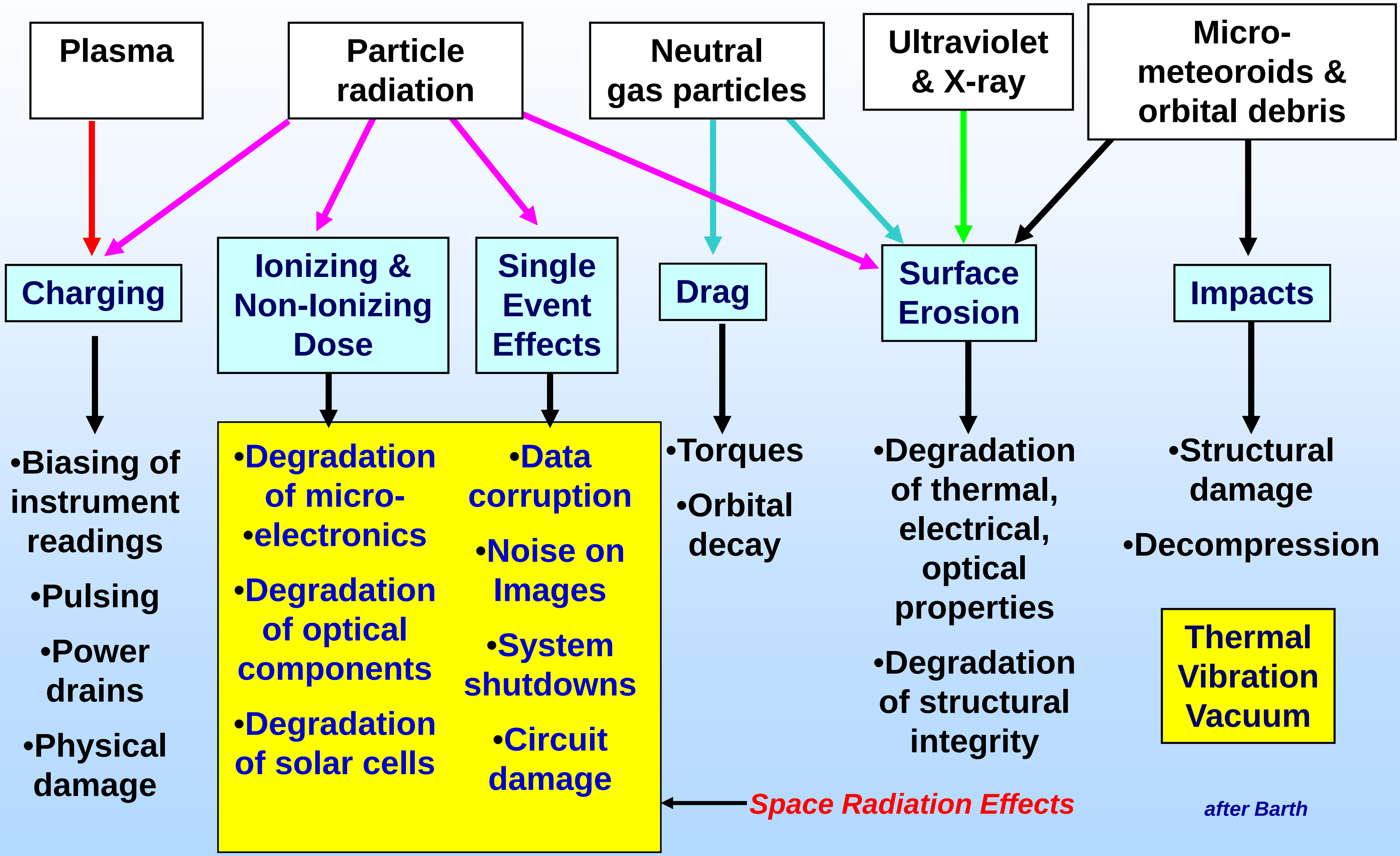
A Few Upfront Comments

- **Aerospace Grade electronics are typically designed and tested to survive a wide range of environment exposures:**
  - **-55C to +125C, as an example.**
- **This allows a "generic" qualification by a manufacturer to encompass a wide array of user mission needs (i.e., one test for a lot of folks rather than a new test for each customer).**
- **Commercial off the shelf (COTS) for terrestrial usage aren't designed/tested to these same levels.**
  - **Doesn't mean they won't work in "your" mission, just means you need to pay attention to the environment considerations.**

We’re Not in Kansas Anymore

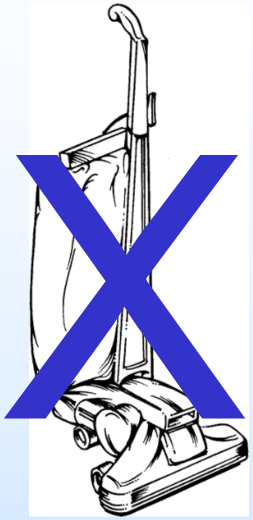
- **CAVEAT: All mission environment exposures are a function of:**
  - **When it flies,**
  - **How long it flies,**
  - **Where it flies, and**
  - **What “protection” is there to mitigate the environment.**
- **Protection can be anything from shielding to thermal control to fault tolerant design.**
  - ***Anomalies and failures are what happens when the protection isn’t sufficient.***
- **In other words, space is a place you can’t hear your electronics scream (with apologies to *Alien*).**

Space Environments and Related Effects



A Vacuum That's Not for Cleaning

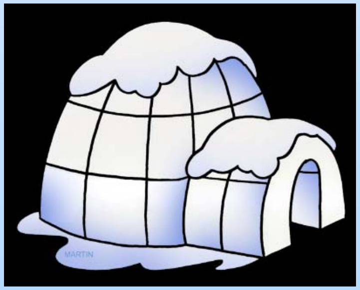
- **When not on a planet with an atmosphere, missions are mostly in a vacuum and are designed to operate there.**
- **Why do we care? Examples include:**
  - **Outgassing: the release of a gas that was dissolved, trapped, frozen or absorbed in some material.**
    - **This can contaminate other portions of your system (optics, for example) or hinder IC operation.**
  - **Material property deterioration – shortens lifetime or changes device characteristics.**
  - **Thermal: no air, means no air cooling. Other means are needed to passively or actively control temperature.**
  - **"Oil-canning" of hermetic packages: A moderate deformation or buckling of sheet material.**
- **Note: Testing of systems usually includes a thermal vacuum test.**



Is It Hot in Here or Just My IC?

- Electronics vary considerably with the temperature range they can operate in.
  - Standard Military Grade is -55C to +125C
  - Standard Commercial is 0 to 70C
  - Extremes for space can go below and above even Military Grade.

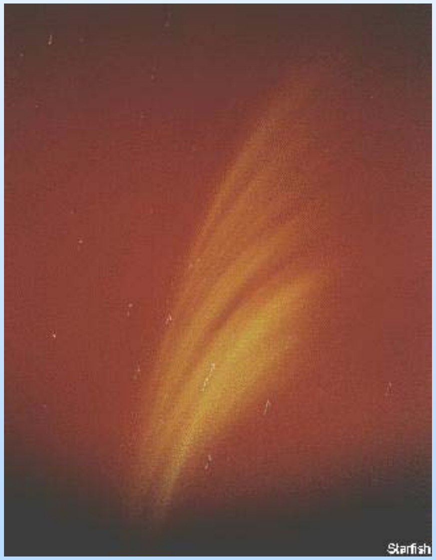
- Operating an IC out of its range can sometimes work, but not always (and margins may be minimalized).
- The temperature of a device in a space mission varies with the orbit and how the spacecraft is facing (i.e., is one side always facing the sun).
  - Actual temperature range at a location within a spacecraft is modeled and is usually smaller than Mil grade range (and sometimes significantly so – maybe a 0 to 20C range or better).
    - BUT, there may be a very high number of thermal cycles!
  - Remember that devices "self-heat" and often need thermal control.



