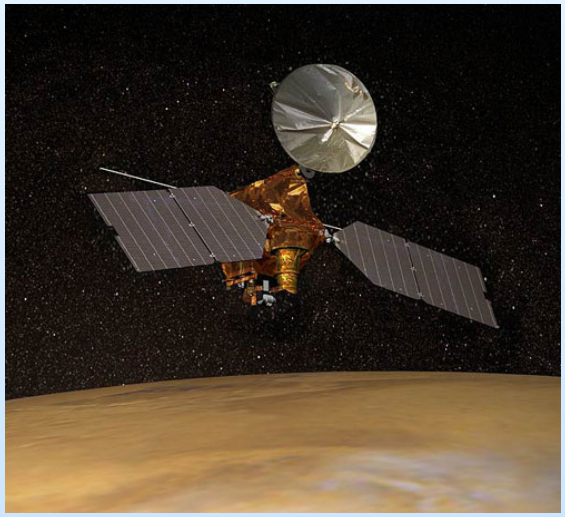
Radiation Impacts on Satellites due to GCRs and SEPs

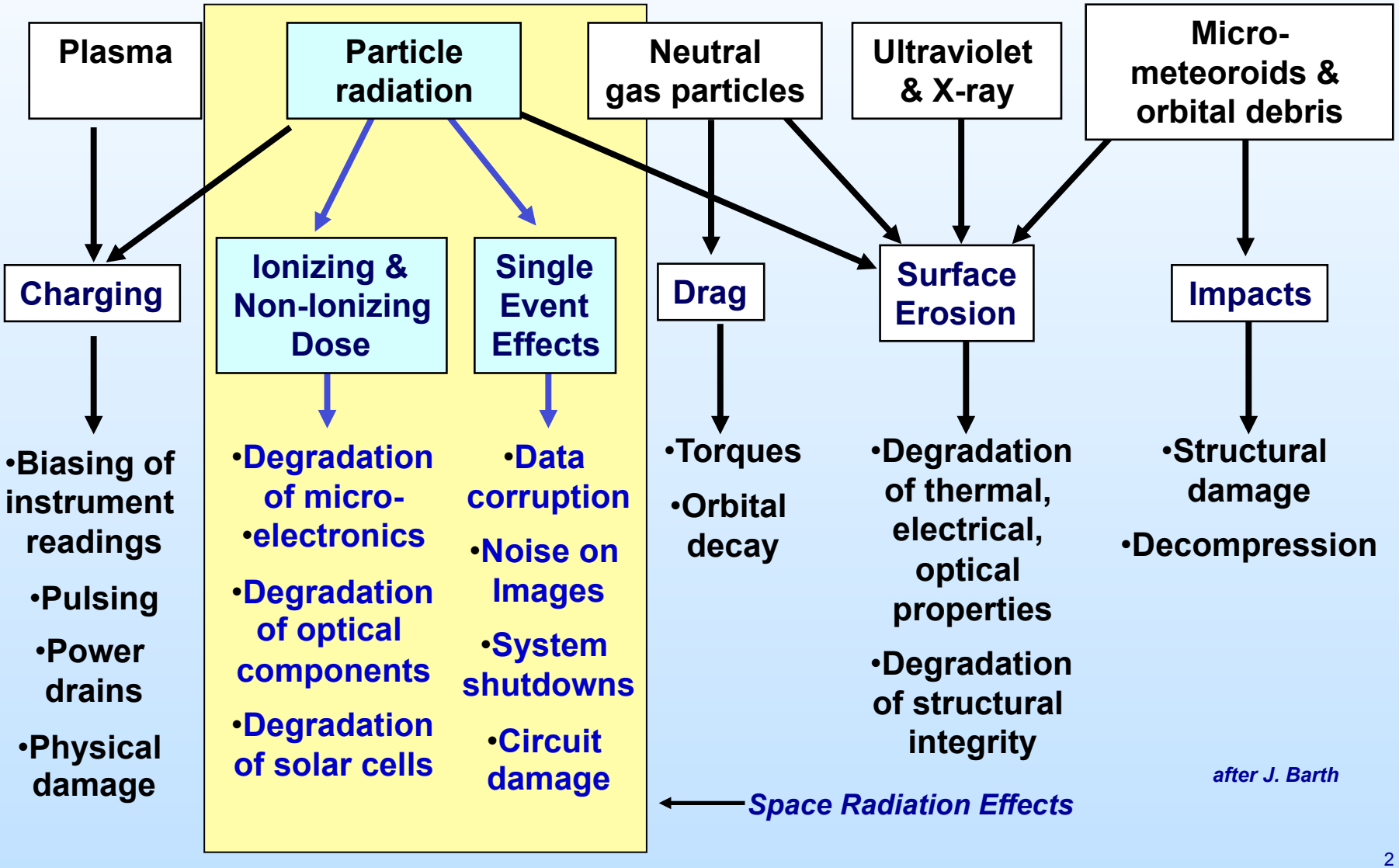
Mike Xapsos

GSFC, Code 561



Space Weather Training for Mission Operators and Engineers
NASA/GSFC
January 29, 2014

