Space Radiation Effects on Electronics:

Simple Concepts and New Challenges

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Outline

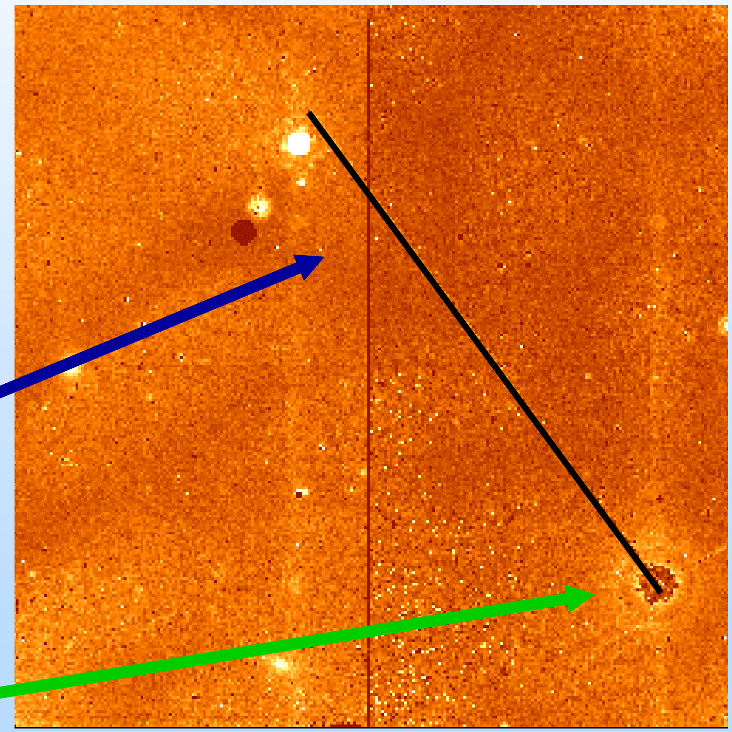
- **The Space Radiation Environment**
- **The Effects on Electronics**
- **The Environment in Action**
- **NASA Approaches to Commercial Electronics**
  - The Mission Mix
  - Flight Projects
  - Proactive Research
- **Final Thoughts**

Atomic Interactions

- Direct Ionization

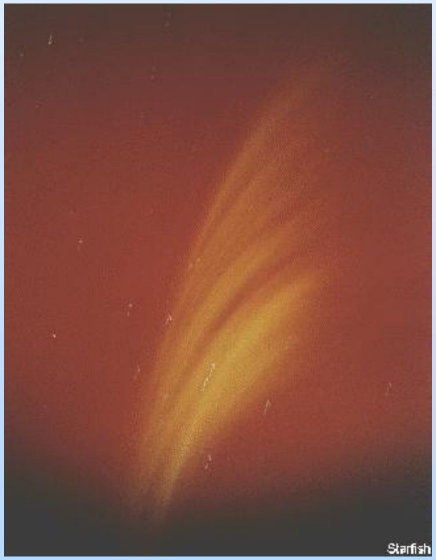
Interaction with Nucleus

- Indirect Ionization
- Nucleus is Displaced



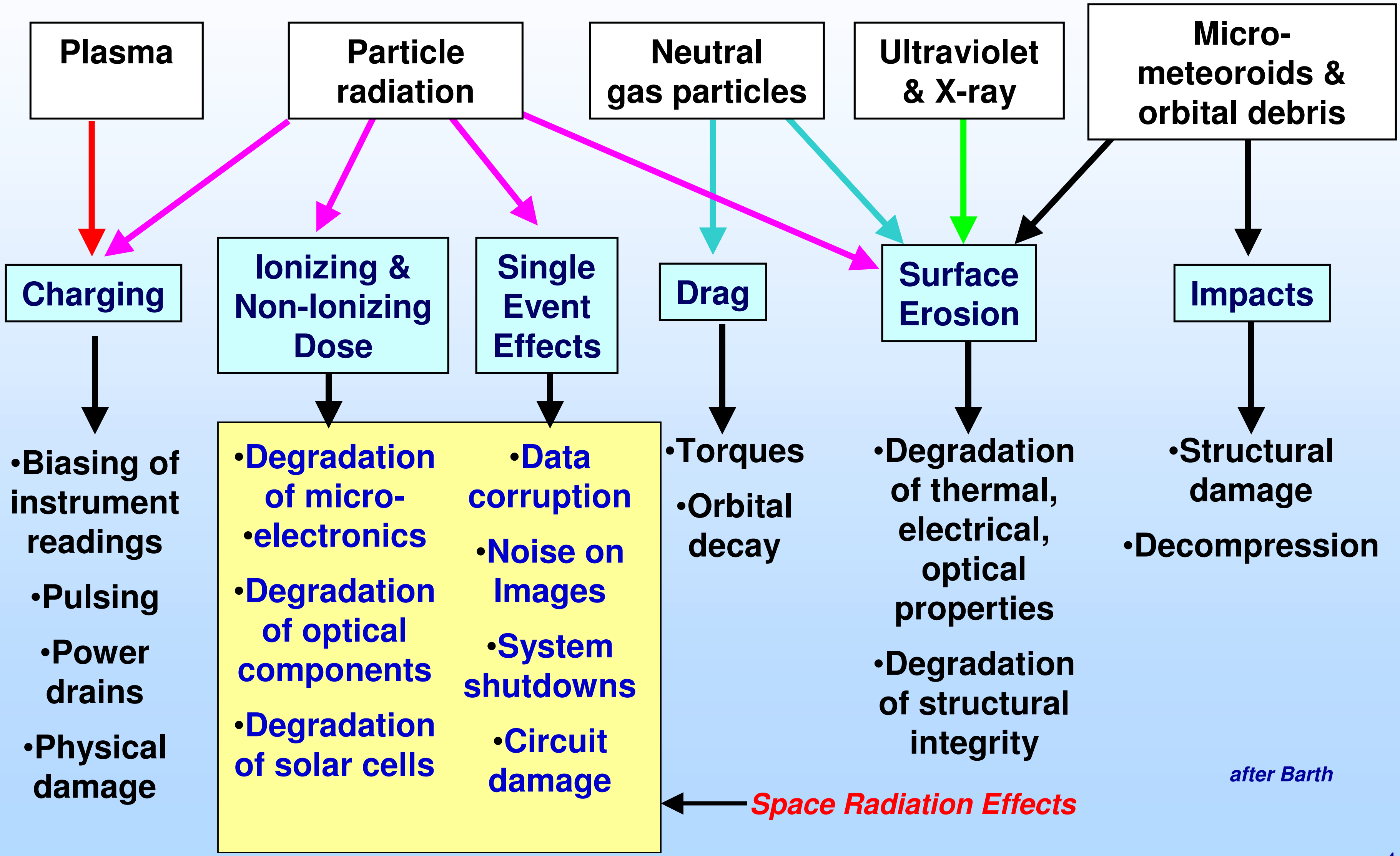
http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html

The Space Radiation Environment



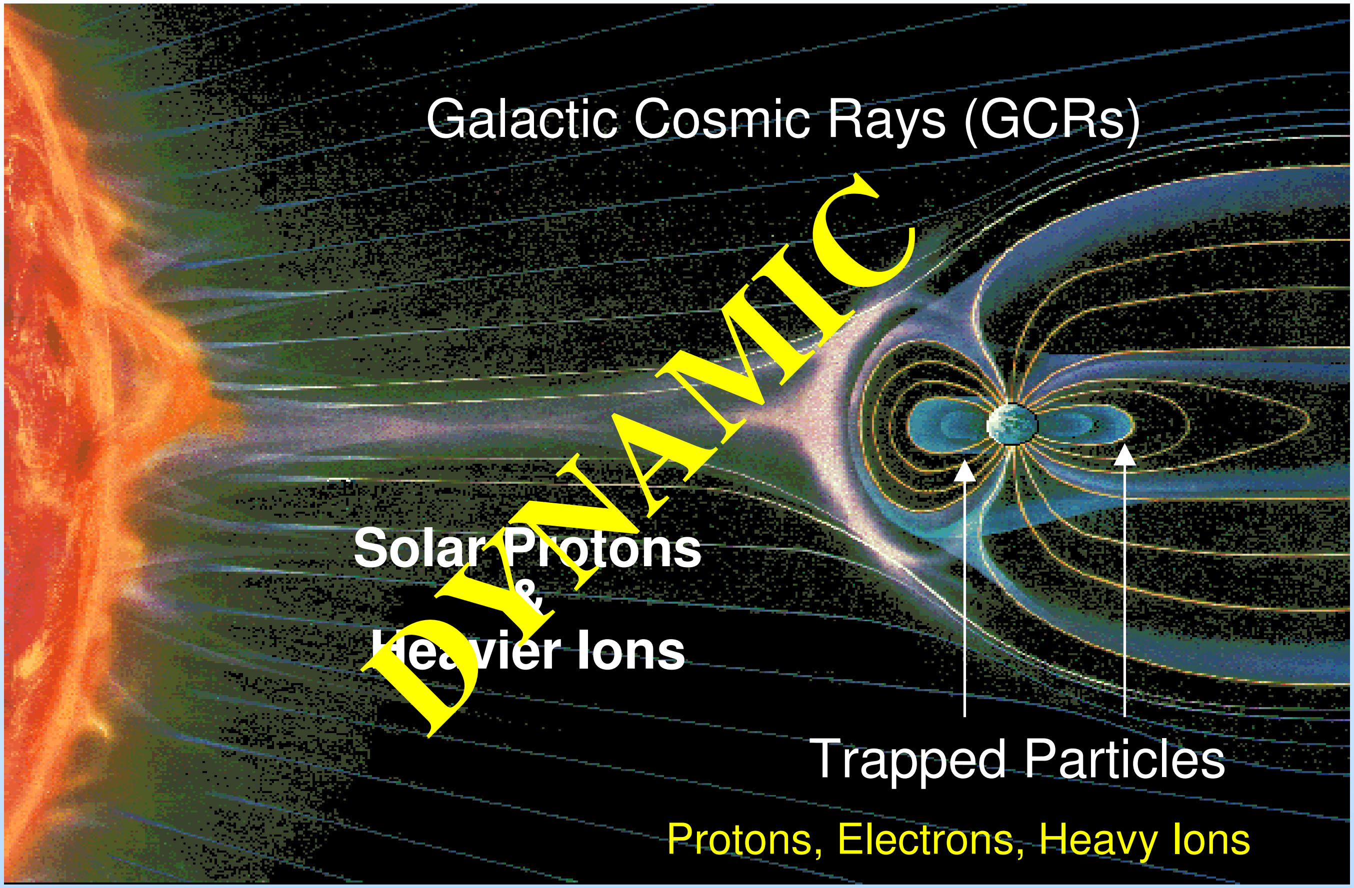
STARFISH detonation –
Nuclear attacks are not considered in this presentation