A Whole Lotta' Shakin' Going On

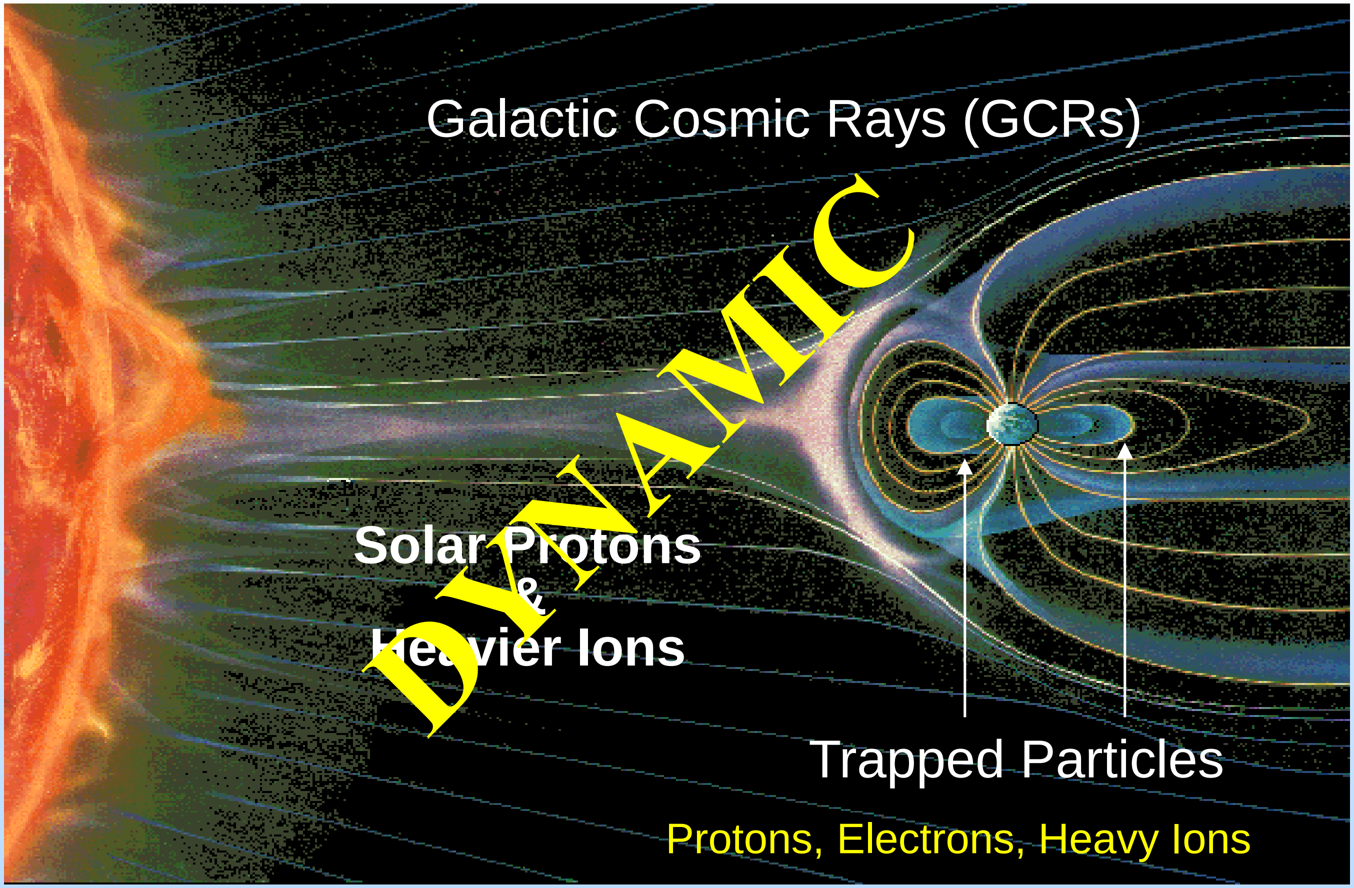
- Vibration and mechanical shock are standard tests to "qualify" against for launch, re-entry, etc
- Problems include:
  - Loose particles inside the package of a device.
    - Particle Impact Noise Detection (PIND) test is the "standard qualifying test".
    - This is usually an acoustic test that provides a nondestructive means of identifying those devices containing particles of sufficient mass that, upon impact within the cavity, excite the transducer.
  - Workmanship: how well are things "attached"?
    - Usually inspection and functional vibration testing performed.

The Space Radiation Environment



STARFISH detonation –
Nuclear attacks are not considered in this presentation

Space Radiation Environment

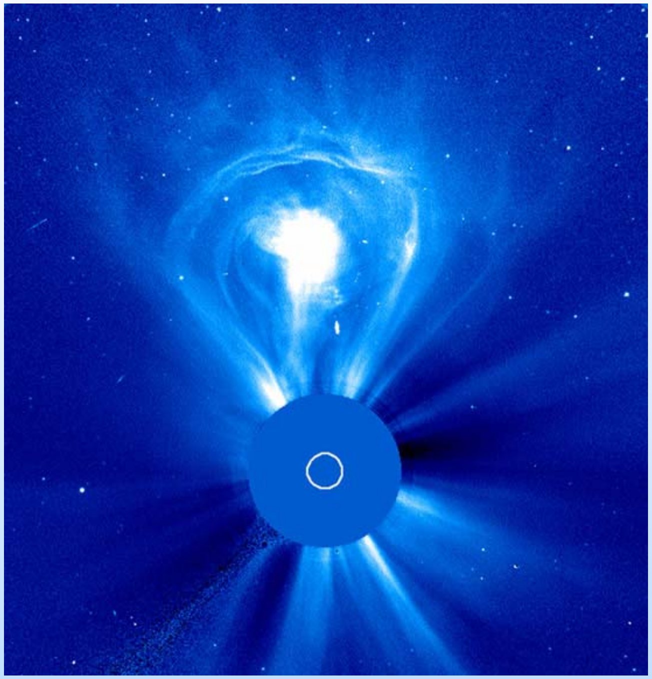


after Nikkei Science, Inc. of Japan, by K. Endo

Deep-space missions may also see: neutrons from background or radioisotope thermal generators (RTGs) or other nuclear source
Atmosphere and terrestrial may see GCR and secondaries