Space Environments and Effects

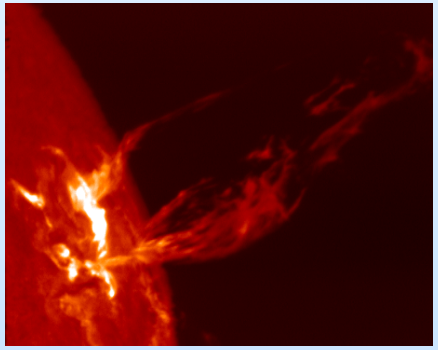


Energetic Particles in Space

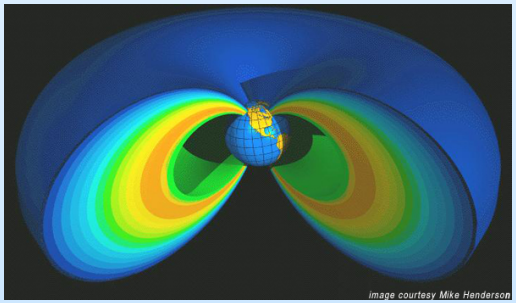
High Energy Particle Radiation

- **Galactic Cosmic Rays**

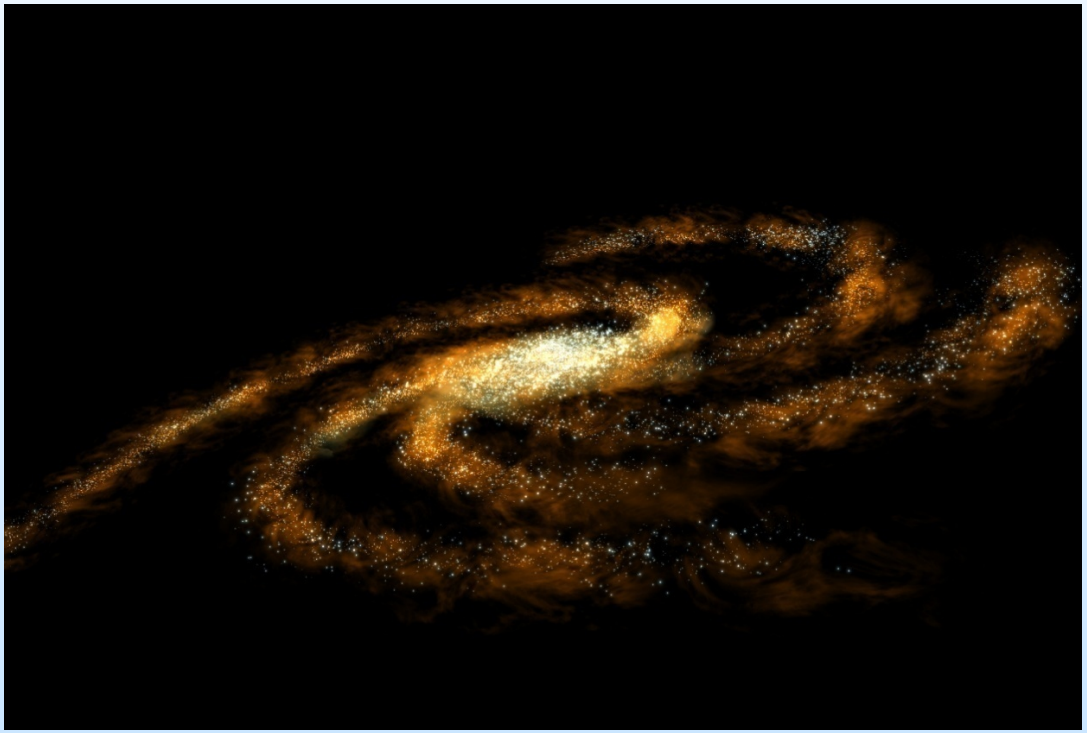
- **Solar Particle Events**



- **Trapped Particles**



Galactic Cosmic Rays

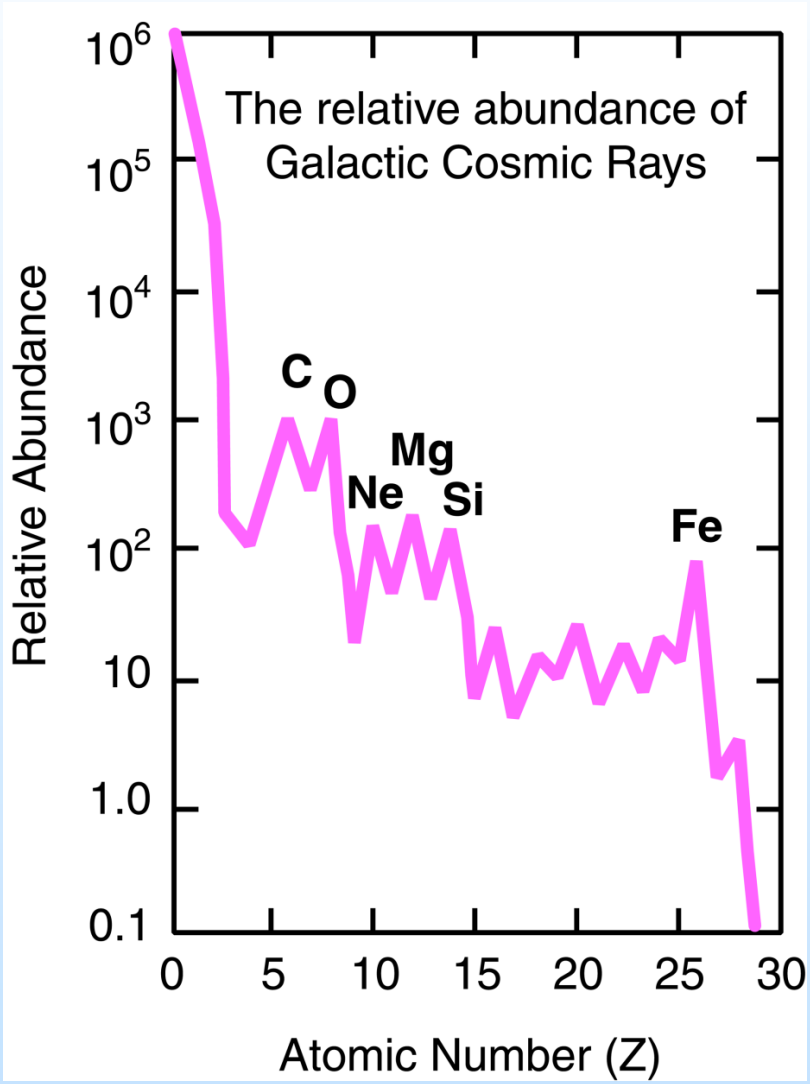


Origin

- Galactic cosmic rays (GCR) are high-energy charged particles that originate outside our solar system.
- Likely multiple sources one of which is believed to be remnants from supernova explosions.

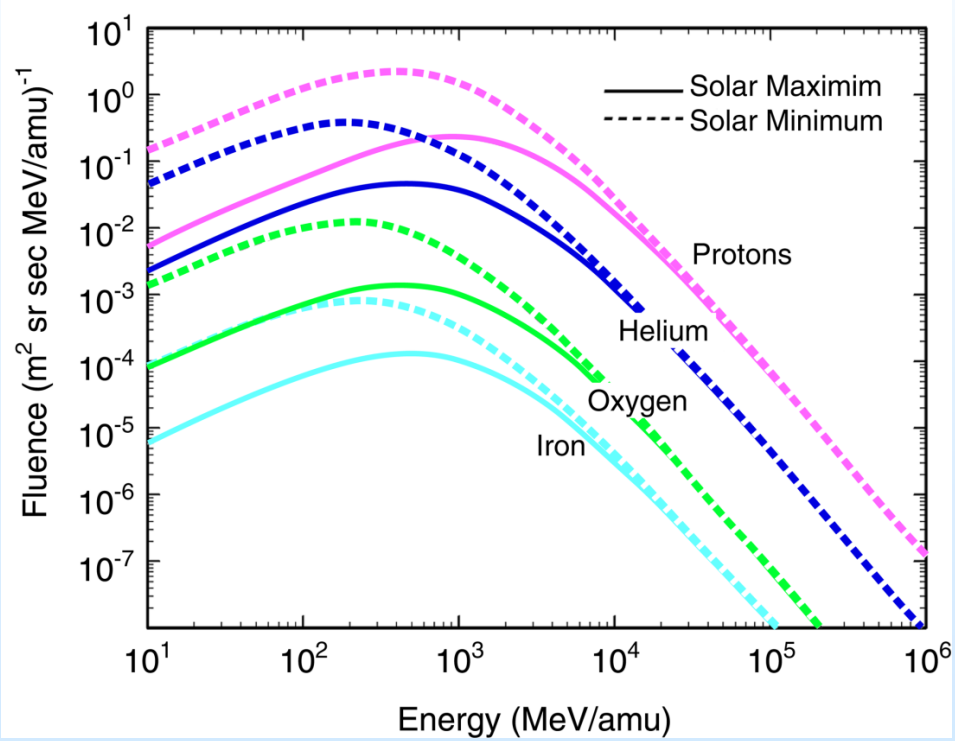
GCR Properties

- **Composed of all naturally occurring elements:**
  - **87% protons**
  - **12% alpha particles**
  - **1% heavier ions**
- **Energies: up to 10^{11} GeV!**
  - **Energetically equivalent to a tennis ball traveling 250 km/hr!**
- **Fluxes: 1 to 10 $cm^{-2}s^{-1}$**