Space Environments and Related Effects



Space Radiation Environment

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

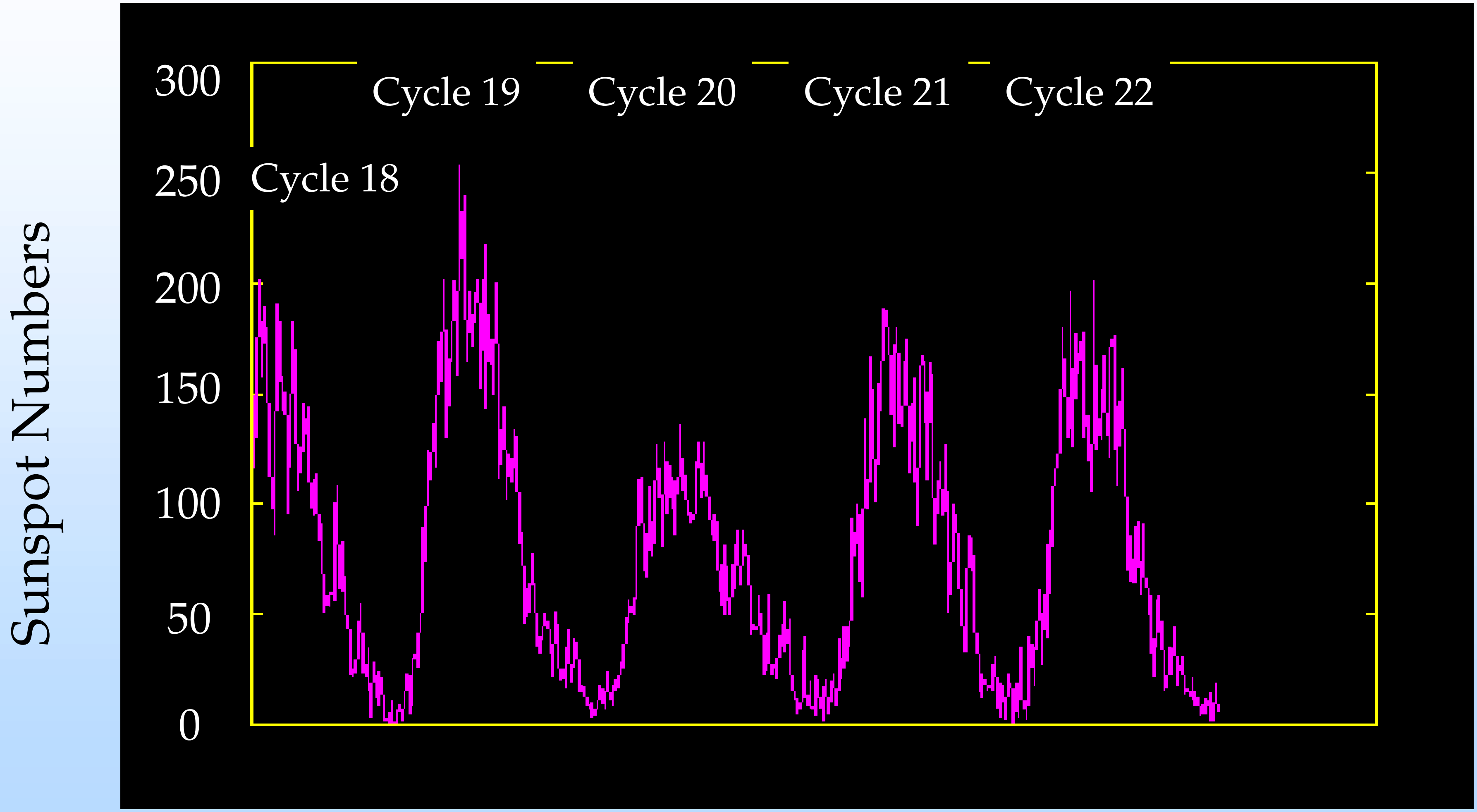


Deep-space missions may also see: neutrons from background or radioisotope thermal generators (RTGs) or other nuclear source

Atmosphere and terrestrial may see GCR and secondaries

Sunspot Cycle: An Indicator of the Solar Cycle

after Lund Observatory

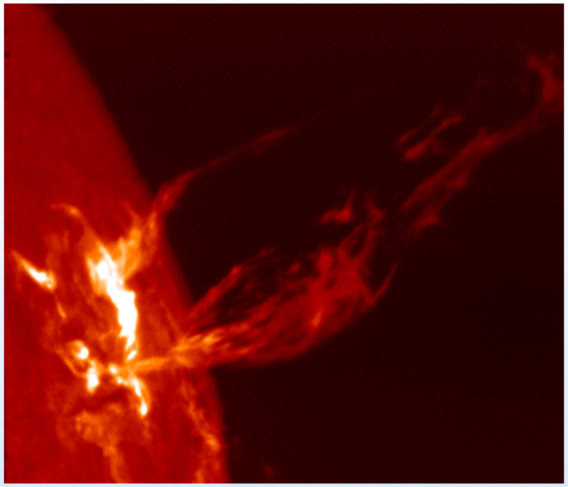


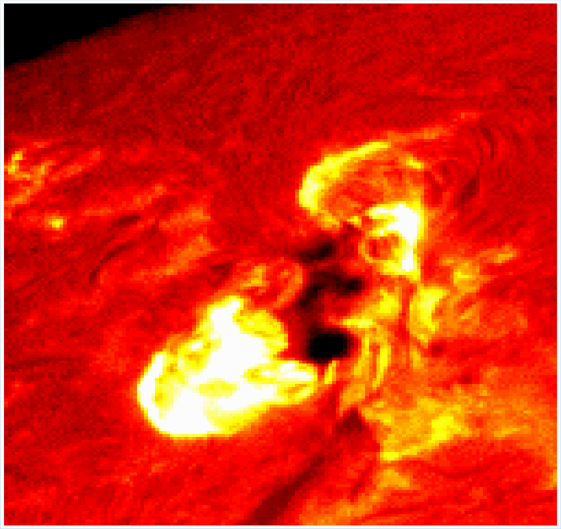
Length Varies from 9 - 13 Years
7 Years Solar Maximum, 4 Years Solar Minimum