Solar Cycle Effects: Modulator and Source

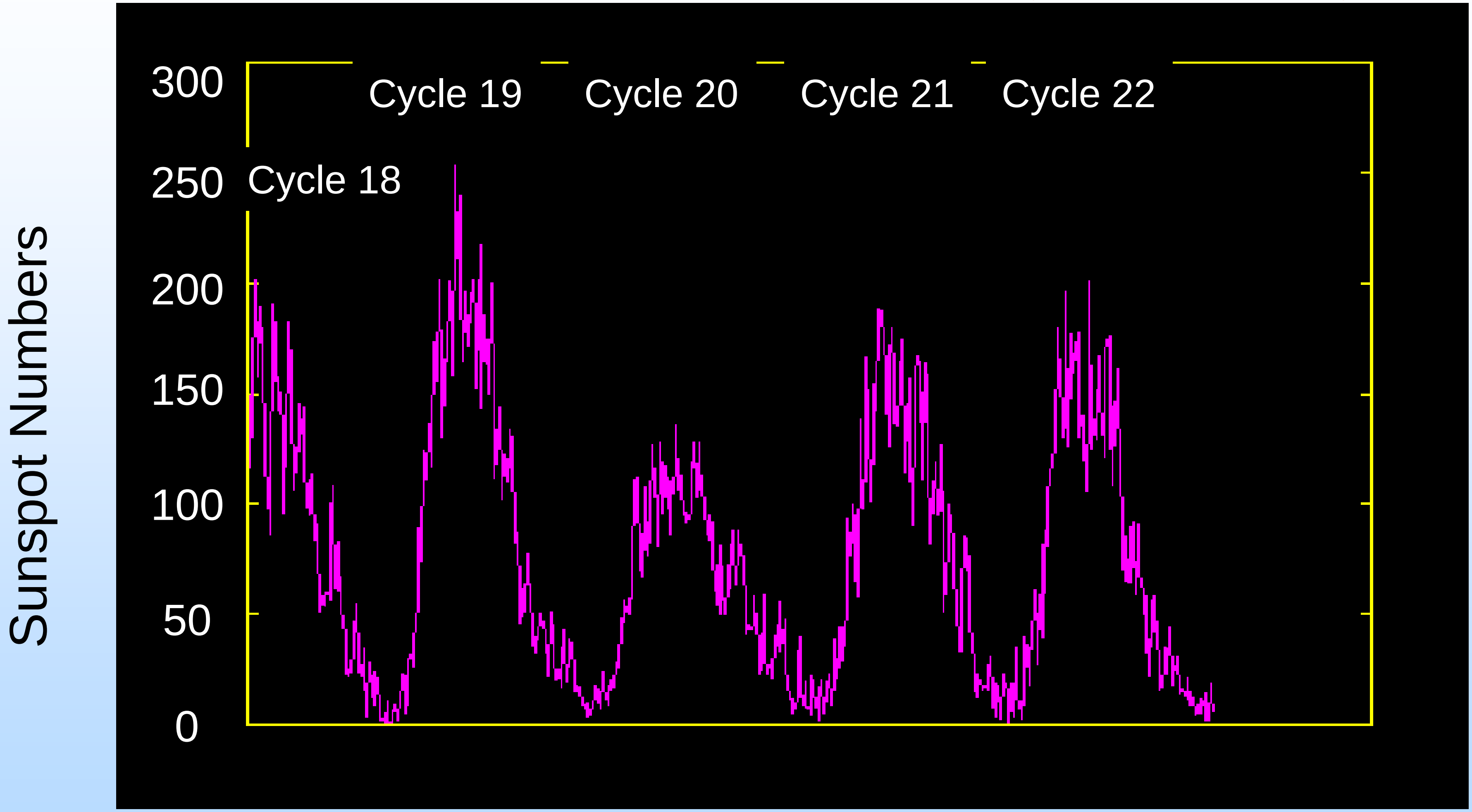
- **Solar Maximum**
  - **Trapped Proton Levels Lower, Electrons Higher**
  - **GCR Levels *Lower***
  - **Neutron Levels in the Atmosphere Are Lower**
  - **Solar Events More Frequent & Greater Intensity**
  - **Magnetic Storms More Frequent --> Can Increase Particle Levels in Belts**
- **Solar Minimum**
  - **Trapped Protons Higher, Electrons Lower**
  - **GCR Levels *Higher***
  - **Neutron Levels in the Atmosphere Are Higher**
  - **Solar Events Are Rare**



Light bulb shaped CME courtesy of SOHO/LASCO C3 Instrument

Sunspot Cycle: An Indicator of the Solar Cycle

after Lund Observatory

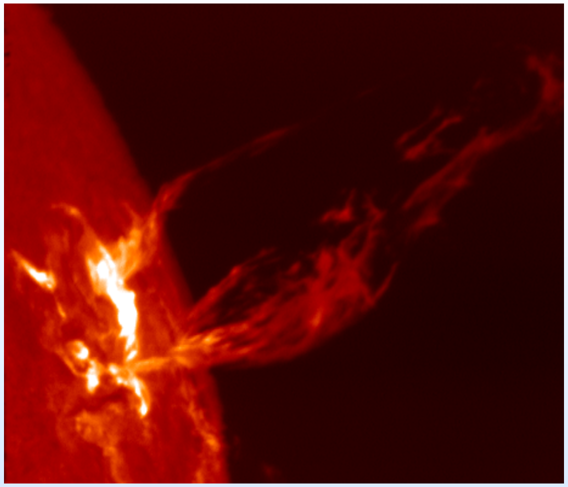


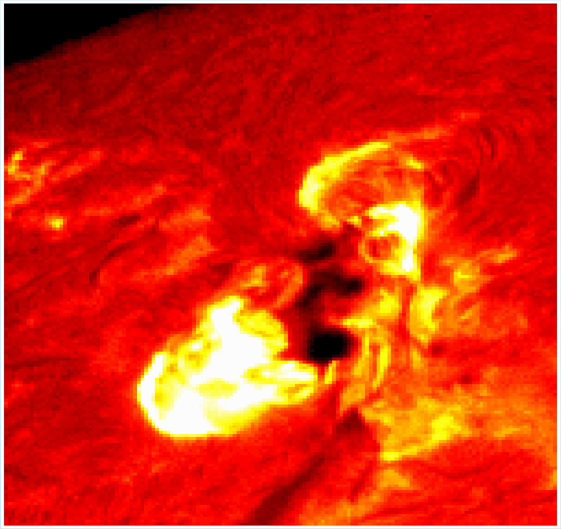
Length Varies from 9 - 13 Years
7 Years Solar Maximum, 4 Years Solar Minimum

Solar Particle Events

- Cyclical (Solar Max, Solar Min)
  - 11-year AVERAGE (9 to 13)
  - Solar Max is more active time period
- Two types of events
  - Gradual (Coronal Mass Ejections – CMEs)
    - Proton rich
  - Impulsive (Solar Flares)
    - Heavy ion rich
- Abundances Dependent on Radial Distance from Sun
- Particles are Partially Ionized
  - Greater Ability to Penetrate Magnetosphere than GCRs