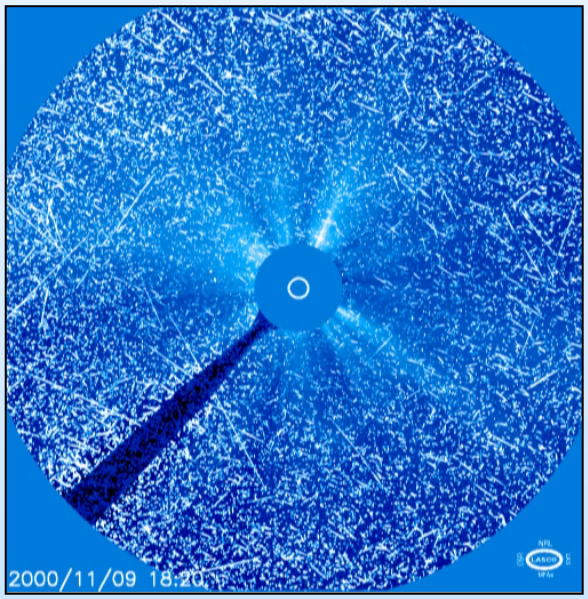
Variation with Solar Cycle

- Energy spectra tend to peak around 0.3 to 1 GeV/ nucleon.
- Fluxes modulated by magnetic field in sun and solar wind
  - High activity solar maximum time period attenuates flux for energies less than about 10 GeV/nucleon.
- Main concern is single event effects
- Shielding not effective

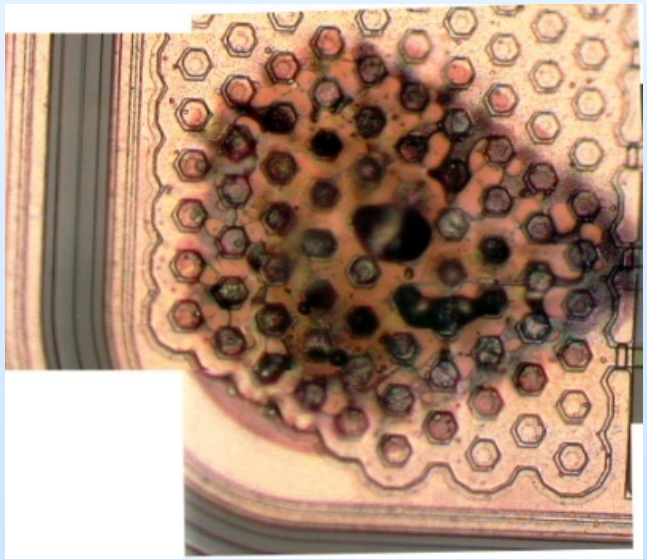


Examples of Single Event Effects

- **Single Event Effect – any measureable effect in a circuit caused by single incident ion**
  - **Non-destructive**
  - **Destructive**



Noise seen on the SOHO/LASCO instrument imager during the November 8-9, 2000 solar particle event

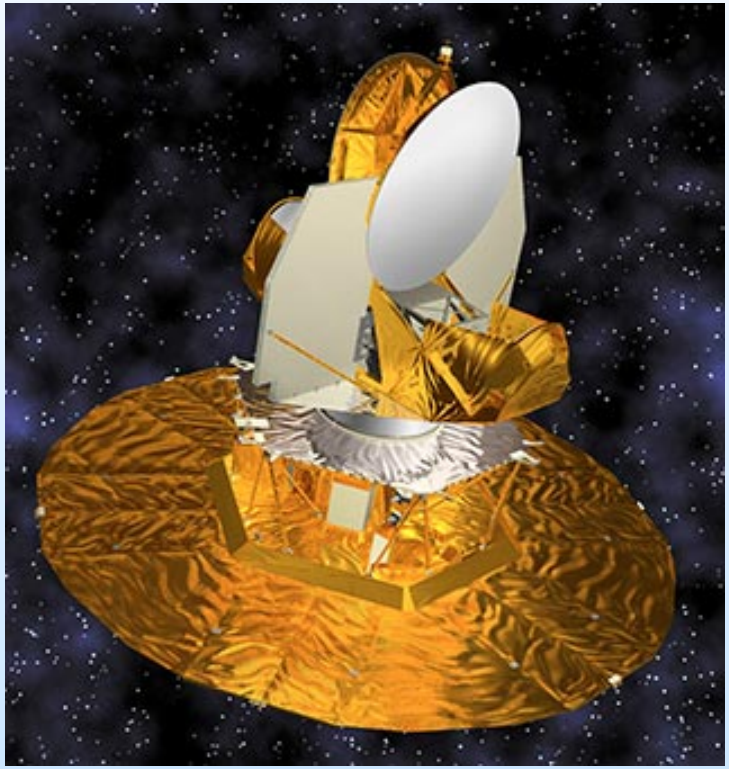


Destructive event in a COTS 120V DC-DC Converter

How Serious Can Single Event Effects Be?

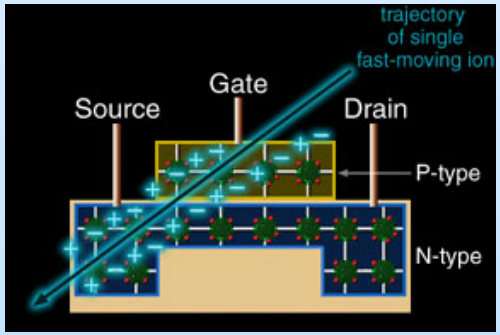
- **Single Event Effects (SEE) in spacecraft electronics can cause a broad range of effects**
  - **Loss of scientific data**
  - **Noise on images**
  - **Circuit damage**
  - **System shutdown**
    - **Single event transient reset spacecraft processor in WMAP, which caused spacecraft to enter a "safehold" condition**