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

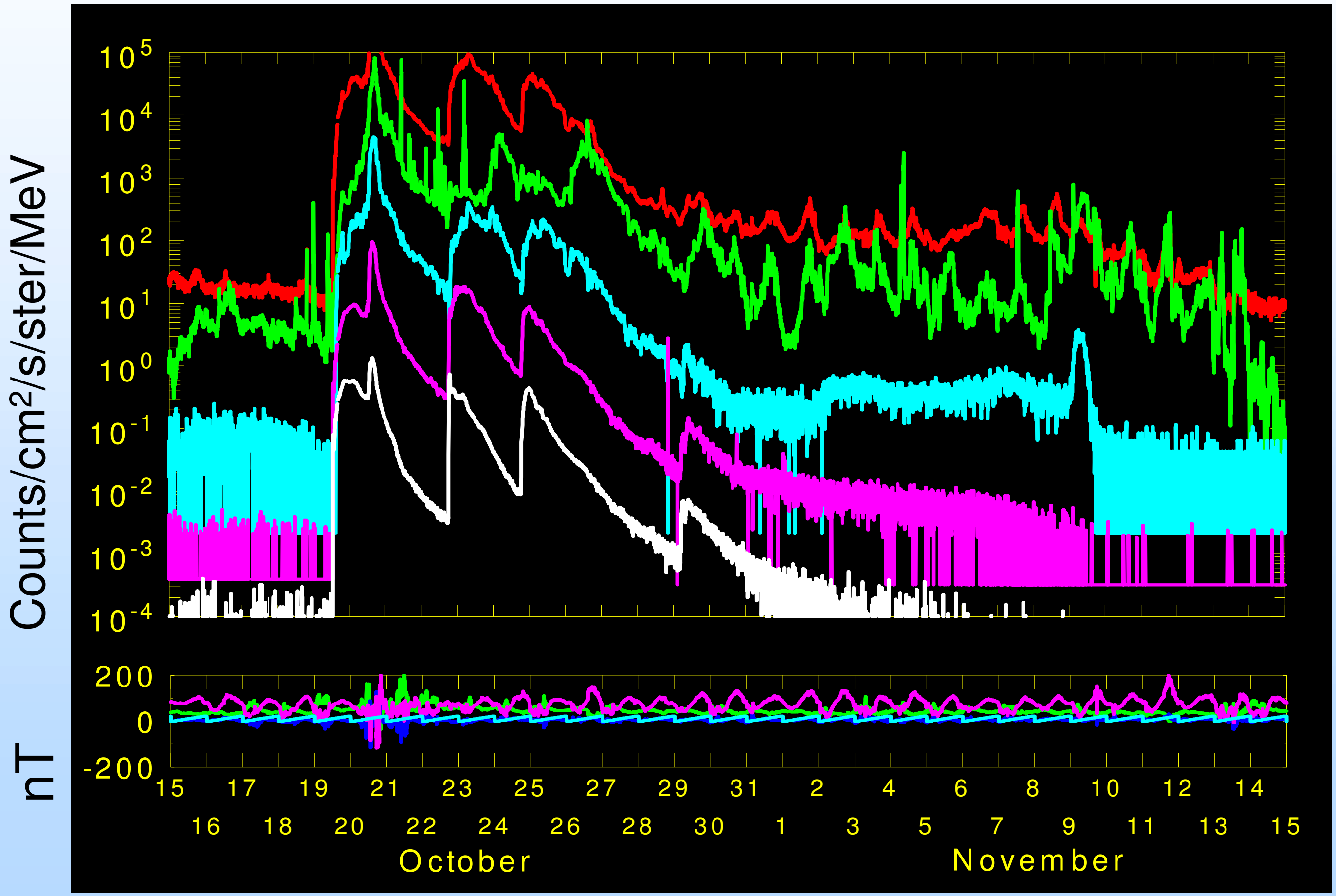
Holloman AFB/SOON





Solar Proton Event - October 1989

Proton Fluxes - 99% Worst Case Event

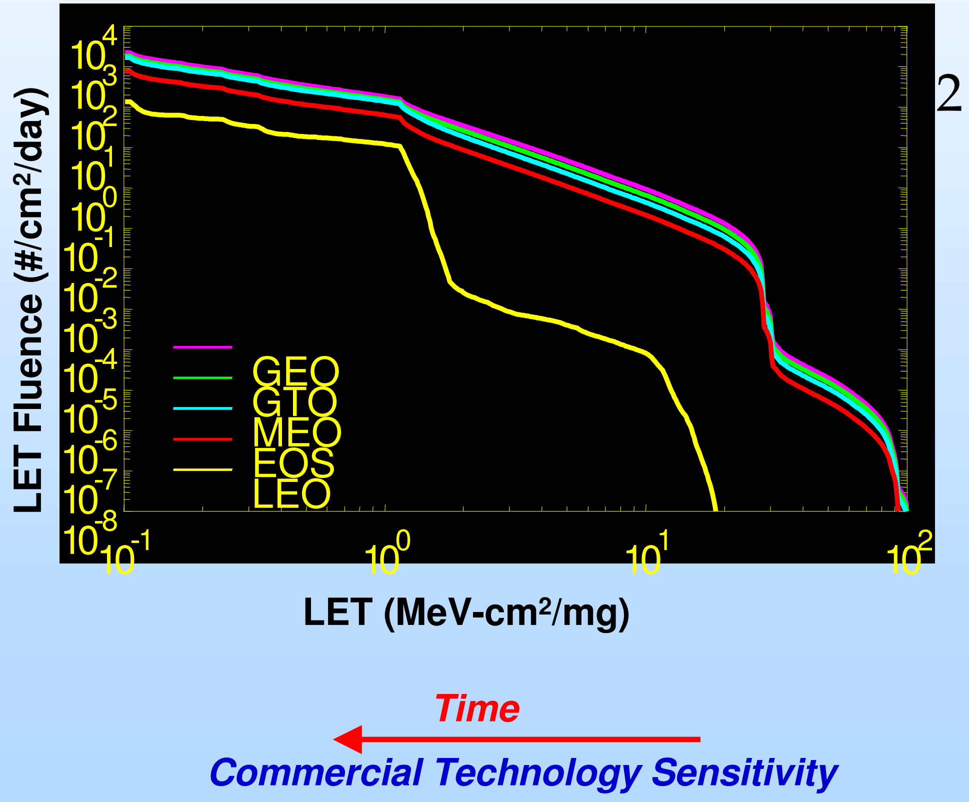


GOES Space Environment Monitor

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

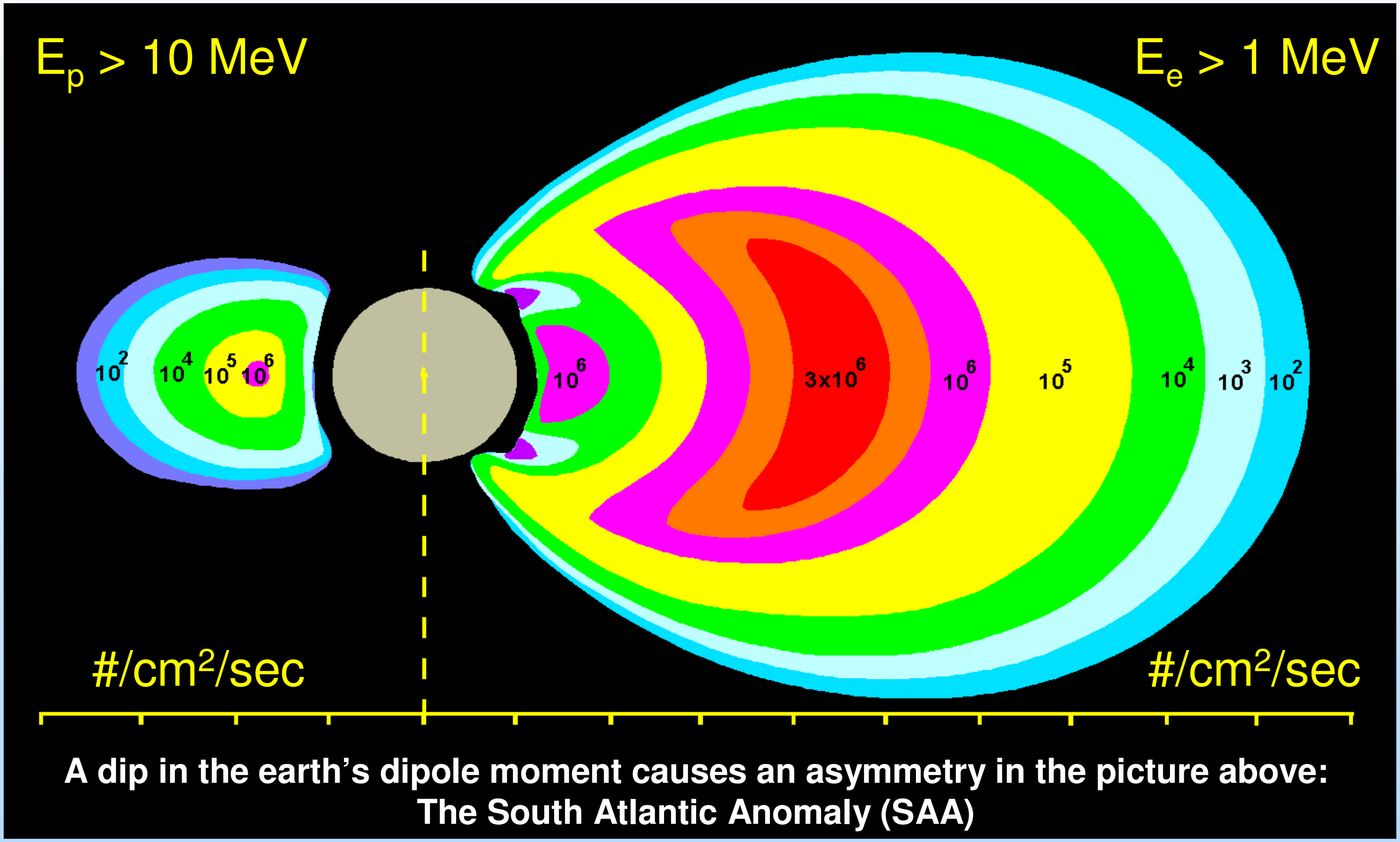
- **Definition**
  - **A GCR ion is a charged particle (H, He, Fe, etc)**
  - **Typically found in free space (galactic cosmic rays or GCRs)**
    - **Energies range from MeV to GeVs for particles of concern for SEE**
    - **Origin is unknown**
  - **Important attribute for impact on electronics is 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



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

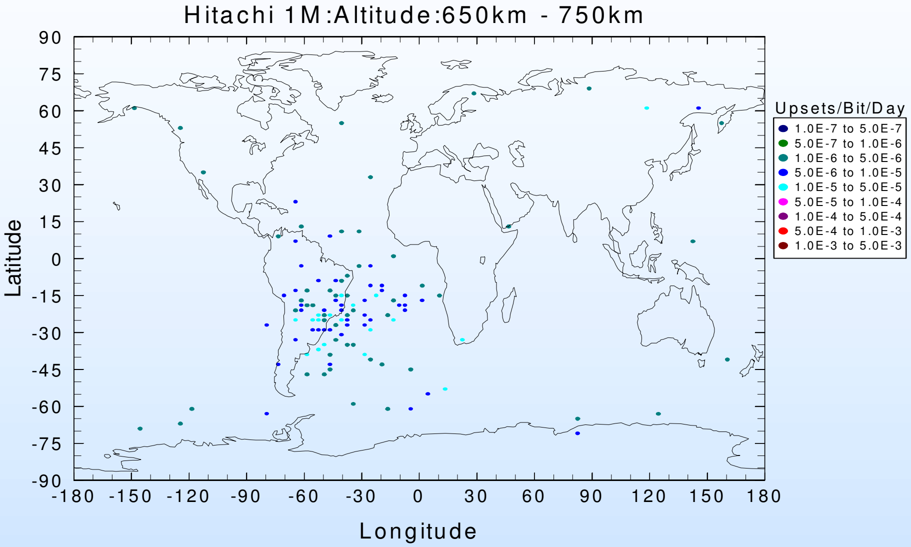
AP-8 Model AE-8 Model

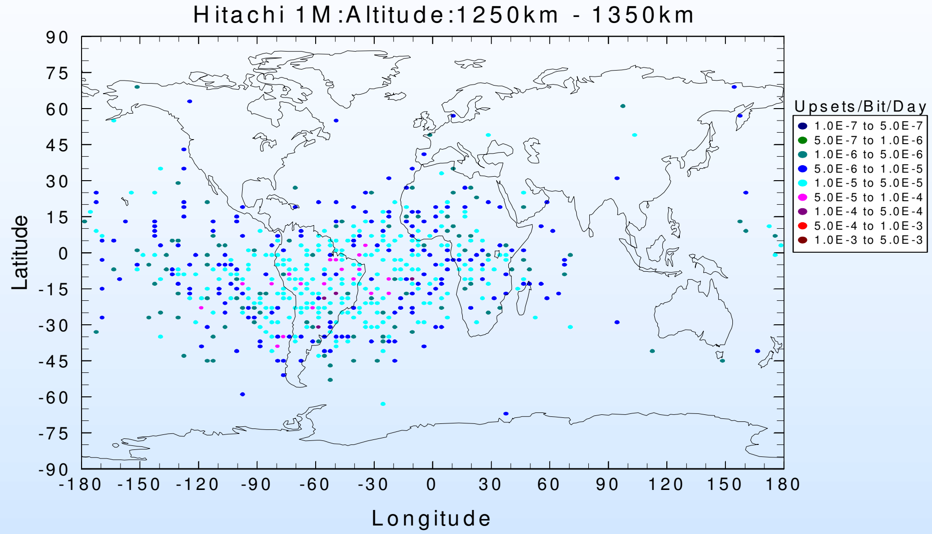


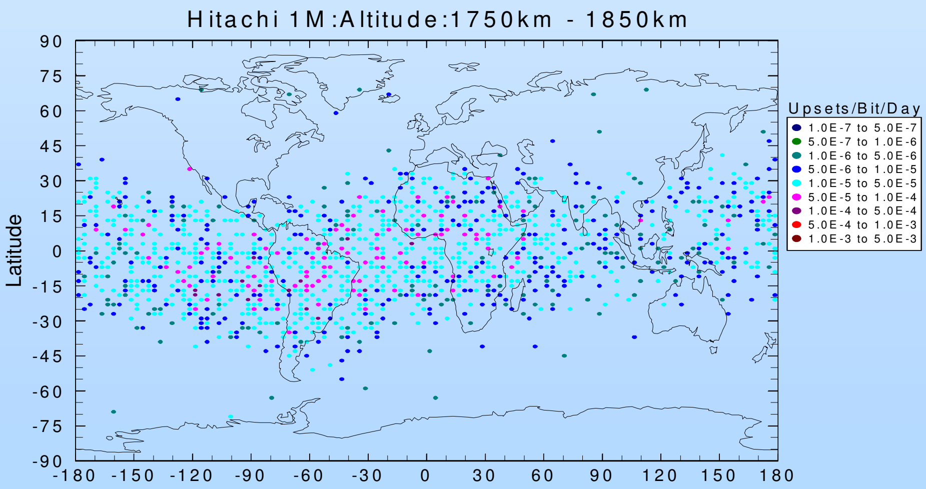
L-Shell

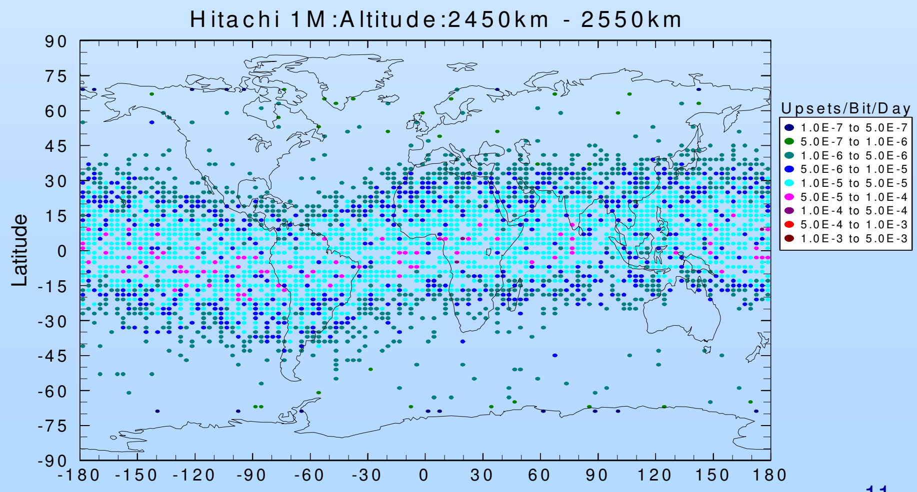
SAA and Trapped Protons:

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



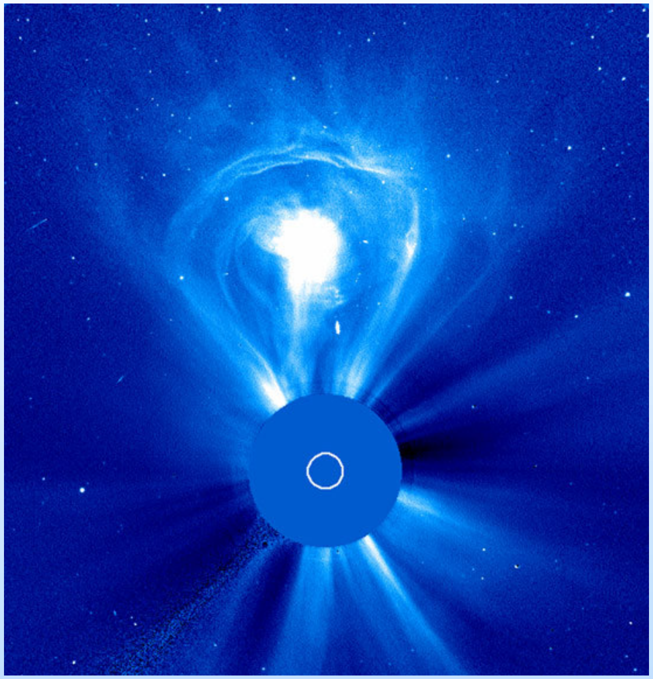






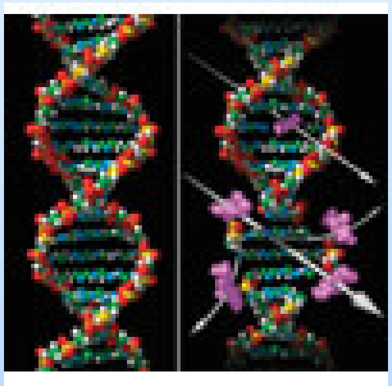
Solar Cycle Effects: Modulator and Source