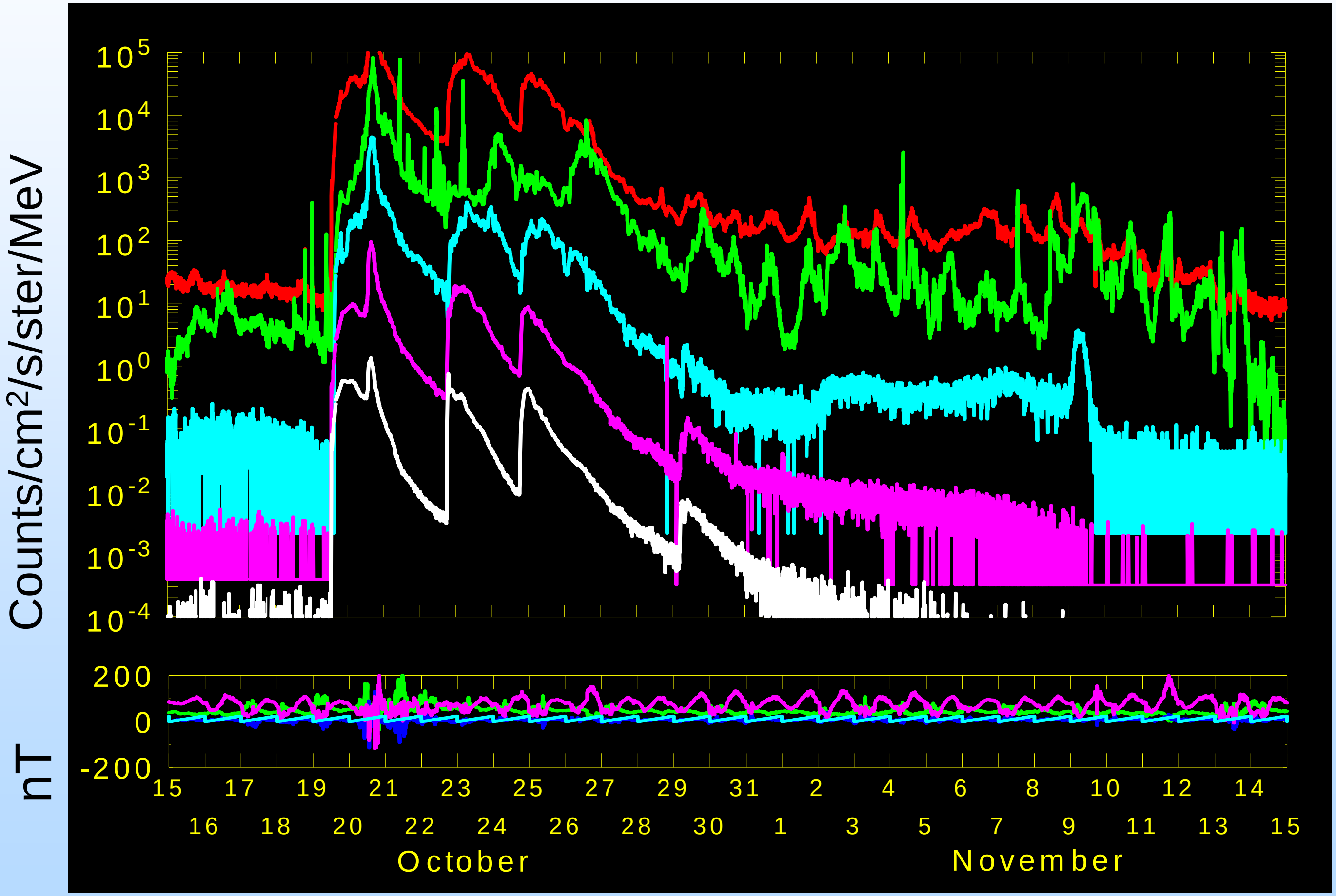
Holloman AFB/SOON





Solar Proton Event - October 1989

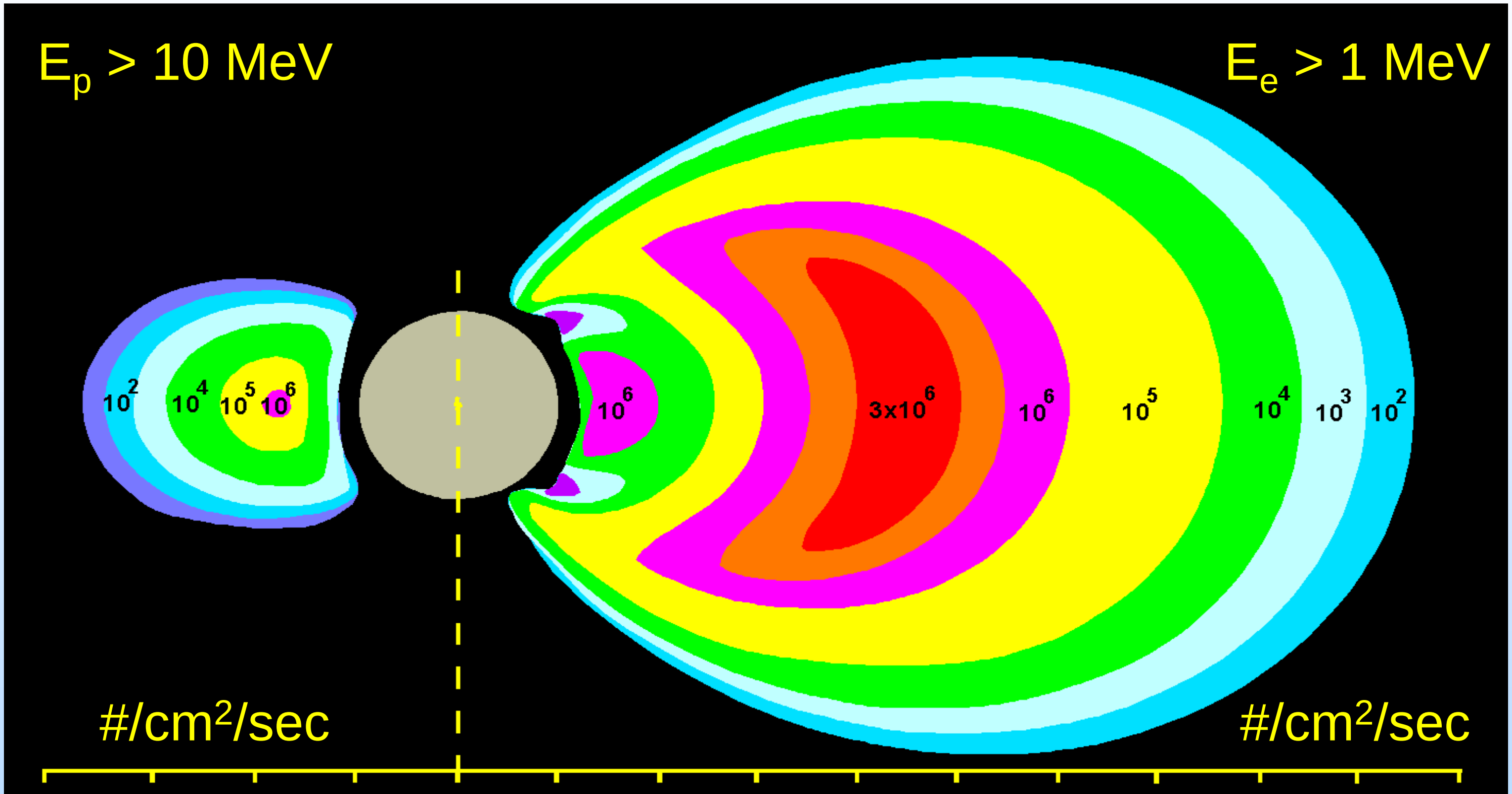
Proton Fluxes - 99% Worst Case Event



GOES Space Environment Monitor

Trapped Particles in the Earth's Magnetic Field: Proton & Electron Intensities

AP-8 Model AE-8 Model



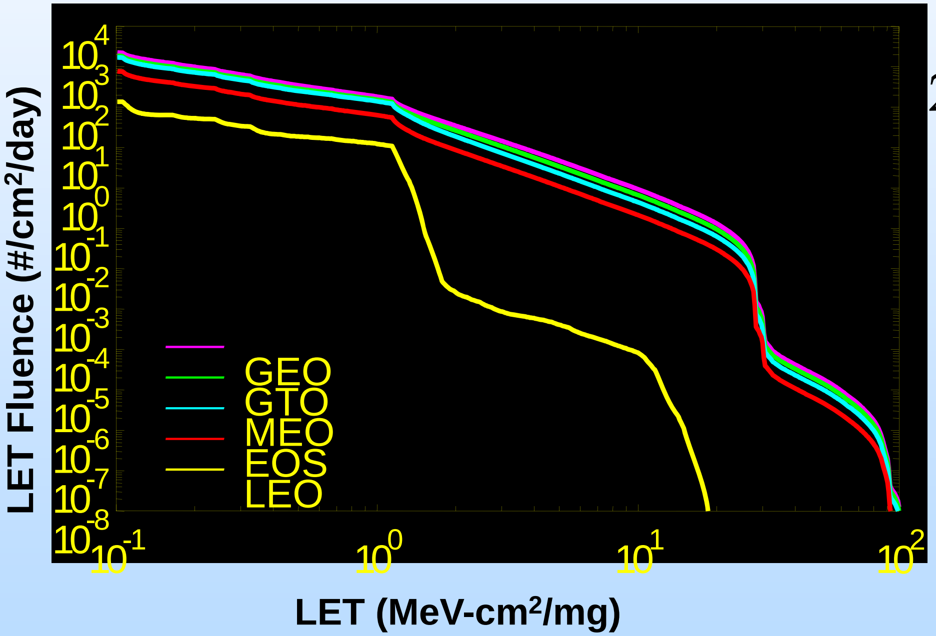
A dip in the earth's dipole moment causes an asymmetry in the picture above: The South Atlantic Anomaly (SAA)

L-Shell

Free-Space Particles: Galactic Cosmic Rays (GCRs) or Heavy Ions

- **Definition**
  - **A GCR ion is a charged particle (H, He, Fe, etc)**
  - **Typically found in free space (galactic cosmic rays or GCRs)**
    - **Energies range from MeV to GeVs for particles of concern for SEE**
    - **Origin is unknown**
  - **Important attribute for impact on electronics is how much energy is deposited by this particle as it passes through a semiconductor material. This is known as Linear Energy Transfer or LET (dE/dX).**