Wilkinson Microwave Anisotropy Probe

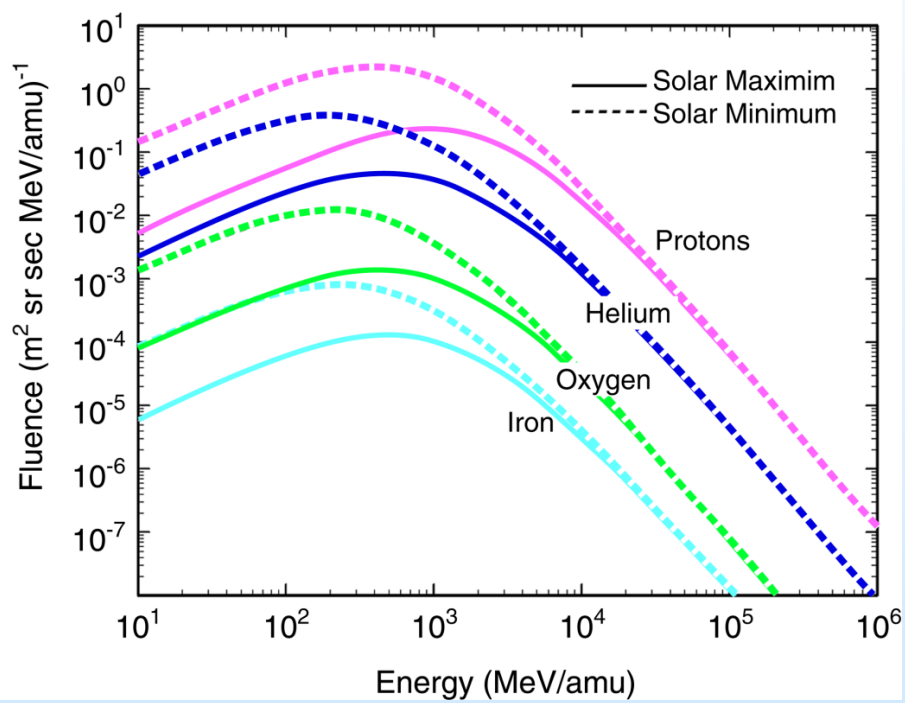


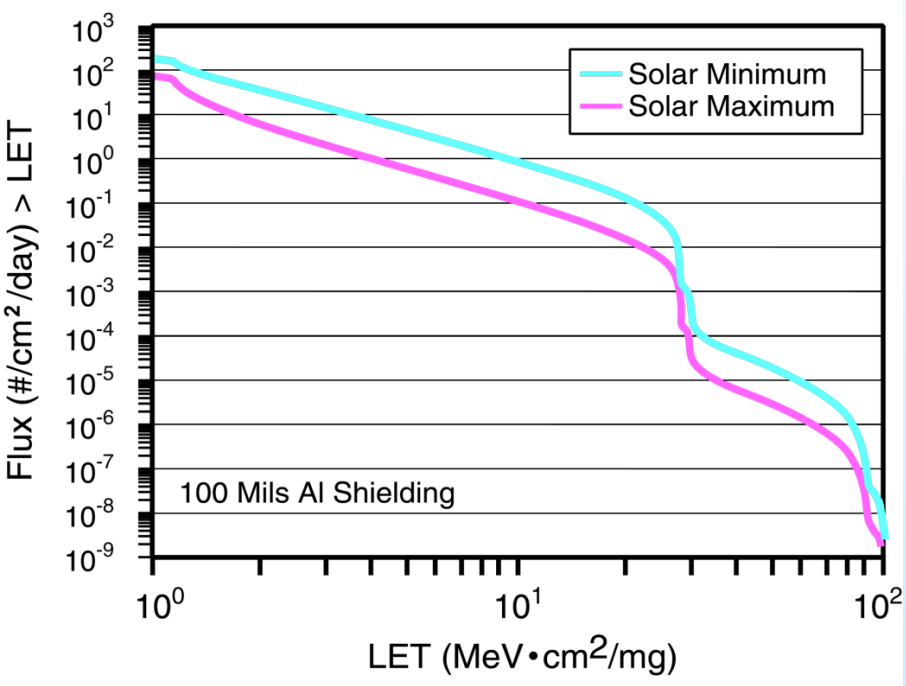
Single Event Effect Metric

- SEE may be caused by:
  - direct ionization (usually the case for incident heavy ions)
  - nuclear reaction products (usually the case for incident protons)
- Metric commonly used for heavy ion induced SEE is Linear Energy Transfer (LET)
- LET = energy lost by ionizing particle per unit path length in sensitive volume
  - Path length often expressed as areal density by dividing by material density
  - LET units commonly used are MeV-cm^2/mg.

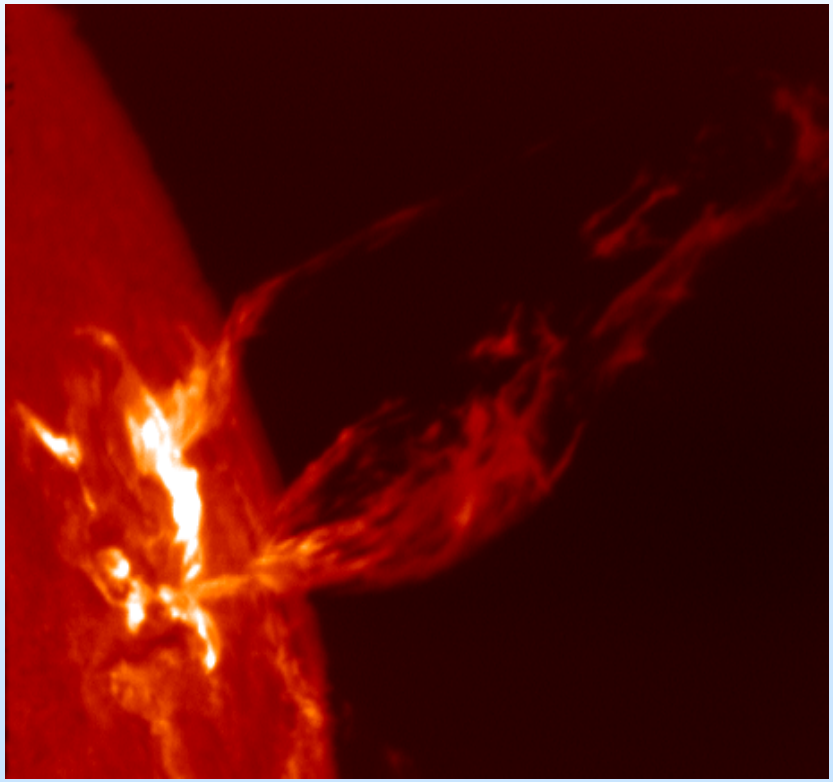


LET Spectra


Solar Maximim
Solar Minimum
Protons
Helium
Oxygen
Iron
Fluence (m^2 sr sec MeV/amu)$^{-1}$
Energy (MeV/amu)