- **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

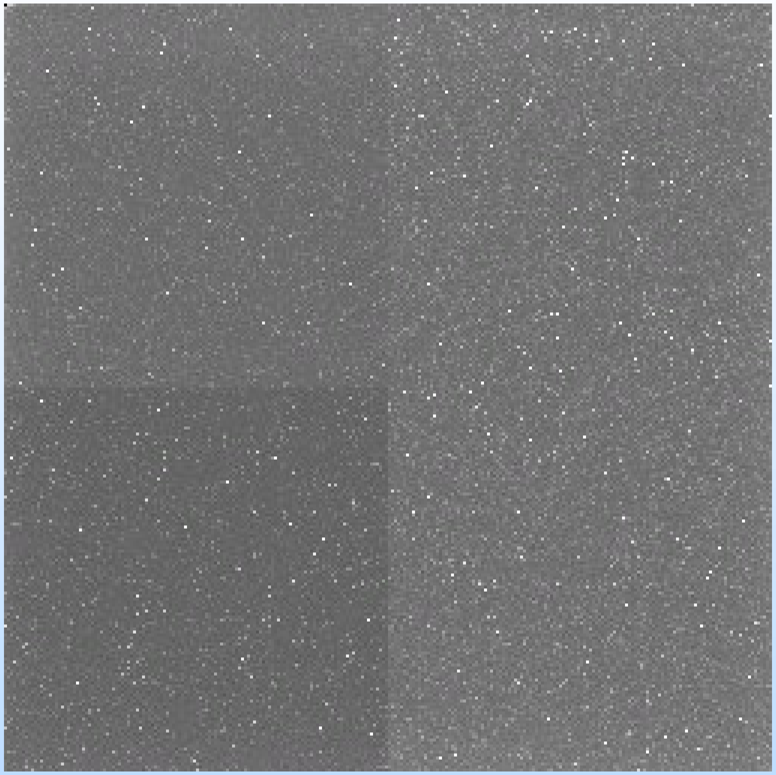
The Effects



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

Radiation Effects and Spacecraft

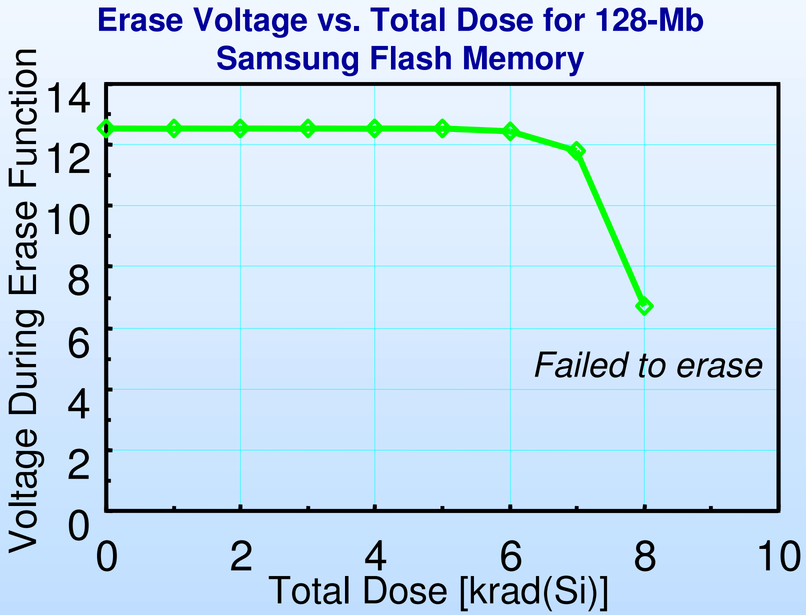
- **Critical areas for design in the natural space radiation environment**
  - **Long-term effects**
    - **Total ionizing dose (TID)**
    - **Displacement damage**
  - **Transient or single particle effects (Single event effects or SEE)**
    - **Soft or hard errors**
- **Mission requirements and philosophies vary to ensure mission performance**
  - ***What works for a shuttle mission may not apply to a deep-space mission***



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
- Effects
  - Threshold Shifts
  - Leakage Current
  - Timing Changes
  - Functional Failures
- Unit of interest is krads(material)
- Can *partially* mitigate with shielding
  - Low energy protons
  - Electrons
- Typical ground testing performed with Co-60 or X-ray sources



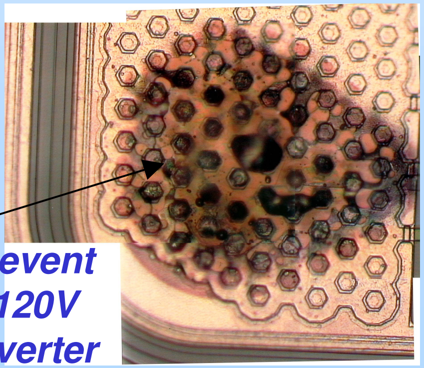
Displacement Damage (DD)

- **Cumulative long term *non-ionizing* damage due to protons, electrons, and neutrons**
- **Effects**
  - **Production of defects which results in device degradation**
  - **May be similar to TID effects**
  - **Optocouplers, solar cells, CCDs, linear bipolar devices**
- **Unit of interest is particle fluence for each energy mapped to test energy**
  - **Non-ionizing energy loss (NIEL) is one means of discussing**
- **Shielding has some effect - depends on location of device**
  - **Reduce significant electron and some proton damage**
- **Typical ground testing performed with protons or neutrons**

Not particularly applicable to CMOS microelectronics

Single Event Effects (SEEs)

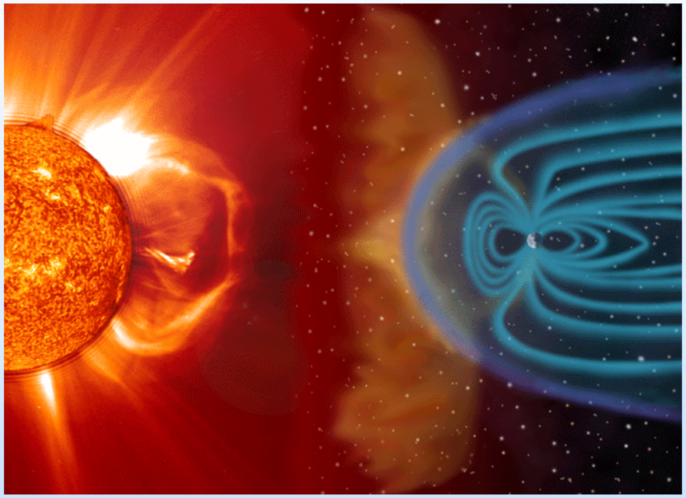
- **An SEE is caused by a *single charged particle* as it passes through a semiconductor material**
  - **Heavy ions**
    - **Direct ionization**
  - **Protons for sensitive devices**
    - **Nuclear reactions for standard devices**
- **Effects on electronics**
  - **If the LET of the particle (or reaction) 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**
- **Typical ground testing performed at:**
  - **Cyclotron or accelerator**



Destructive event in a COTS 120V DC-DC Converter

Radiation Effects on Electronics and the Space Environment

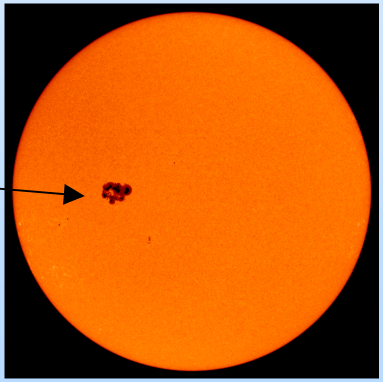
- **Three portions of the natural space environment contribute to the radiation hazard**
  - **Solar particles**
    - **Protons and heavier ions**
      - **SEE, TID, DD**
  - **Free-space particles**
    - **GCR**
      - **For earth-orbiting craft, the earth's magnetic field provides some protection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



