THE SINGLE EVENT EFFECTS ENVIRONMENT OF SPACE

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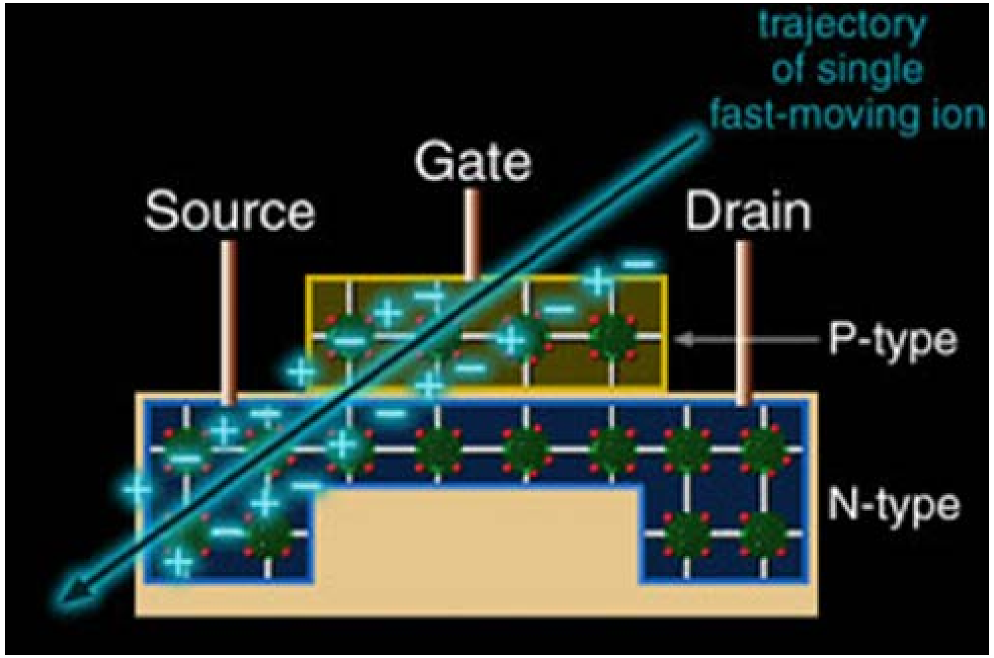
Outline

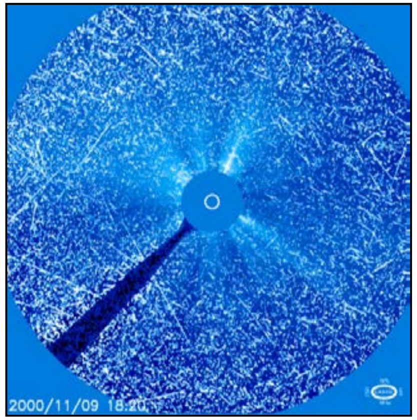
- Single Event Effects (SEE) Background
- The Solar Cycle
- The Quiet Time Environment
  - Galactic Cosmic Rays (GCR)
  - Trapped Protons in the Van Allen Belts
- The Worst Case Environment
  - Solar Particle Events
- Single Event Upset (SEU) Examples
  - Measured SEU Rates
  - Effect of Shielding
- Summary



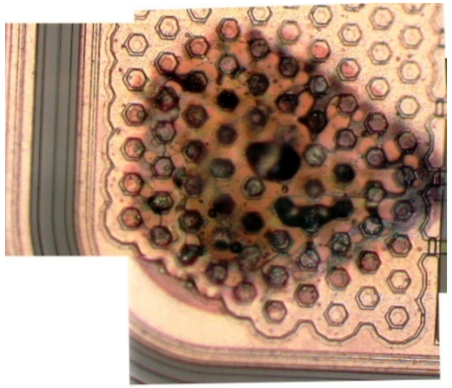
M.A. Xapsos, 2018 Nuclear & Space Radiation Effects Conference (NSREC) Short Course

Single Event Effects

- **Single Event Effect – any measureable effect in a circuit caused by a single incident particle**
  - **Non-destructive – single event upset (SEU), single event transient (SET)**
  - **Destructive – single event latch-up (SEL), single event burnout (SEB)**