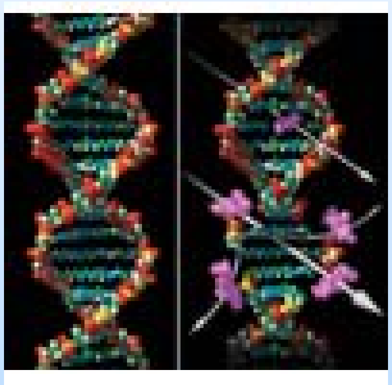
CREME 96, Solar Minimum, 100 mils (2.54 mm) Al



Time

Commercial Technology Sensitivity

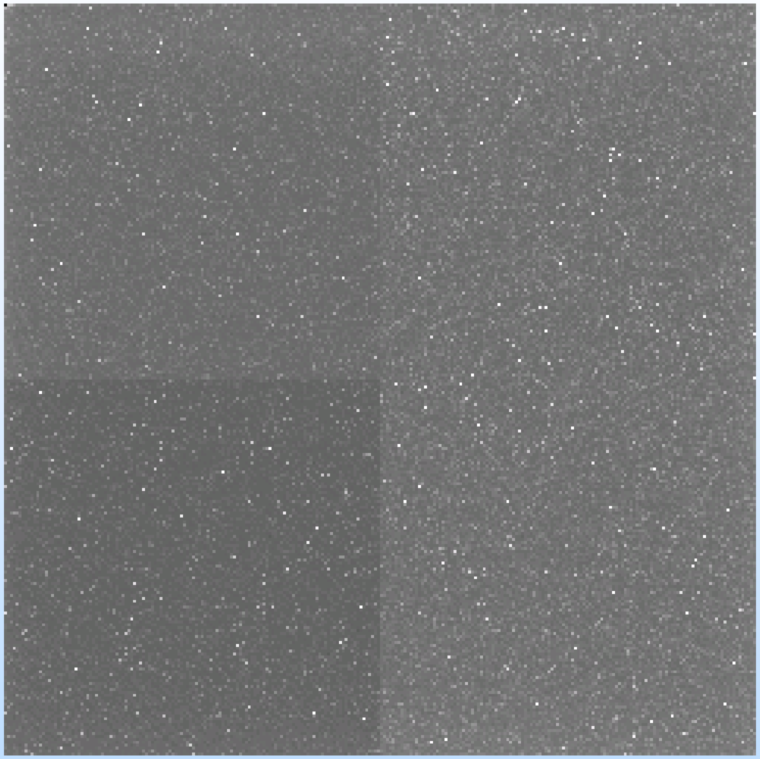
The Effects



DNA double helix
Pre and Post Irradiation
Biological effects are a key concern for lunar and Mars missions

Radiation Effects and Spacecraft

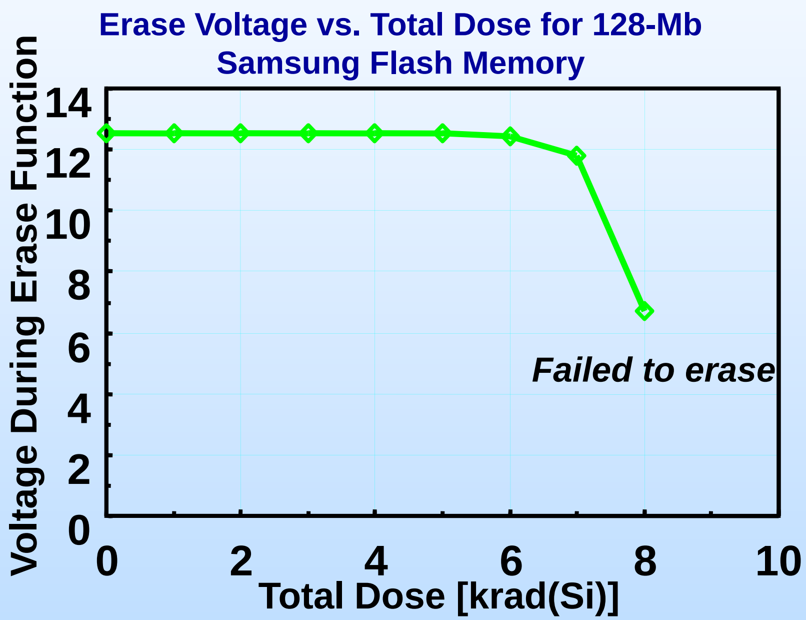
- **Critical areas for design in the natural space radiation environment**
  - **Long-term effects causing parametric and /or functional failures**
    - **Total ionizing dose (TID)**
    - **Displacement damage**
  - **Transient or single particle effects (Single event effects or SEE)**
    - **Soft or hard errors caused by proton (through nuclear interactions) or heavy ion (direct deposition) passing through the semiconductor material and depositing energy**



An Active Pixel Sensor (APS) imager under irradiation with heavy ions at Texas A&M University Cyclotron

Total Ionizing Dose (TID)

- Cumulative long term *ionizing* damage due to protons & electrons
  - keV to MeV range
- Electronic Effects
  - Threshold Shifts
  - Leakage Current
  - Timing Changes
  - Functional Failures
- Unit of interest is krads(material)
- Can *partially* mitigate with shielding
  - Reduces low energy protons and electrons



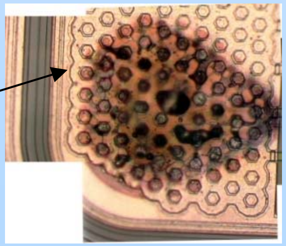
Displacement Damage (DD)

- **Cumulative long term *non-ionizing* damage due to protons, electrons, and neutrons**
  - **keV to MeV range**
- **Electronic Effects**
  - **Production of defects which results in device degradation**
  - **May be similar to TID effects**
  - **Optocouplers, solar cells, charge coupled devices (CCDs), linear bipolar devices**
    - **Lesser issue for digital CMOS**
- **Unit of interest is particle fluence for each energy mapped to test energy**
  - **Non-ionizing energy loss (NIEL) is one means of discussing**
- **Can *partially* mitigate with shielding**
  - **Reduces low energy protons and electrons**

Single Event Effects (SEEs)

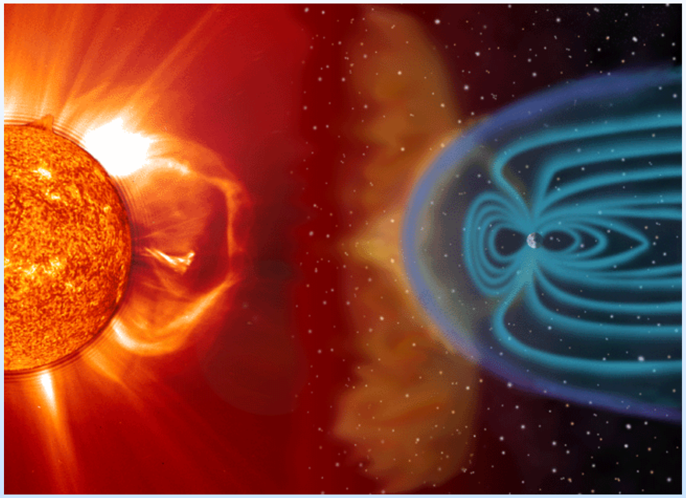
- **An SEE is caused by a *single charged particle* as it passes through a semiconductor material**
  - **Heavy ions (cosmic rays and solar)**
    - **Direct ionization**
  - **Protons(trapped and solar - >10 MeV)/neutrons (secondary or nuclear) for sensitive devices**
    - **Nuclear reactions for electronics**
    - **Optical systems, etc are sensitive to direct ionization**
- **Unit of interest: linear energy transfer (LET). The amount of energy deposited/lost as a particle passes through a material.**
  - **Total charge collected may be more appropriate**
- **Effects on electronics**
  - **If the LET of the particle (or reaction) is greater than the amount of energy or critical charge required, an effect may be seen**
    - **Soft errors such as upsets (SEUs) or transients (SETs), or**
    - **Hard (destructive) errors such as latchup (SEL), burnout (SEB), or gate rupture (SEGR)**
- **Severity of effect is dependent on**
  - **type of effect**
  - **system criticality**