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

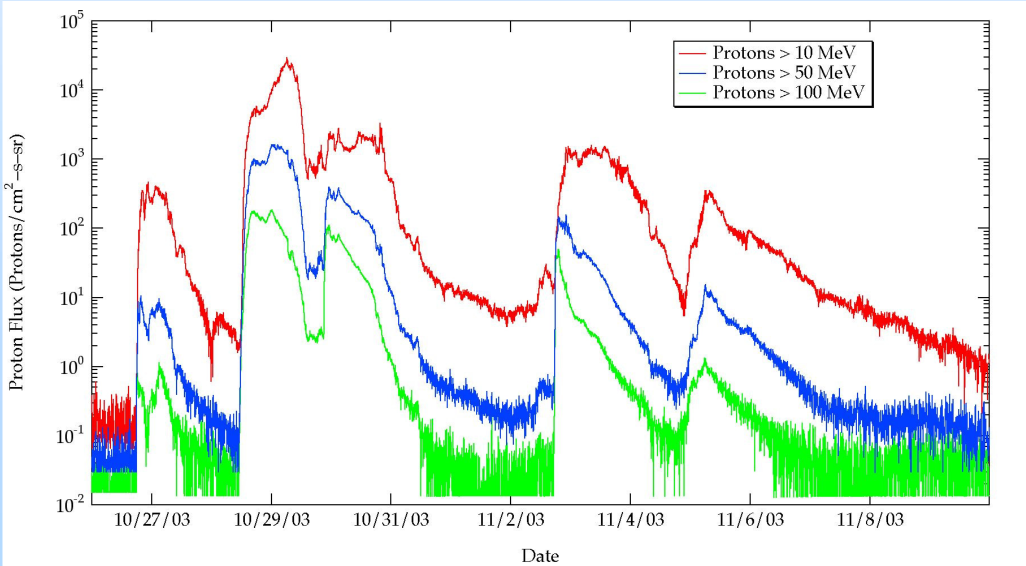
The Environment in Action

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

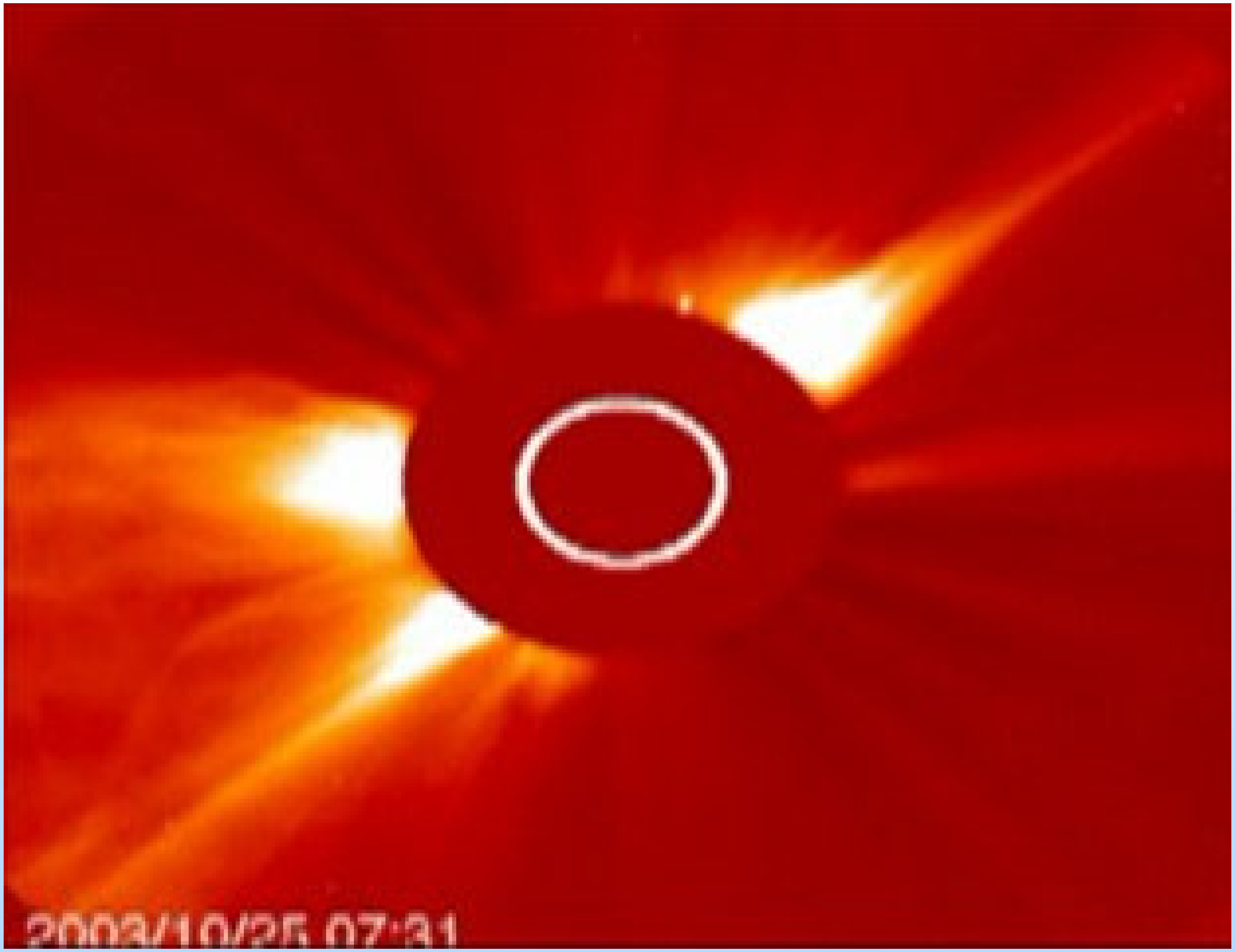


Recent Solar Events – A Few Notes and Implications

- In Oct-Nov of this year, a series of X-class (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…

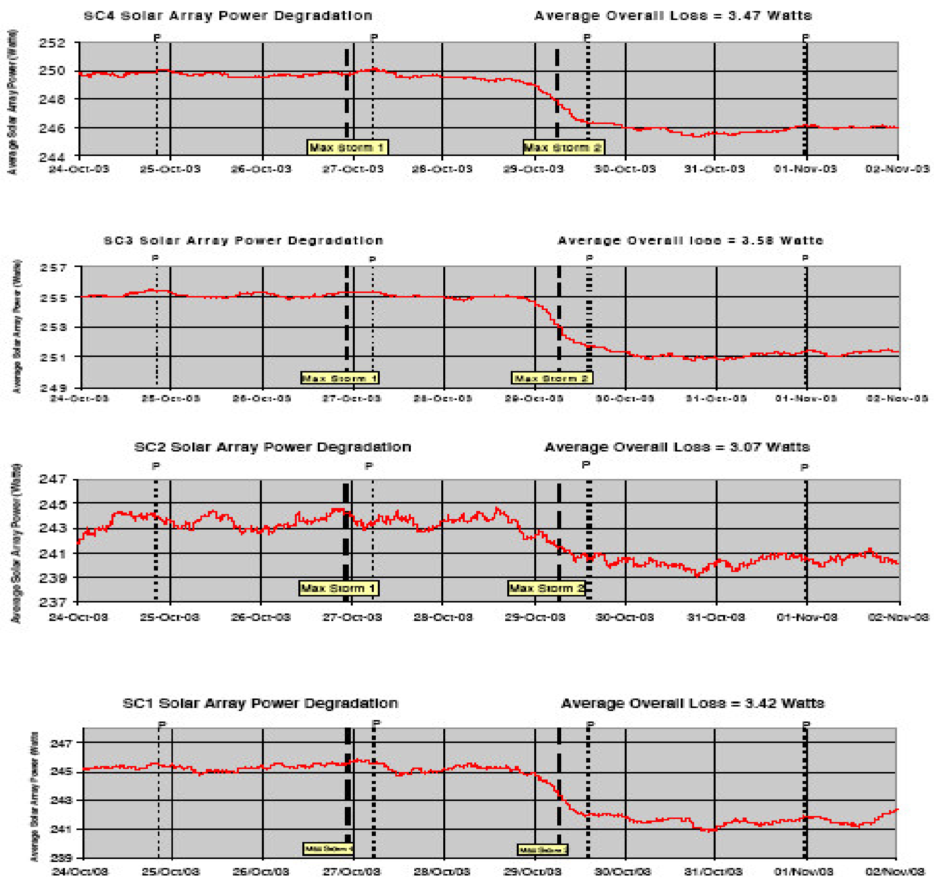


SOHO LASCO C2 of the Solar Event



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 Recent 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 Recent 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**

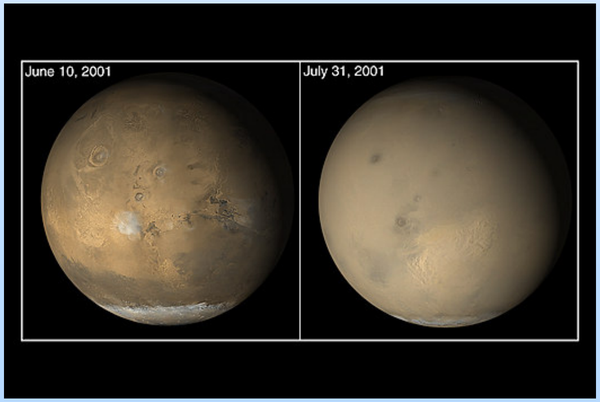
A NASA-built radiation monitor that can aid anomaly resolution, lifetime degradation, protection alerts, etc.

NASA Approaches to Electronics: *Flight Projects and Proactive Research*

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

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

Implications of NASA Mix

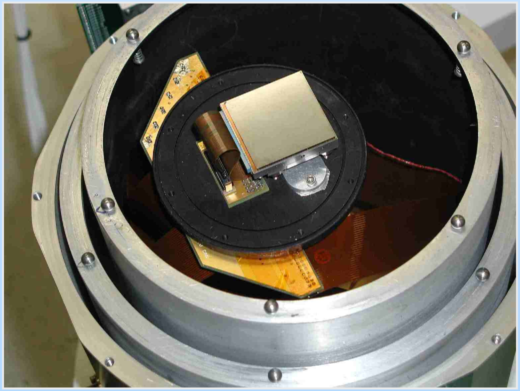
- **Prior to the new Presidential "Moon-Mars" vision**
  - **>90% of NASA missions required 100 krad(Si) or less for device total ionizing dose (TID) tolerance**
    - **Single Event Effects (SEEs) were prime driver**
      - **Sensor hardness also a limiting factor**
    - **Many missions could accept risk of anomalies as long as recoverable over time**
- **Implications of the new vision are still TBD for radiation and reliability specifics, however,**
  - **Nuclear power/propulsion changes radiation issues (TID and displacement damage)**
  - **Long-duration missions such as permanent stations on the moon require long-life high-reliability for infrastructure**
    - **Human presence requires conservative approaches to reliability**
      - ***Drives stricter radiation tolerance requirements and fault tolerant architectures***

Lunar footprint
Courtesy of NASA archives

NASA Approach to RHA

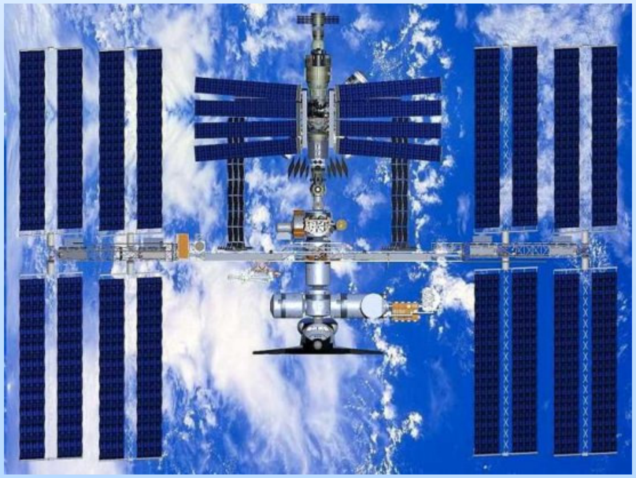
- **With commercial technology sensitivity to SEU increasing and limited radiation hardened offerings, a dual approach to RHA needs to be installed**
  - **A systems approach at the flight mission level, and**
  - **Proactive investigation into new technologies**

Rockwell/Hawaii 2048x2048
5µm HgCdTe NGST FPA (ARC)



Candidate James Webb Space Telescope (JWST) IR array preparing for rad tests. The ultra-low noise requirement of JWST is the driver.

A Systematic Approach to Flight Project Radiation Hardness Assurance (RHA)

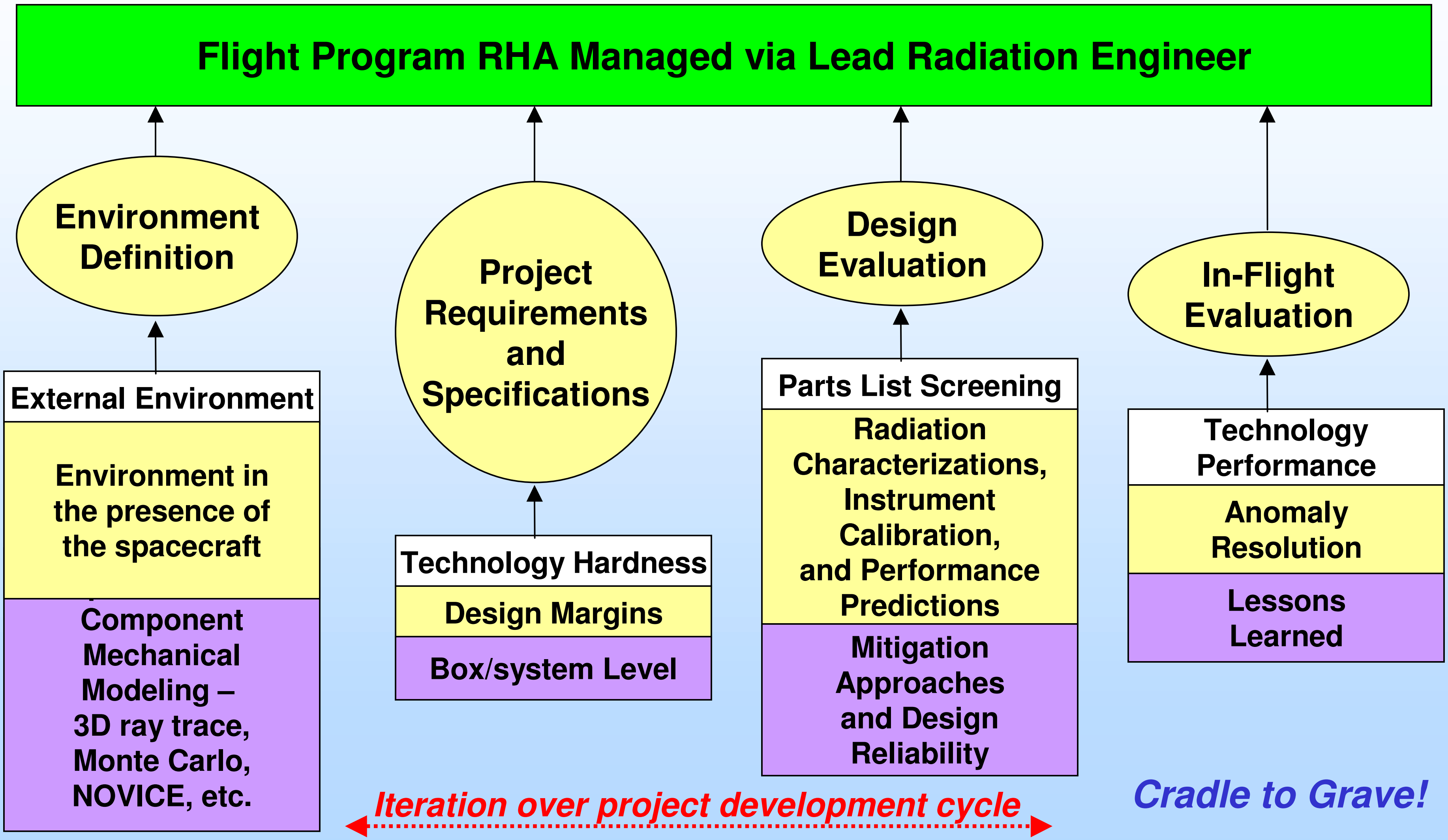


Size, complexity, and human presence are among the factors im deciding how RHA is to be implemented

Sensible Programmatics for Flight RHA:
A Two-Pronged Approach for Missions

- Assign a lead radiation engineer to each spaceflight project
  - Treat radiation like other engineering disciplines
    - Parts, thermal,...
  - Provides a single point of contact for all radiation issues
    - Environment, parts evaluation, testing,…
- Each program follows a systematic approach to RHA
  - RHA active early in program reduces cost in the long run
    - Issues discovered late in programs can be expensive and stressful
      - What is the cost of reworking a flight board if a device has RHA issues?