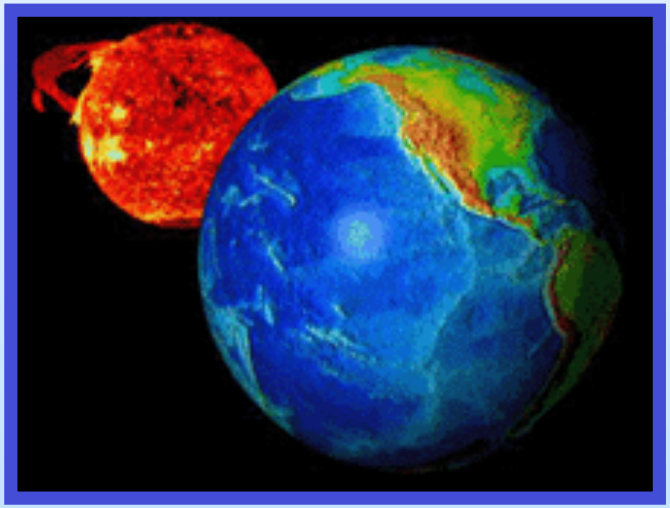

Solar Minimum
Solar Maximum
100 Mils Al Shielding
Flux (#/cm^2/day) > LET
LET (MeV•cm^2/mg)

Solar Energetic Particles

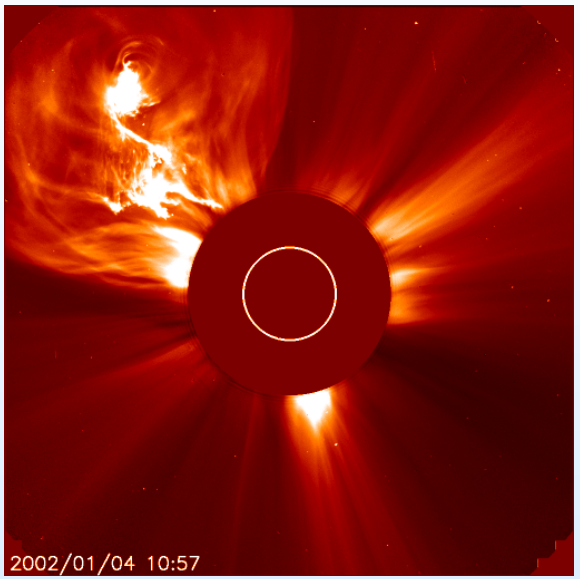


Solar Particle Events

- **A solar particle event is a sudden burst of energy that is released from the sun's magnetic field**
  - **Solar flare**
  - **Coronal Mass Ejection (CME)**
    - **Responsible for major disturbances in interplanetary space and in Earth's magnetosphere**
    - **A large CME contains enough energy to boil the north Atlantic Ocean**
  - **Energy is released in the form of e, p, heavy ions and electromagnetic radiation.**