Destructive event in a COTS 120V DC-DC Converter



Radiation Effects on Electronics and the Space Environment

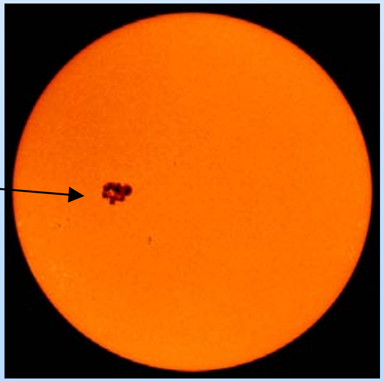
- **Three portions of the natural space environment contribute to the radiation hazard**
  - **Solar particles**
    - **Protons and heavier ions**
      - **SEE, TID, DD**
  - **Free-space particles**
    - **GCR**
      - **For earth-orbiting craft, the earth's magnetic field provides some protection for GCR**
      - **SEE**
  - **Trapped particles (in the belts)**
    - **Protons and electrons including the South Atlantic Anomaly (SAA)**
      - **SEE (Protons)**
      - **DD, TID (Protons, Electrons)**
- **Note: Jovian Environment is dominated by higher energy electrons**



The sun acts as a modulator and source in the space environment

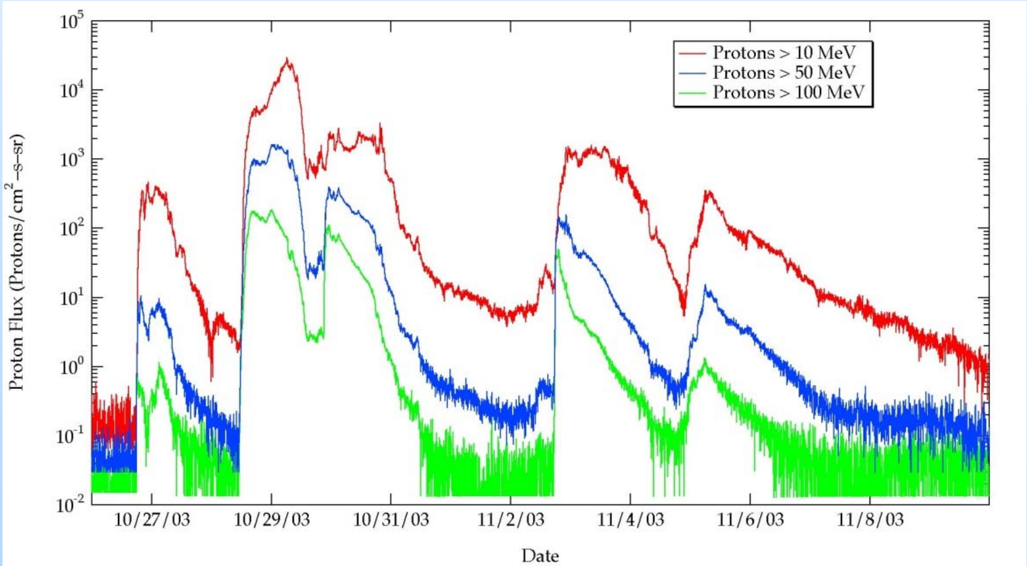
The Environment in Action

“There’s a little black spot on the sun today”

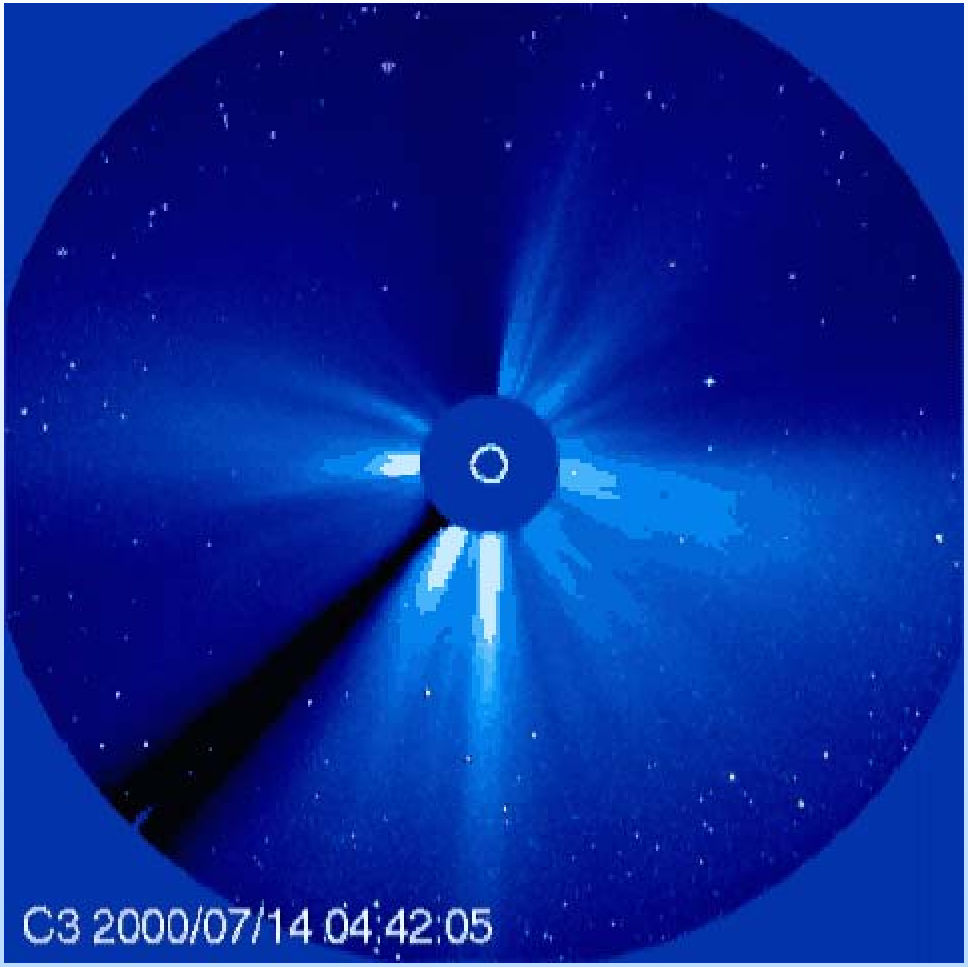


Solar Events – A Few Notes and Implications

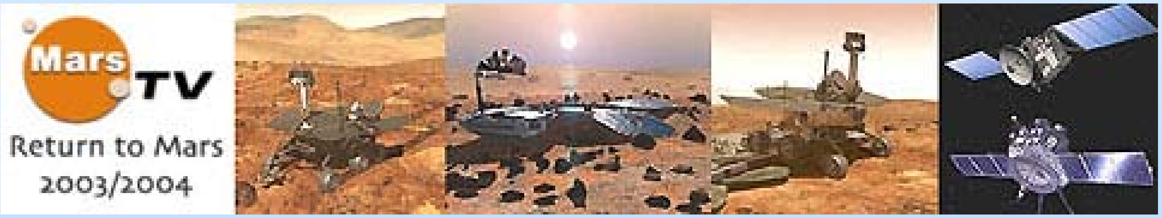
- In Oct-Nov of 2003, a series of X-class (BIG X-45!) solar events took place
  – High particle fluxes were noted
  – Many spacecraft performed safing maneuvers
  – Many systems experienced higher than normal (but correctable) data error rates
  – Several spacecraft had anomalies causing spacecraft safing
  – Increased noise seen in many instruments
  – Drag and heating issues noted
  – Instrument FAILURES occurred
  – Two known spacecraft FAILURES occurred
- Power grid systems affected, communication systems affected…