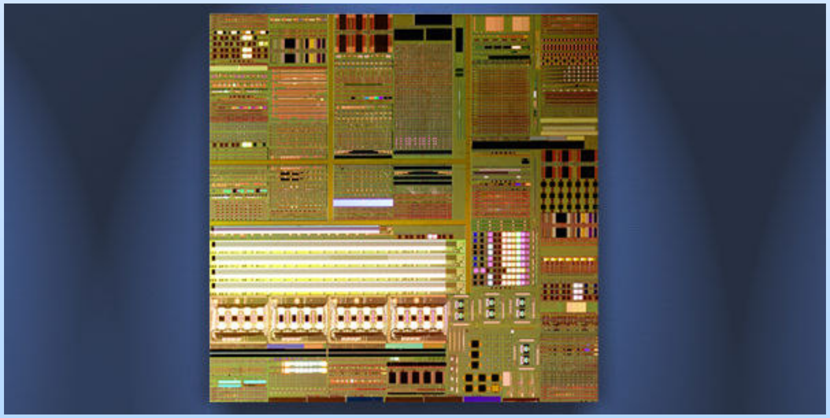
Flight Program Radiation Hardness Assurance (RHA) Flow



Radiation and Systems Engineering: A Rational Approach for Space Systems

- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
  - Define criticality factors
- **Evaluate Design/Components**
  - Existing data/Testing/Performance characteristics
- **"Engineer" with Designers**
  - Parts replacement/Mitigation schemes
- **Iterate Process**
  - Review parts list based on updated knowledge

Approach to Insertion of New Electronics

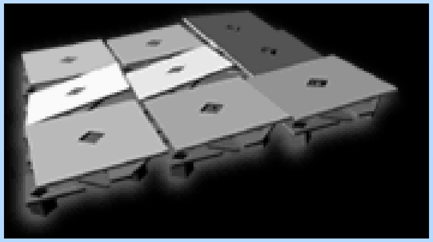


IBM CMOS 8SF ASIC

Microelectronics: Categories

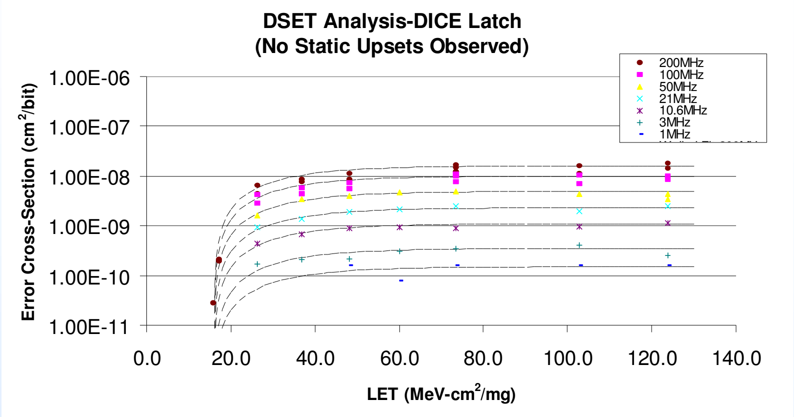
- Microelectronics can be split several ways
  – Digital, analog, mixed signal, other
  – Complementary Metal Oxide Semiconductor (CMOS), Bipolar, etc...
  – Function (microprocessor, memory, …)
- There are only two commercial foundries (where they build devices) in the US dedicated to building radiation hardened digital devices
  – Efforts within DoD to provide alternate means of developing hardened devices
    - Hardened-by-design (HBD)
    - Provides path for custom devices, but not necessarily off-the-shelf devices
  – Commercial devices can have great variance in radiation tolerance from device-to-device and even on multiple samples of same device
    - No guarantees!
  – Analog foundry situation is even worse
- New technologies have many unknowns
  – Ultra-high speed, nanotechnologies, microelectromechanical systems (MEMS and the optical versions – MOEMS), …

A MOEMS in action

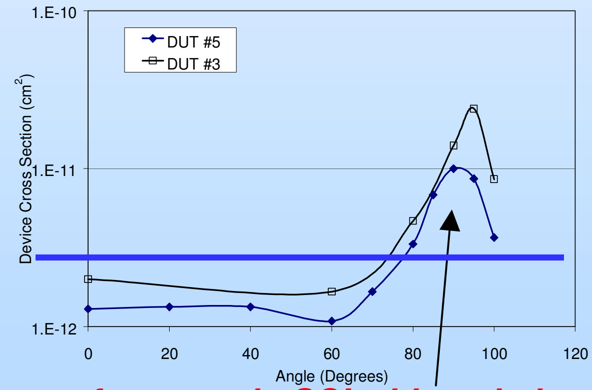


The Digital Logic Trends

- **Standard CMOS**
  - **Feature sizes are scaling (shrinking) to sub-0.1 micron sizes**
    - **Faster devices, lower operating voltages**
      - **Reduced electrical margins within devices**
  - **New dielectrics are being used**
  - **Thickness of gate oxide is being diminished**
  - **Implications (general)**
    - **Improved TID tolerance**
      - **DD not an issue (except possibly at nuclear levels)**
    - **Improved SEL tolerance**
    - **Increased SEU sensitivity**
      - **Technology speed increase drives this issue (SETs in logic propagate)**
    - **Unknown effect of other technology changes**
  - **Increased use of silicon-on-insulator (SOI) substrates**

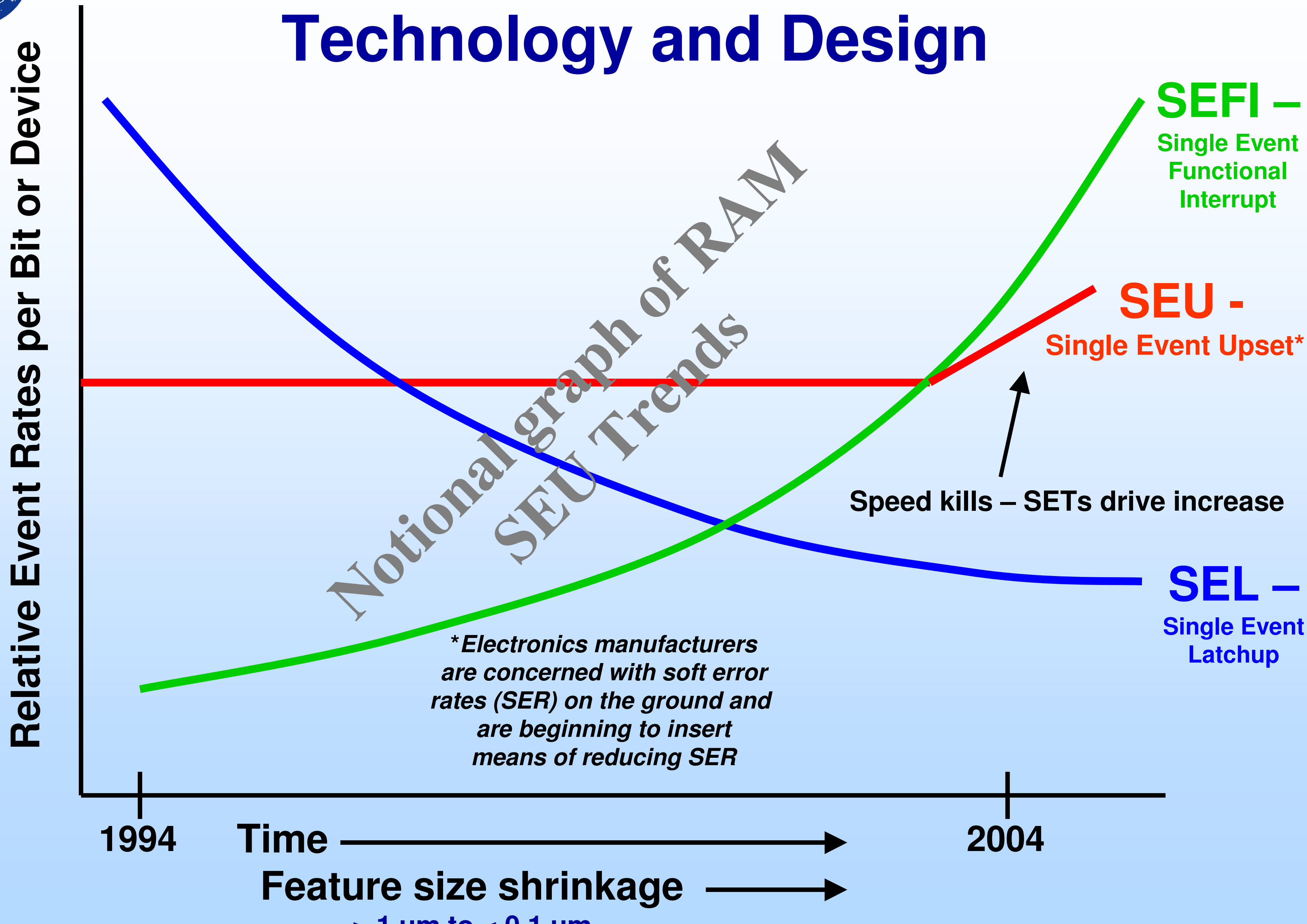


Higher speed digital operation can defeat Radiation Hardening techniques after Benedetto, 2004



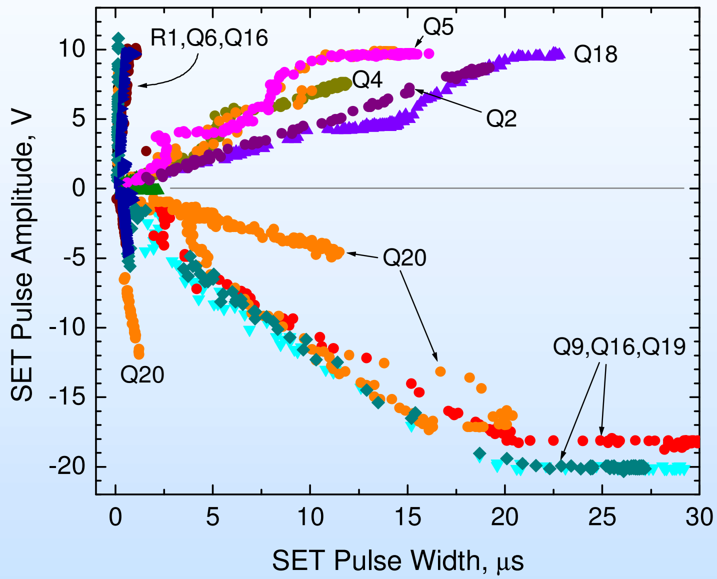
Effects of protons in SOI with varied angular direction of the particle;
Blue line represents expected response with "standard" CMOS devices.
after Reed 2002