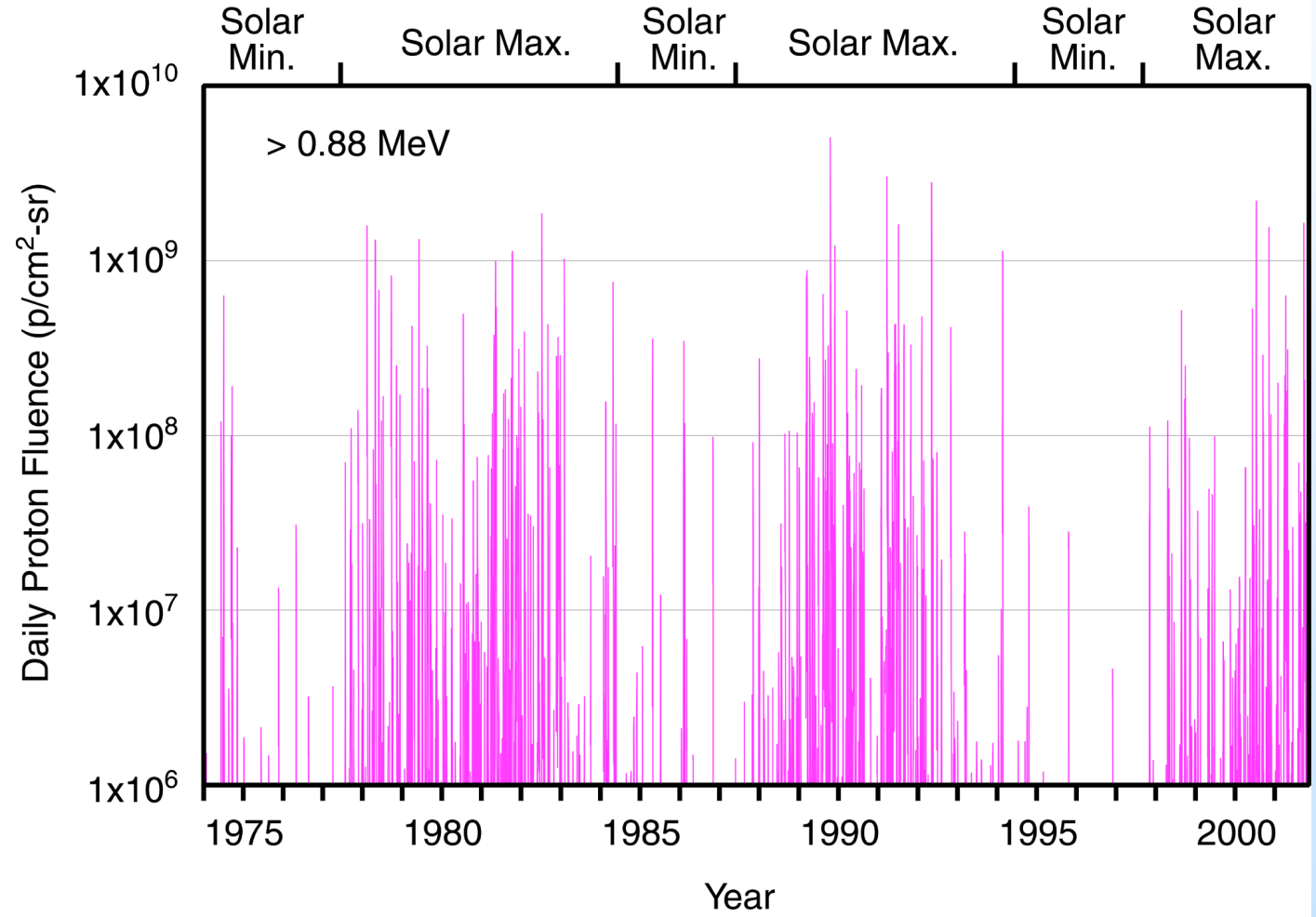


Characteristics of CMEs



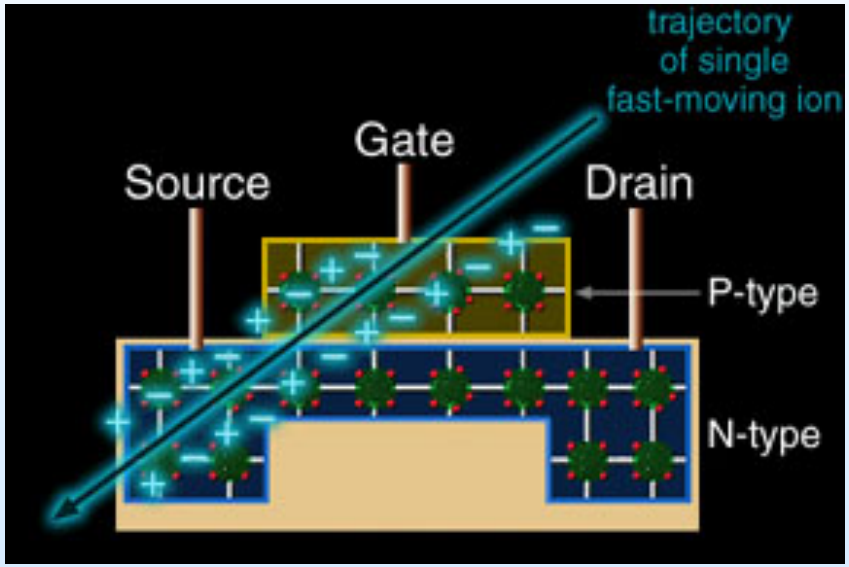
- **Composition:**
  - 96.4% protons
  - 3.5% alpha particles
  - 0.1% heavier ions (not to be neglected!)
- **Energies: up to ~ GeV/nucleon**
- **Event magnitudes:**
  - > 10 MeV/nucleon integral fluence: can exceed 10^{9} cm^{-2}
  - > 10 MeV/nucleon peak flux: can exceed 10^{5} $cm^{-2}s^{-1}$

Solar Cycle Dependence



Radiation Effects
Solar Particle Events

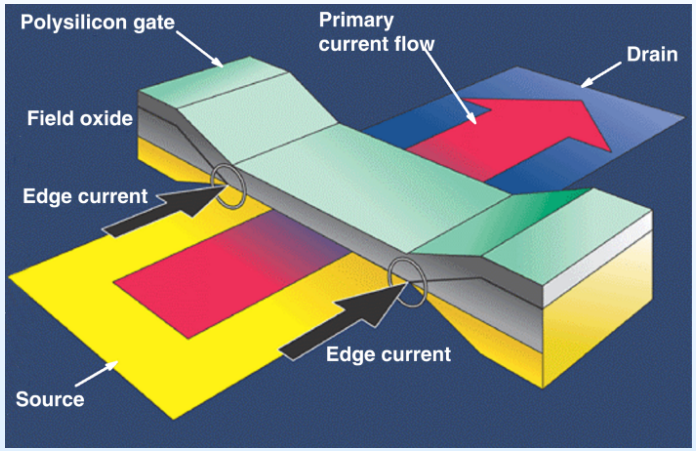
- **Solar particle events cause:**
  - **SEE - Concern is how high the SEE rate can get during an event**
  - **Cumulative degradation**
    - **Total Ionizing Dose**
    - **Displacement Damage**
    - **Largely due to protons**

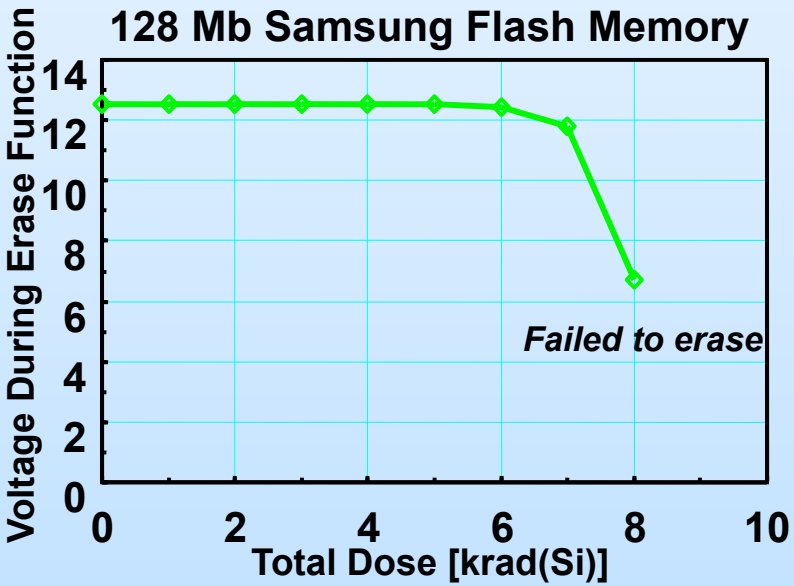


Total Ionizing Dose Effects

- Cumulative damage resulting from ionization (electron-hole pair formation) causing
  - Threshold voltage shifts
  - Timing skews
  - Leakage currents
- Metric used for TID:

  Dose = energy deposited per unit mass of material in the sensitive volume
  - 1 rad = 100 erg/g



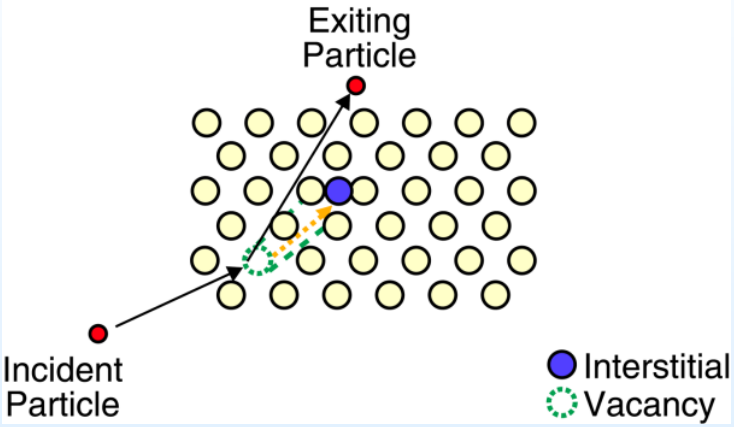


Displacement Damage Effects

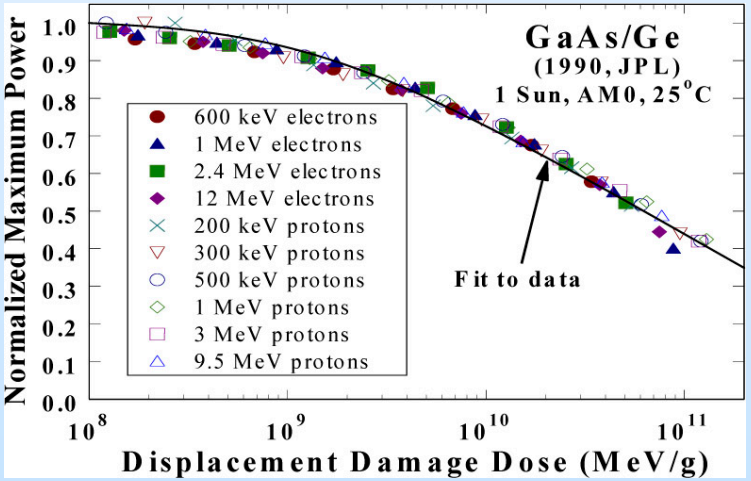
- Cumulative damage resulting from displacement of atoms in semiconductor lattice structure causing:
  - Carrier lifetime shortening
  - Mobility degradation
- Two metrics used:

  Displacement Damage Dose = energy going into displaced atoms (nonionizing energy) per unit mass of material in the sensitive volume

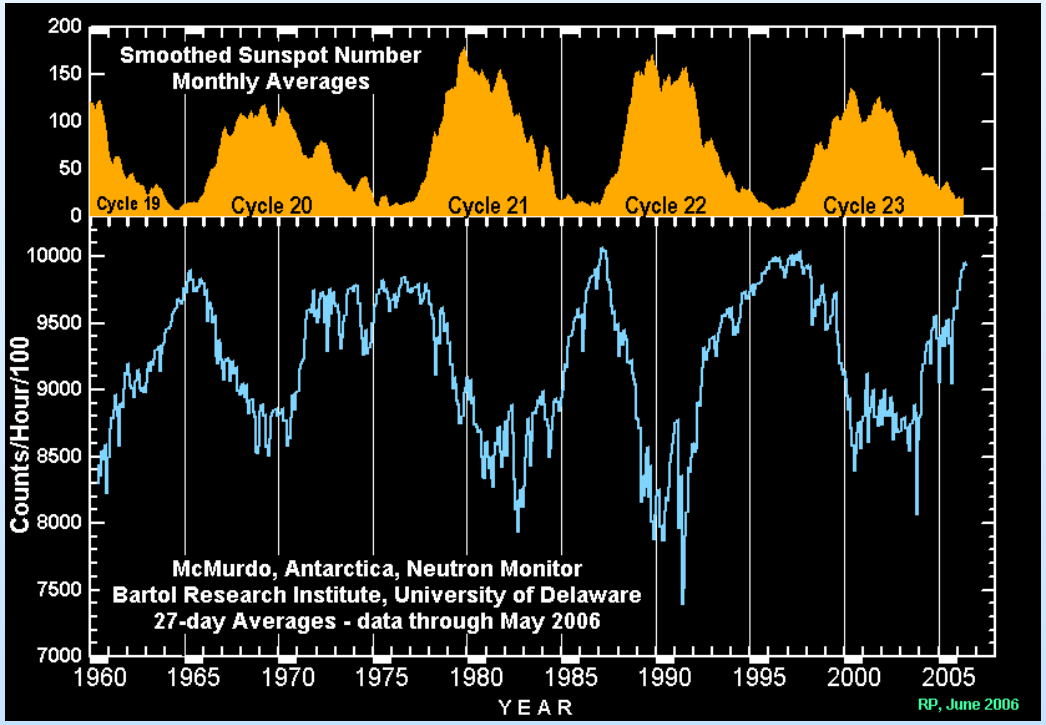
  Equivalent Proton Fluences (10 MeV often-used standard)



Solar Array Degradation



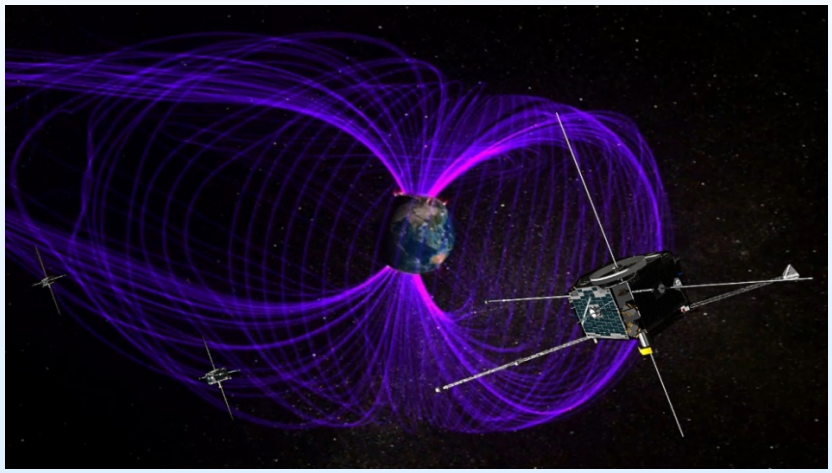
Examples of Long-term Observations of Anomalies in Spacecraft



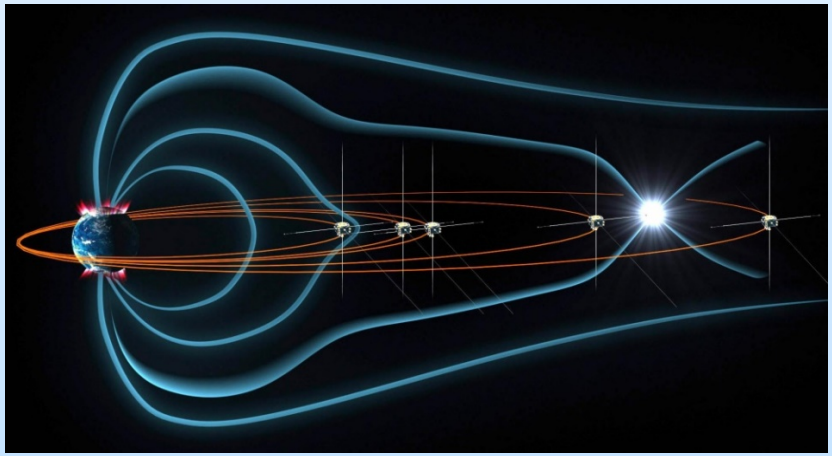
THEMIS Space Weather Anomalies

- **Five synchronized probes launched Feb. 2007**
  - **Highly Elliptical Orbits with apogees 10 – 30 R_E**
  - **Two probes in lunar orbit since 2011**
- **Total of 76 anomalies observed, 51 of which attributed to space weather by UC Berkeley group**
  - **Spacecraft bus anomalies mainly in ColdFire processor**
  - **Instrument anomalies entirely in data processing unit**

Time History of Events and Macroscale Interactions during Substorms (THEMIS)