SOHO LASCO C2 of the Solar Event



NASA Missions:
Flight Projects and Radiation



It doesn't matter where you go
as long as you follow a
programmatic assurance approach

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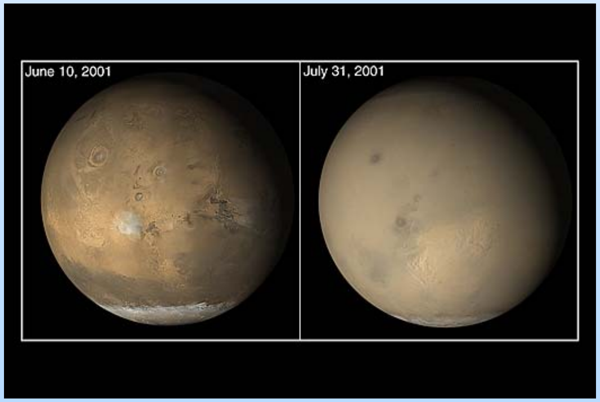
NASA Missions –
A Wide Range of Needs

- **NASA typically has over 200 missions in some stage of development**
  - **Range from balloon and short-duration low-earth investigations to long-life deep space**
  - **Robotic to Human Presence**
- **Radiation and reliability needs vary commensurately**



Mars Global Surveyor
Dust Storms in 2001

Summary of Environment Hazards for Electronic Parts in NASA Missions

	Plasma (charging)	Trapped Protons	Trapped Electrons	Solar Particles	Cosmic Rays	Human Presence	Long Lifetime (>10 years)	Nuclear Exposure	Repeated Launch	Extreme Temperature	Planetary Contaminates (Dust, etc)
GEO	Yes	No	Severe	Yes	Yes	No	Yes	No	No	No	No
LEO (low-incl)	No	Yes	Moderate	No	No	No	Not usual	No	No	No	No
LEO Polar	No	Yes	Moderate	Yes	Yes	No	Not usual	No	No	No	No
Shuttle	No	Yes	Moderate	No	No	Yes	Yes	No	Yes	Rocket Motors	No
ISS	No	Yes	Moderate	Yes - partial	Minimal	Yes	Yes	No	No	No	No
Interplanetary	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	Yes	Yes	No	Yes	Maybe	No	Yes	Maybe
Exploration - CEV	Phasing orbits	During phasing orbits	During phasing orbits	Yes	Yes	Yes	Yes	No	Yes	Rocket Motors	No
Exploration – Lunar, Mars	Phasing orbits	During phasing orbits	During phasing orbits	Yes	Yes	Yes	Yes	Maybe	No	Yes	Yes

+ thermal, vacuum, and vibration

Final Comments and Future Considerations

Space Challenges for Complex Non-hermetic Packages

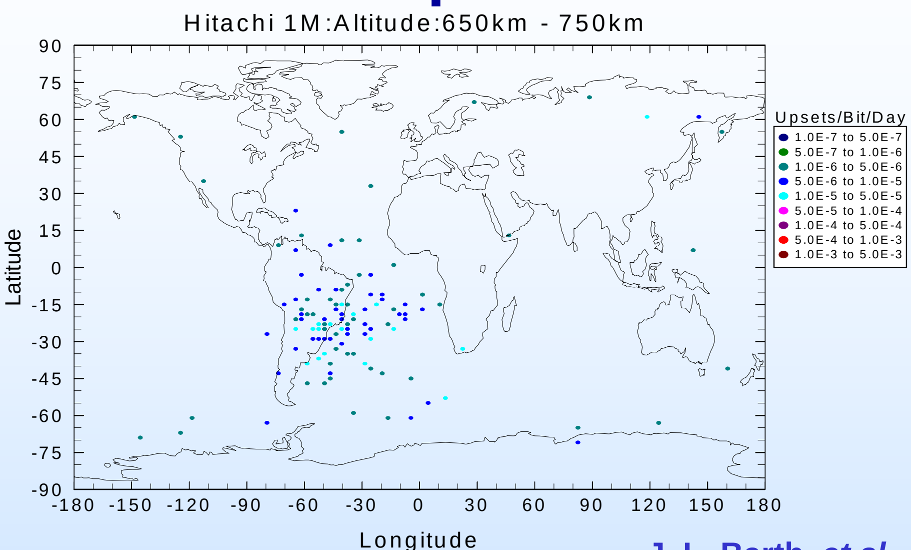
- **Vacuum:**
  - **Outgassing (or offgassing), property deterioration**
- **Foreign Object Debris (FOD)**
  - **From the package threat to the system, or a threat to the package**
- **Shock and vibration**
  - **During launch, deployments and operation**
- **Thermal cycling**
  - **Usually small range; high number of cycles in Low Earth Orbit (LEO)**
- **Thermal management**
  - **Only conduction and radiation transfer heat**
- **Thousands of interconnects**
  - **Opportunities for opens, intermittent - possibly latent**
- **Low volume assembly**
  - **Limited automation, lots of rework**
- **Long life**
  - **Costs for space are high, make the most of the investment**
- **Novel hardware**
  - **Lots of "one offs" – is this model chaging?**
- **Rigorous test and inspection**
  - **To try to find the latent threats to reliability**

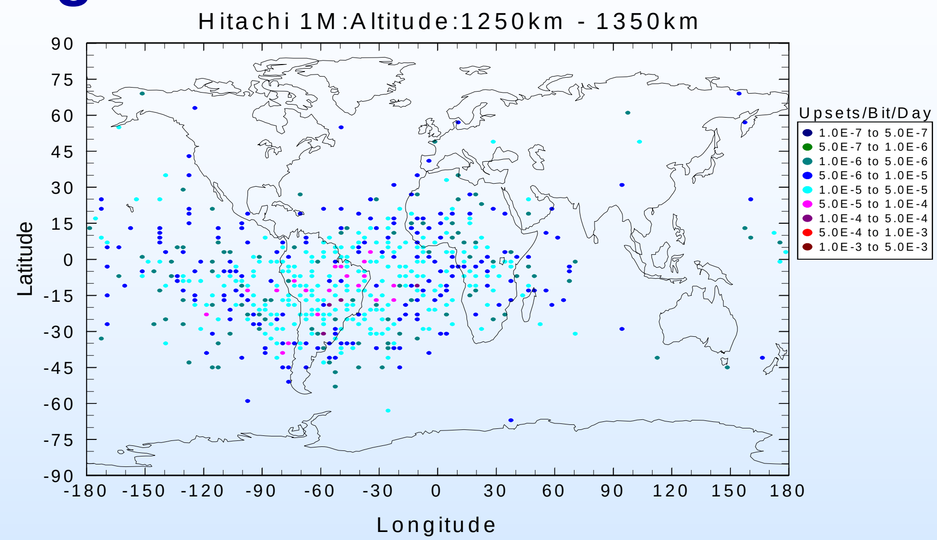
ONE STRIKE AND YOU'RE OUT!