The New Challenge: Changes in CMOS Technology and Design



Analog/mixed signal

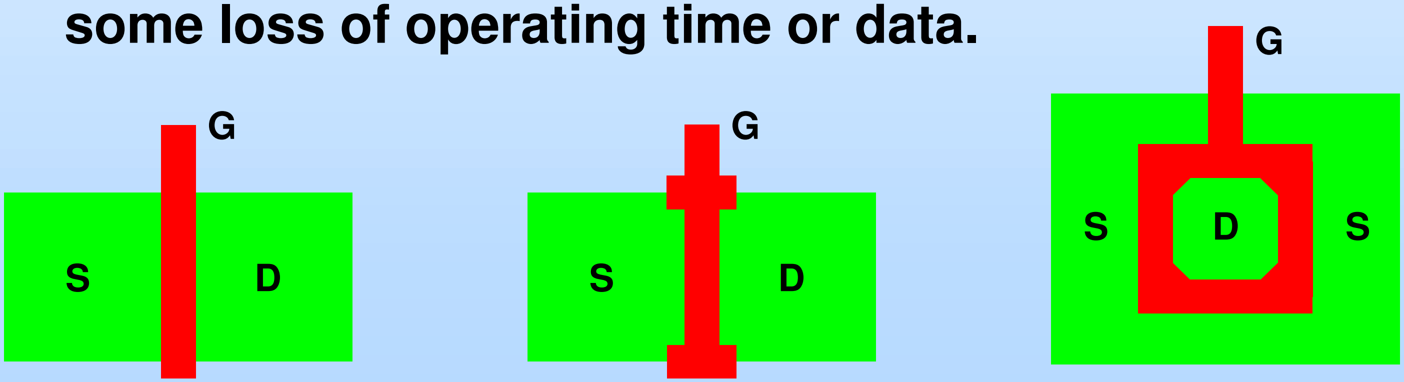
- **Not scaled as aggressively (need higher voltages to get analog range)**
  - **Efforts to improve electrical performance have reduced reliability and signal margins within the device**
  - **Increased sensitivity to**
    - **SETs (noise propagation that can be invasive to operations)**
      - **The higher the resolution or speed, the worse this becomes**
    - **TID and DD**
      - **Commercial device failure noted as low as 1 krad(Si)**
        - » **Even short duration missions would have concerns without test data**



LASER SEU tests on a LM124 Op Amp. Note the variety of transients generated depending on particle arrival point and circuit application

Efforts to "Harden" Commercial Microelectronics

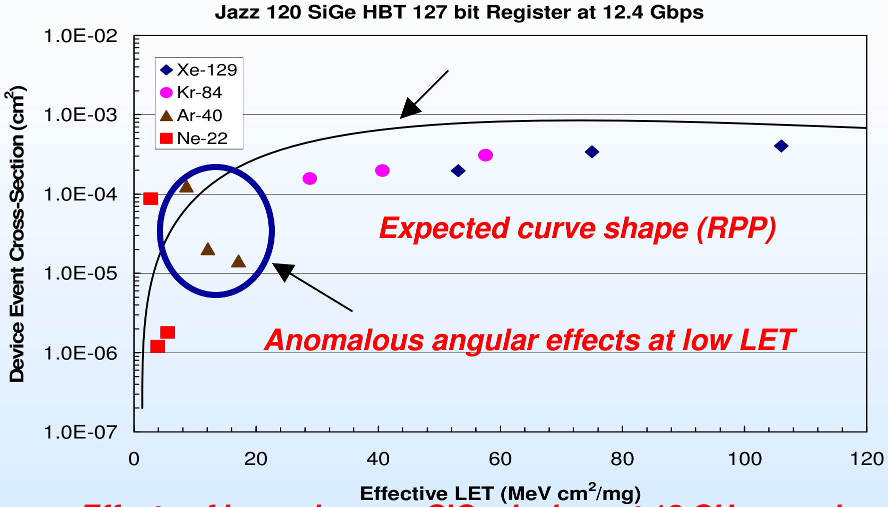
- **With limited radiation hardened by process (RHBP) foundries available, many organizations are seeking alternate approaches:**
  - **Radiation-hardened by design (RHBD) – using non-invasive circuit techniques to utilize commercial foundries to build hardened circuits, and**
  - **Radiation-tolerant system architectures – building a system that can detect and recover from errors with some loss of operating time or data.**



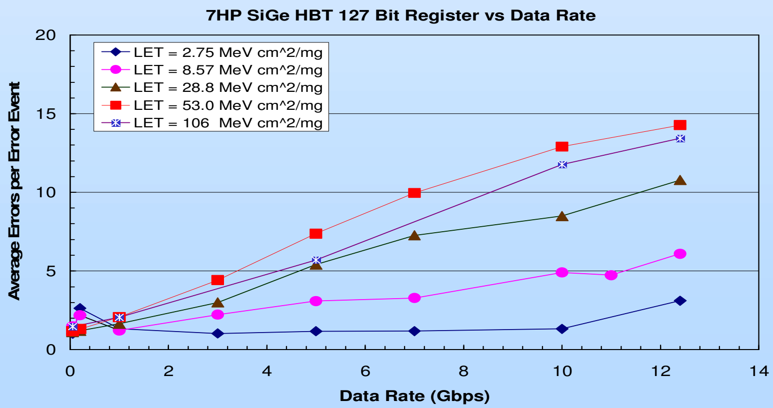
Conventional **Dog Bone** **Annular**

New Technologies – Sample Issues

- **Ultra-high speed**
  - Devices that may be relatively tolerant at low-speed (<100 MHz) have vastly increased SEU sensitivity at high-speeds (>1 GHz)
    - Speed can defeat HBD methods
    - New technologies don't fit old models
- **Sensors**
  - Noise, damage, etc. can limit device performance (such as an imager) and lifetime
    - Small effort at DoD to provide hardened solutions
- **MEMS**
  - Combined effects of electrical, optical, and mechanical degradation
- **Nanotechnologies**
  - A great unknown for radiation effects and protection



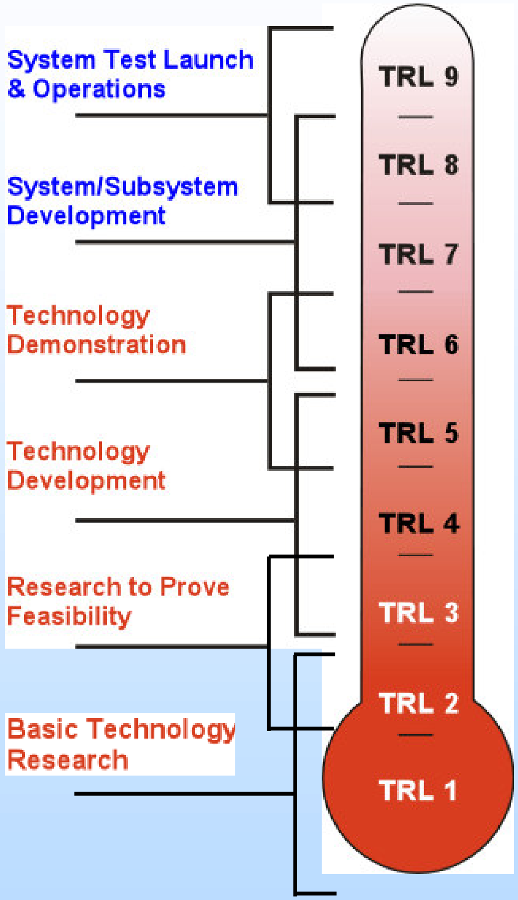
Effects of heavy ions on SiGe devices at 12 GHz speeds; Drawn line represents expected response with "standard" models.



Timescales of individual single particle events may impact multiple clock cycles within a device

Insertion of New Technologies – A Mission Perspective

- NASA mission timeframes rarely allow for a technology development path
  - For a 2008 launch, for example, technology freeze dates are likely 2005 or earlier
    - Technology must be moderately mature when a mission is being developed
      - *There may be time to qualify a device, but there may not be time to develop/validate a new technology solution!*
    - Risk versus performance reward for using less mature or commercial off-the-shelf (COTS) technologies
- Technology development and evaluation programs need to be in place prior to mission design
  - *Strategic planning*

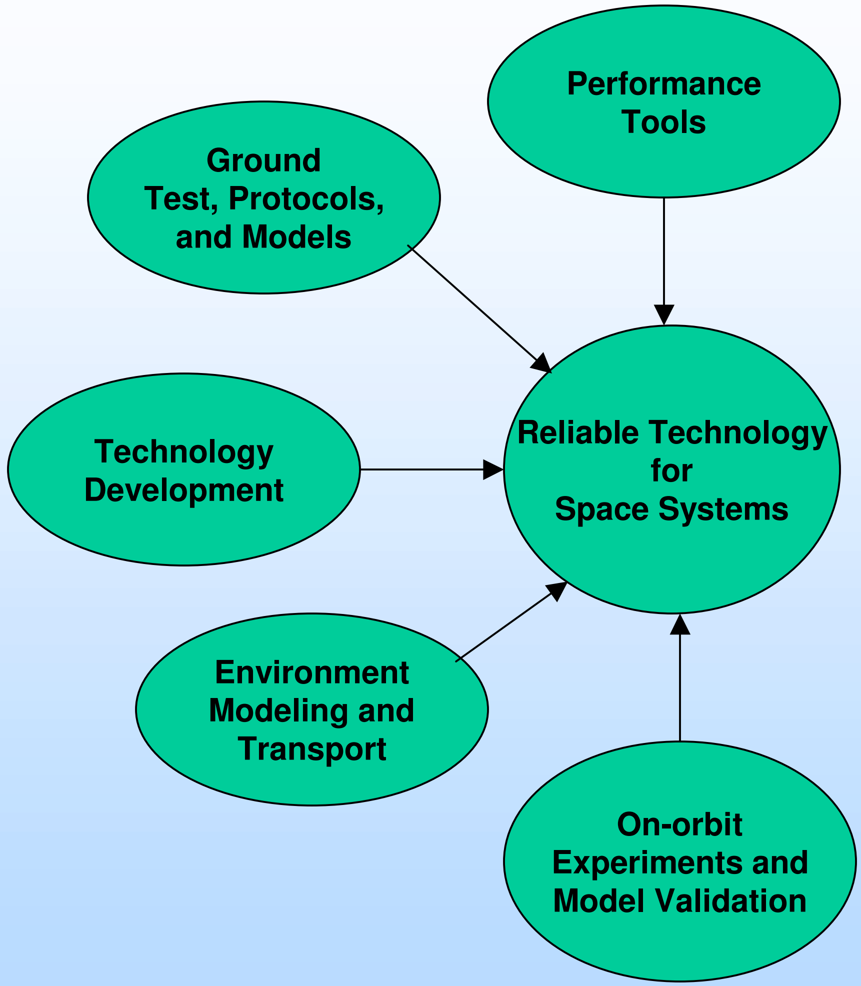


NASA Technology Readiness Levels (TRLs)