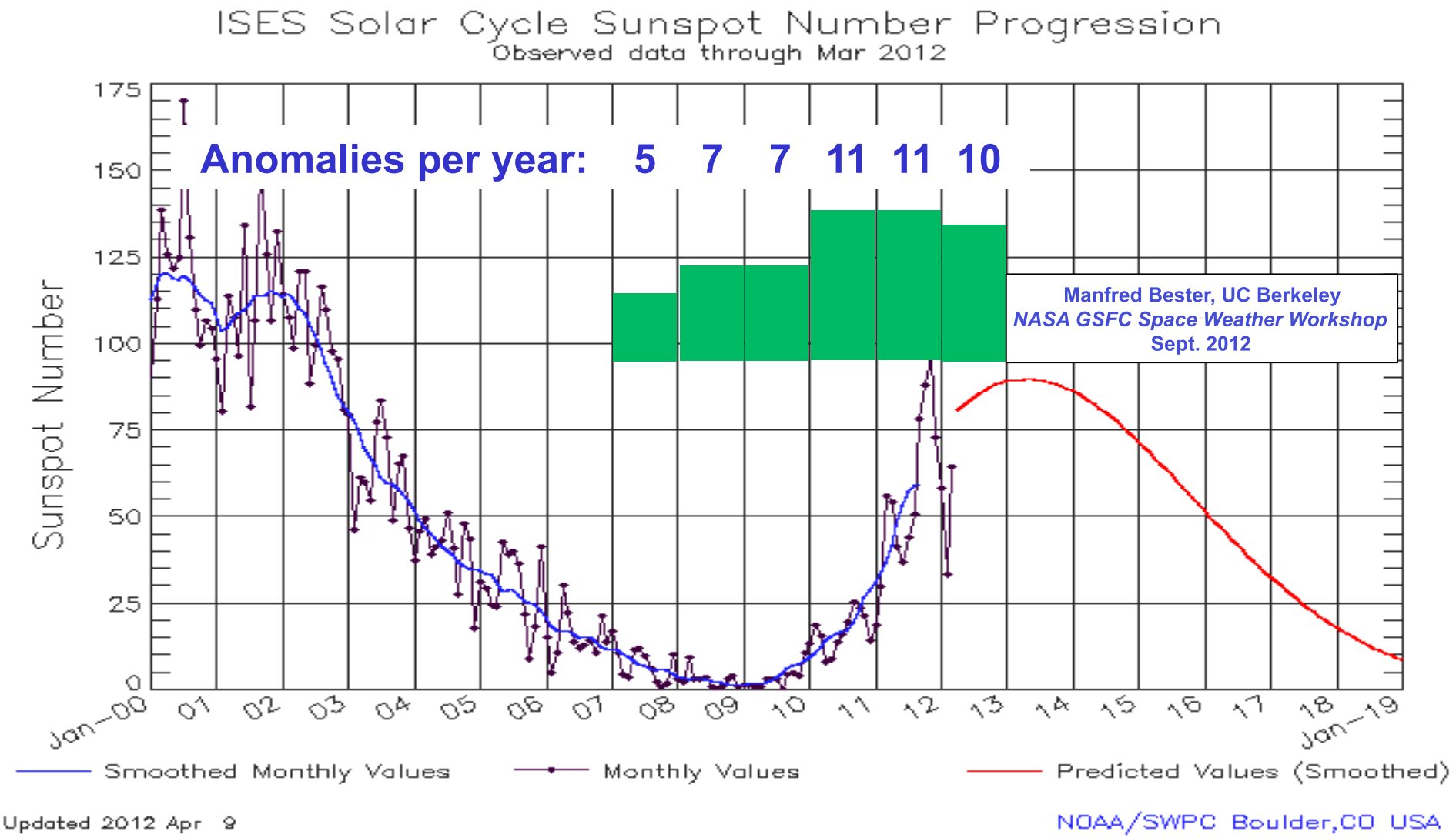


http://www.nasa.gov/mission_pages/themis/main/index.html

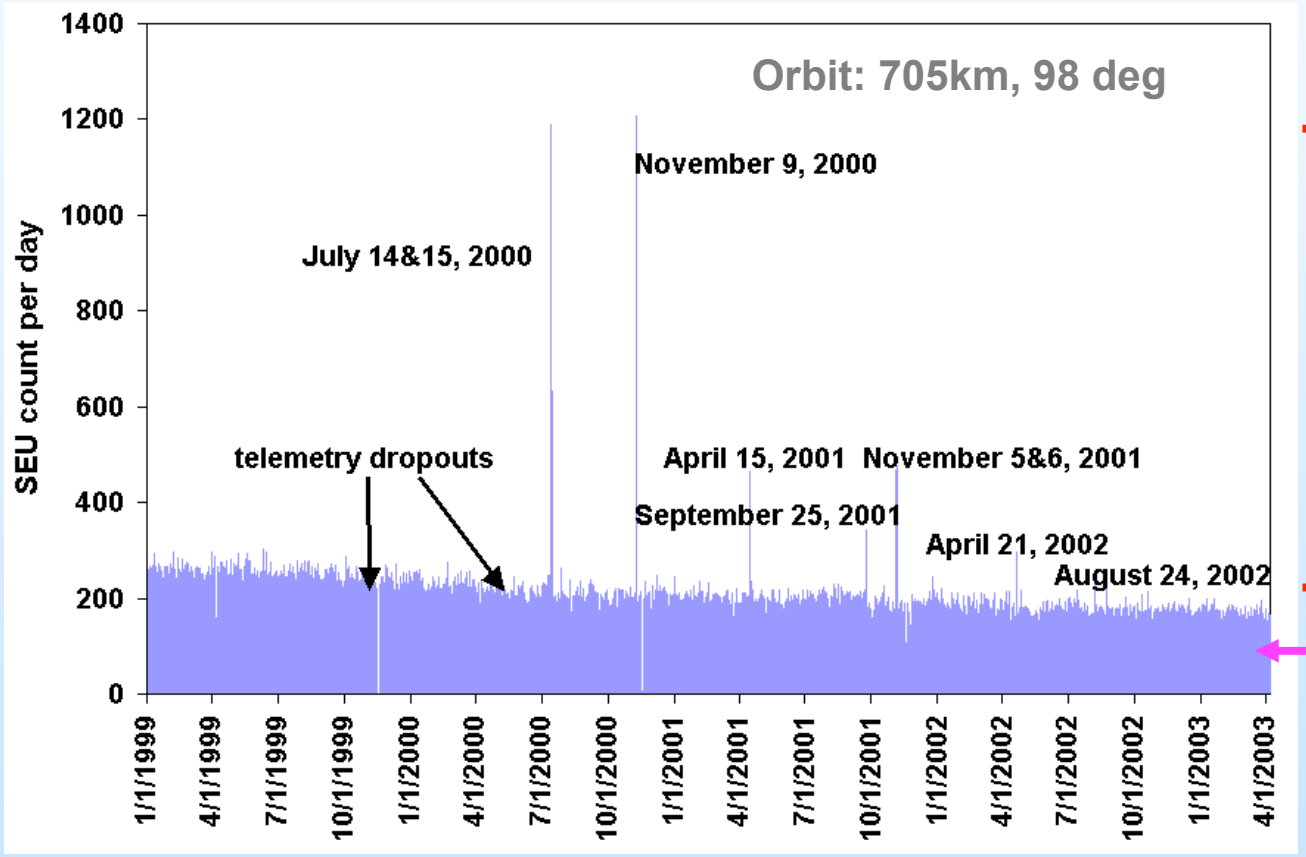


http://www.nasa.gov/mission_pages/themis/news/Themis_tech_space.html

THEMIS Space Weather Anomalies



Single Event Upsets
SEASTAR Solid State Recorder



Solar particle events

Background
Trapped protons & galactic cosmic rays

CREDIT: J. Barth