Backup

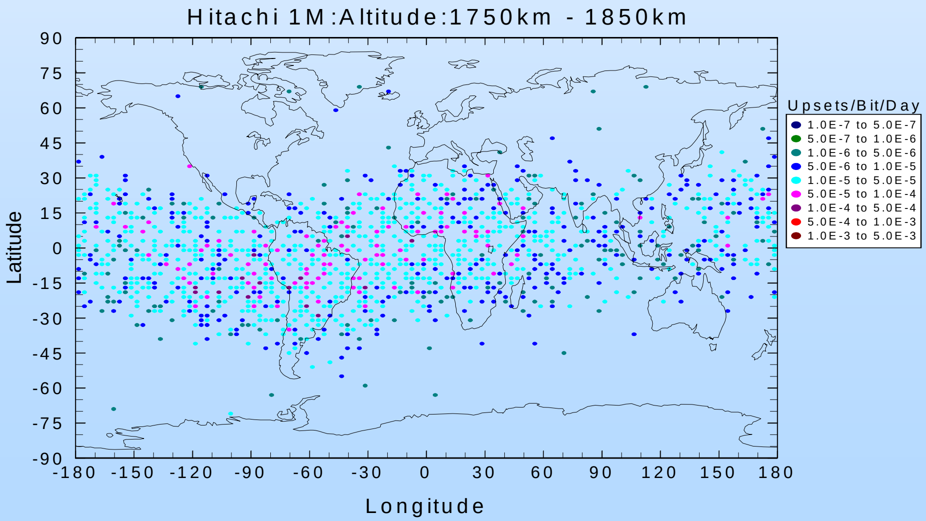
SAA and Trapped Protons:

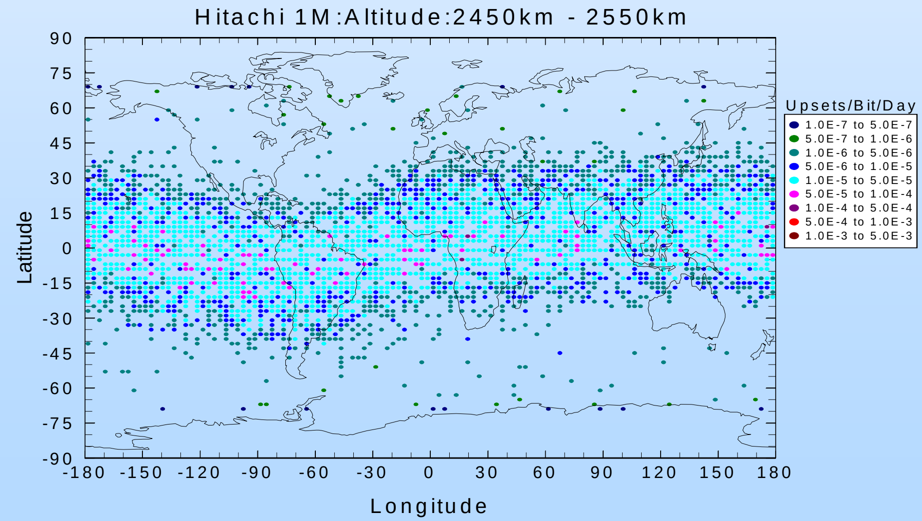
Effects of the Asymmetry in the Proton Belts on SRAM Upset Rate at Varying Altitudes on CRUX/APEX





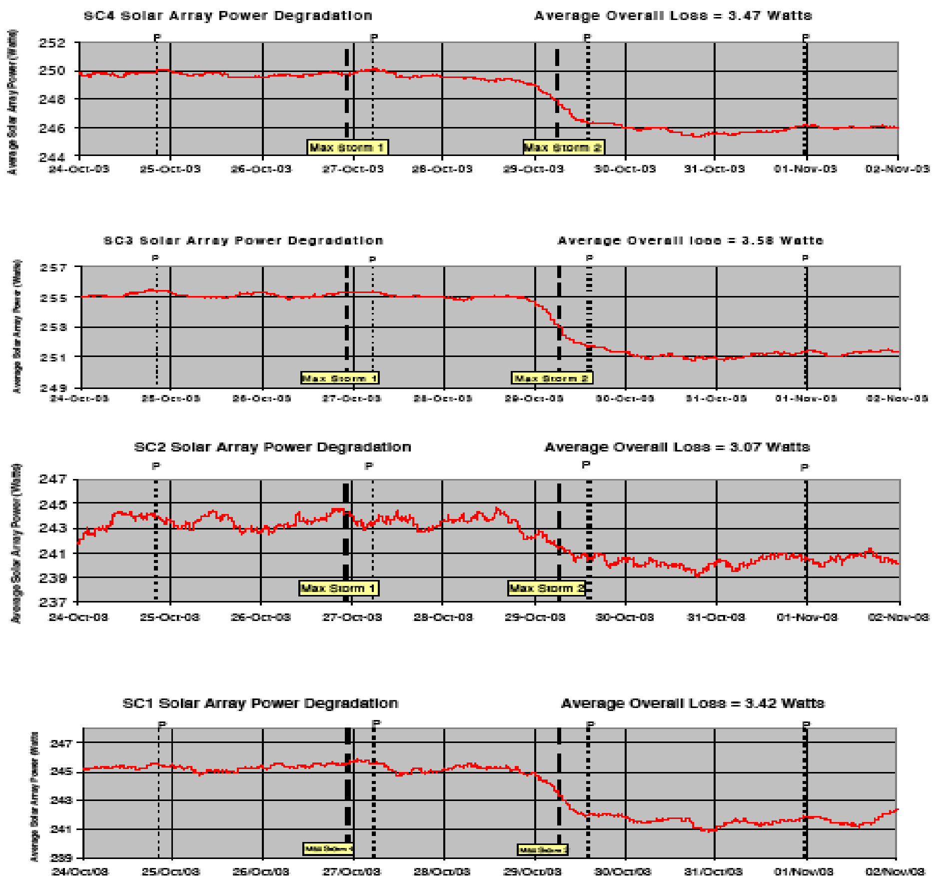
J. L. Barth, *et al.*, *IEEE TNS*, 1998.





Solar Event Effect - Solar Array Degradation on CLUSTER Spacecraft

ANNEX 1: Evolution of the Solar Array Power from 24-Oct to 02-Nov 2003 when two solar radiation storms occurred (the time of their maximum is indicated in the plot "---"). The degradation of the panels was about 1.4% and the average power loss is shown for each spacecraft.
The perigee passes are marked as "….." and labeled with "P"



Many other spacecraft to noted degradation as well.

Science Spacecraft Anomalies During Halloween 2003 Solar Events

Type of Event	Spacecraft/ Instrument	Notes
Spontaneous Processor Resets	RHESSI	3 events; all recoverable
	CLUSTER	Seen on some of 4 spacecraft; recoverable
	ChipSAT	S/C tumbled and required ground command to correct
High Bit Error Rates	GOES 9,10	
Magnetic Torquers Disabled	GOES 9, 10, 12	
Star Tracker Errors	MER	Excessive event counts
	MAP	Star Tracker Reset occurred
Read Errors	Stardust	Entered safe mode; recovered
Failure?	Midori-2	
Memory Errors	GENESIS	19 errors on 10/29
	Many	Increase in correctable error rates on solid-state recorders noted in many spacecraft

Science Instrument Anomalies During Halloween 2003 Solar Events

Type of Event	Spacecraft/ Instrument	Notes
Instrument Failure	GOES-8 XRS	Under investigation as to cause
	Mars Odyssey/Marie	Under investigation as to cause; power consumption increase noted; S/C also had a safehold event – memory errors
	NOAA-17/AMSU-A1	Lost scanner; under investigation
Excessive Count Rates	ACE, WIND	Plasma observations lost
	GALEX UV Detectors	Excess charge – turned off high voltages; Also Upset noted in instrument
	ACE	Solar Proton Detector saturated
Upset	Integral	Entered Safe mode
	POLAR/TIDE	Instrument reset spontaneously
Hot Pixels	SIRTF/IRAC	Increase in hot pixels on IR arrays; Proton heating also noted
Safe Mode	Many	Many instruments were placed in Safe mode prior to or during the solar events for protection

Selected Other Consequences

- **Orbits affected on several spacecraft**
- **Power system failure**
  - **Malmo, Sweden**
- **High Current in power transmission lines**
  - **Wisconsin and New York**
- **Communication noise increase**
- **FAA issued a radiation dose alert for planes flying over 25,000 ft**

A NASA-built radiation monitor that can aid anomaly resolution, lifetime degradation, protection alerts, etc.