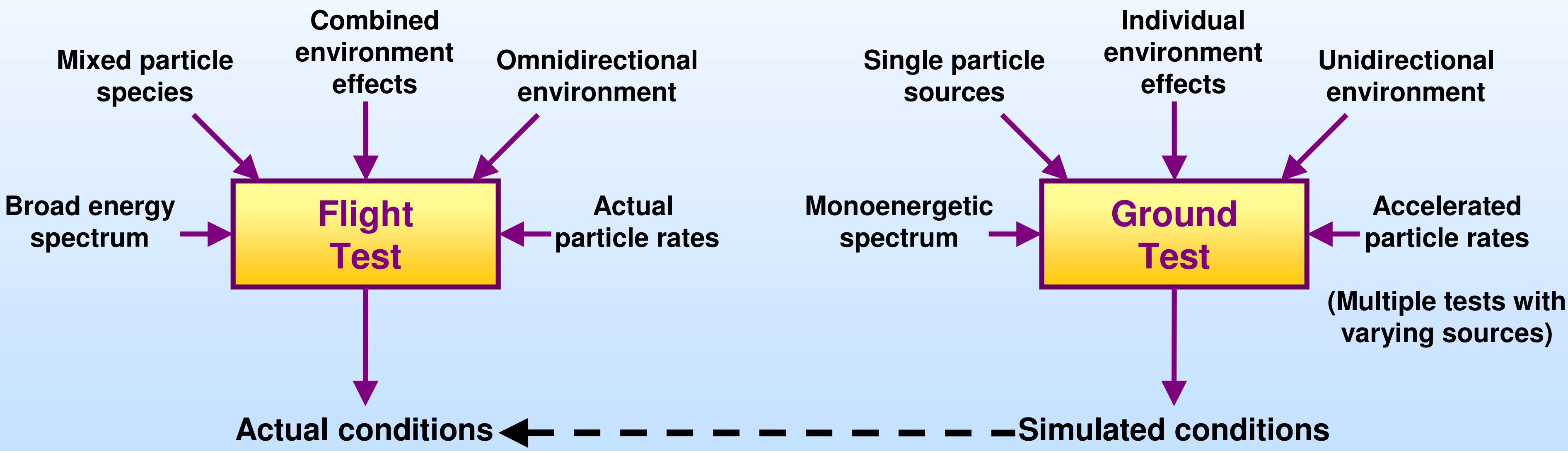
Insertion of New Technologies

An Approach

- Develop knowledge-base of existing technology information
- Determine reliability/radiation gaps
- Performance ground-based tests
  - May be sufficient to "qualify" for a specific mission, but not generically for all
- Develop technology-specific models/test protocols
  - Performance Predictions
- Validate models with flight data
  - Requires in-situ environment monitoring

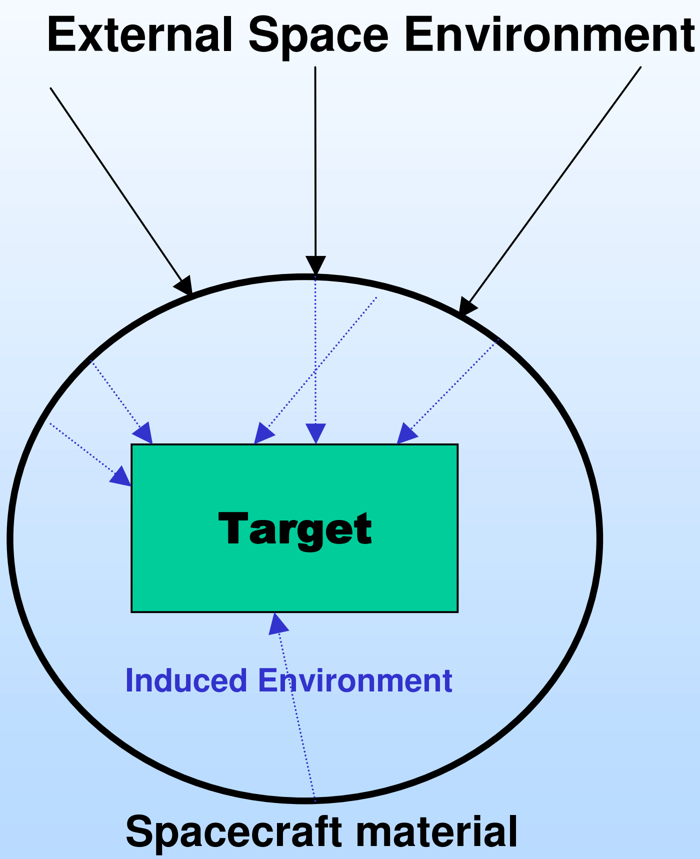


Radiation Test Issues - Fidelity



How accurate is the ground test in predicting Space Performance?

The Physics Models of Space Radiation – Environment to Target



– Predictive model of the external space radiation environment that impinges on the spacecraft

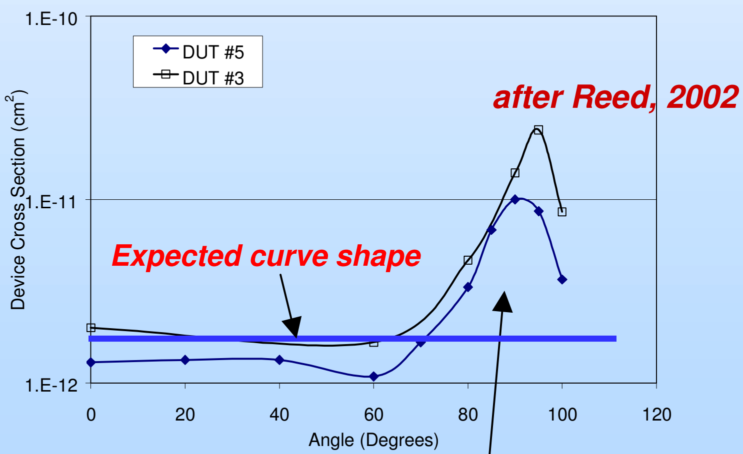
– Predictive model of the interaction of that environment with the spacecraft

- •This is the induced or internal environment that impinges on electrical, mechanical, or biological systems
  - •May need to consider spacecraft transport and local material transport separately

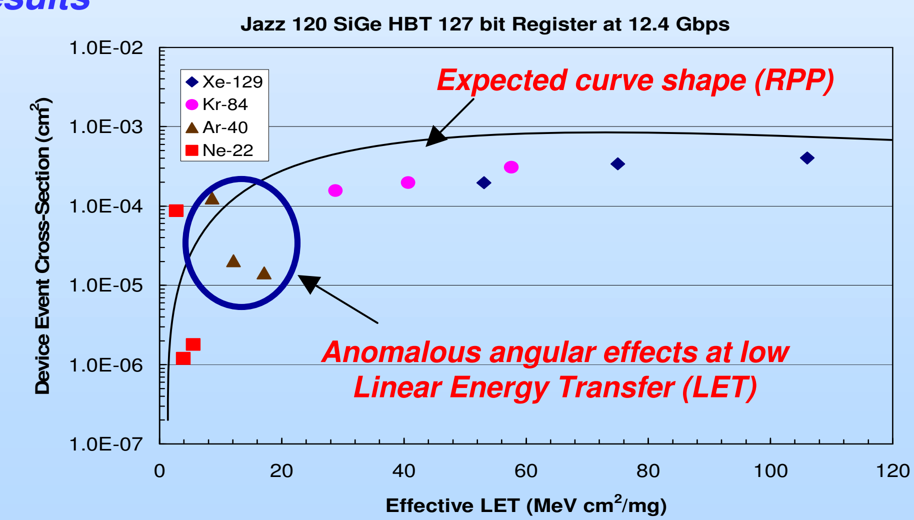
– Predictive model for the effects of the interactions of the induced environment with semiconductor, material, or biological systems (the target)

Gaps for New Technologies

- **Simple example citing tool limitations**
  - **CREME96 Tool (standard SEU rate tool)**
    - **Assumes the sensitive portion of the device (flip-flop) looks like a rectangular parallel-piped (RPP)**
    - **Data over the last few years has shown the RPP model doesn't always fit modern technology/circuits**
      - *Single event transient (SET) issues for higher speeds*
      - *Diffusion effects noted in SDRAMs (synchronous dynamic random access memories)*
      - *Non-bulk CMOS test results*



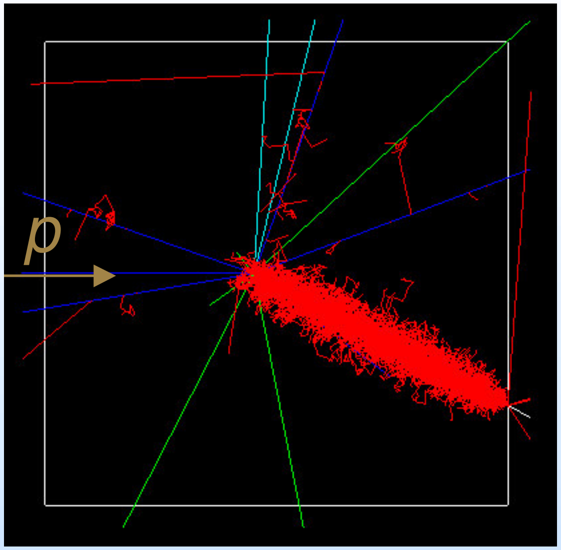
Proton-induced angular effects in SOI device with high aspect ratio



RPP model does not fit SiGe

Implications of Space Radiation Technology "Gaps"

- **Simplifying assumptions (such as RPP) used in many existing tools are inadequate for new technology performance**
  - **Use of existing tools for predictive purposes may add large risk factors onto NASA missions (significant under or over prediction of performance)**
  - ***Physics-based models could provide a more accurate solution using physics-modeling codes (GEANT4, MCNPX, etc.)***
- **Comprehensive tool suite is desired using physics-based codes**
  - **Requires careful technology characterization and modeling effort**
    - **Challenge is to make the tool suite realizable (i.e., physics-based codes could take long periods of time to calculate results)**
      - **Simplifying assumptions and 1st order model development**
- **New effort is to define the gaps and begin development of a Space Computational Radiation Interaction Performance Tools (SCRIPT) suite**
  - **Note: CNES and ESA collaboration with GEANT4 is part of the picture (Space User's Group)**



Sample particle interaction of a 100 MeV proton in a 5um Si block using the GEANT4 toolkit.
after Weller, 2004

Flight Experiments - Validating Technology and Environment Interactions

- Differences exist between ground-based radiation tests and the actual space environment
  - Energy spectrum
  - Directionality
  - Mixed environment
  - Particle arrival rates (flux or dose)
- Flight experiments and/or monitoring technology performance are required to validate ground-based models and tools
  - In-situ technology AND environment measurements desired
- Brief History of Electronics and NASA Flight Radiation Experiments
  - Microelectronic and Photonics Testbed (MPTB)
    - Fiber optic data bus, commercial electronics
  - Space Technology Research Vehicle -1d (STRV-1d) – mission failed 12 days after launch
    - Optocouplers, state-of-the art digital electronics, pulse height analyzer (PHA) instrument, dosimetry
  - Others
    - CRUX, HOST, commercial airplane
    - Engineering data from SAMPEX, TOMS/Meteor, SeaStar, XTE, TRMM, EOS, et al

Flight technology experiments such as ACTS help provide validation for ground-based technology models and concepts

NASA's Living With a Star (LWS) Space Environment Testbed (SET) – A Dual Approach to Flight Validation

- **Data mining**
  - The use of existing flight data to validate or develop improved models and tools
- **Examples**
  - Linear device performance on Microelectronics and Photonics TestBed (MPTB)
  - Physics-based Solar Array Degradation Tool (SAVANT)
- **Flight experiments**
  - Focus on correlating technology (semiconductor to material) performance with solar-variant space environment (radiation, UV, etc.)
    - Model/technology validation and not device validation are the goals
  - In-situ environment monitoring allows for ground test protocol/model correlation
  - Multiple flight opportunities
  - Carrier under development

Investigations are selected via NASA Research Announcements (NRAs) or provided under partnering arrangements

Final Comments and Future Considerations

Technology, Testing, and Flight

- Technology complicates radiation effects
  - Speed, Thermal, Fault Isolation, Packaging: die access!, etc
    - SETs are the "new" effect in digital devices
  - Ultra-low noise science instruments
- Future facility issues
  - Beam structure
    - Issue: At-speed testing
  - Microbeam
    - Issue: Isolation of errors / Identification of sensitive junctions
  - High energy heavy ions – Michigan State University (MSU) National Superconducting Cyclotron Labs (NSCL) now open for business
    - Issue: Increased fidelity to space environment
    - Issue: Improved ion penetration (packaging issues!)
    - Issue: Thermal (open air testing possible)
    - Issue: Speed (reduced cabling requirements)
- Nanotechnologies? MEMS?
- A proactive radiation test and modeling program is required to allow successful system RHA

Ion Penetration depth depends on energy