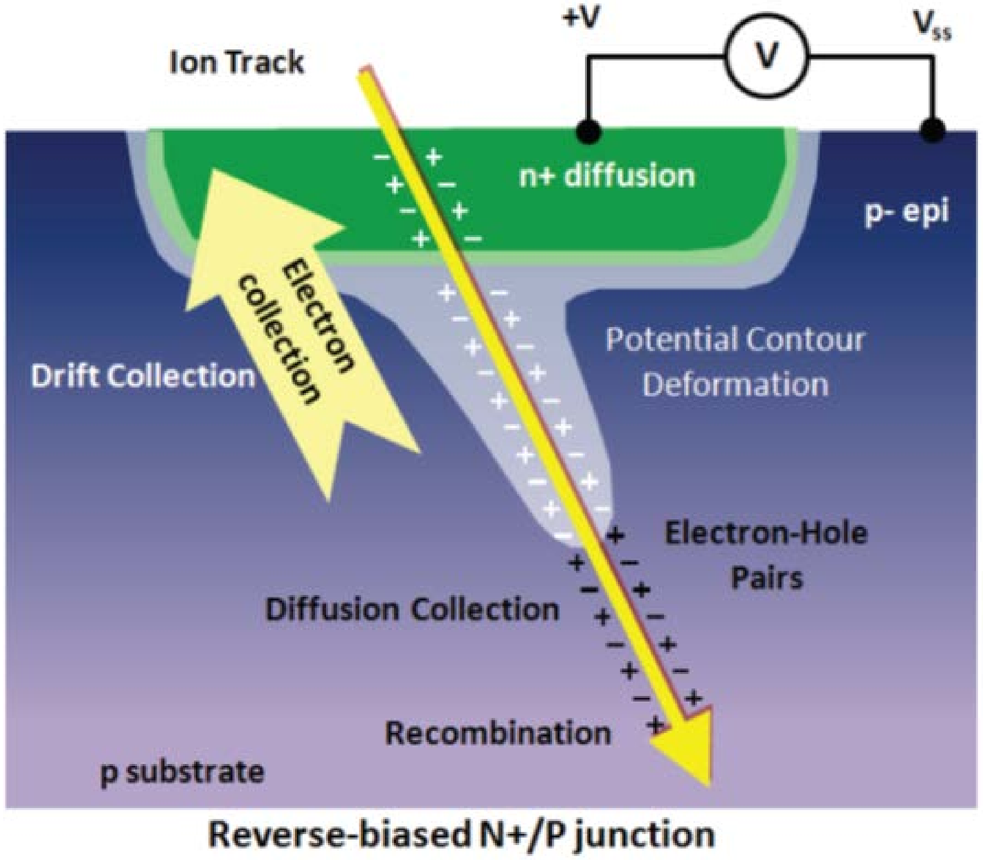
Noise on SOHO/LASCO imager during Nov. 8-9, 2000 solar particle event



DC-DC Converter
Credit: NASA Electronics Parts & Packaging Program

Single Event Metric

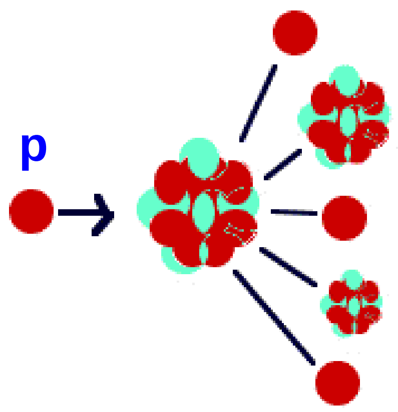
- SEE may be caused by direct ionization
  - Usually the case for incident heavy ions
- Metric used to calculate single event rates is charge collected in sensitive volume
  - Q = C x LET x s
    - Linear Energy Transfer (LET) is energy lost by ion per unit path length
      - Units are MeV/cm or MeV-cm^2/mg
    - s is path length through sensitive volume
- For some modern devices LET parameter may not be sufficient



R.C. Baumann, 2013 NSREC Short Course

Single Event Metric

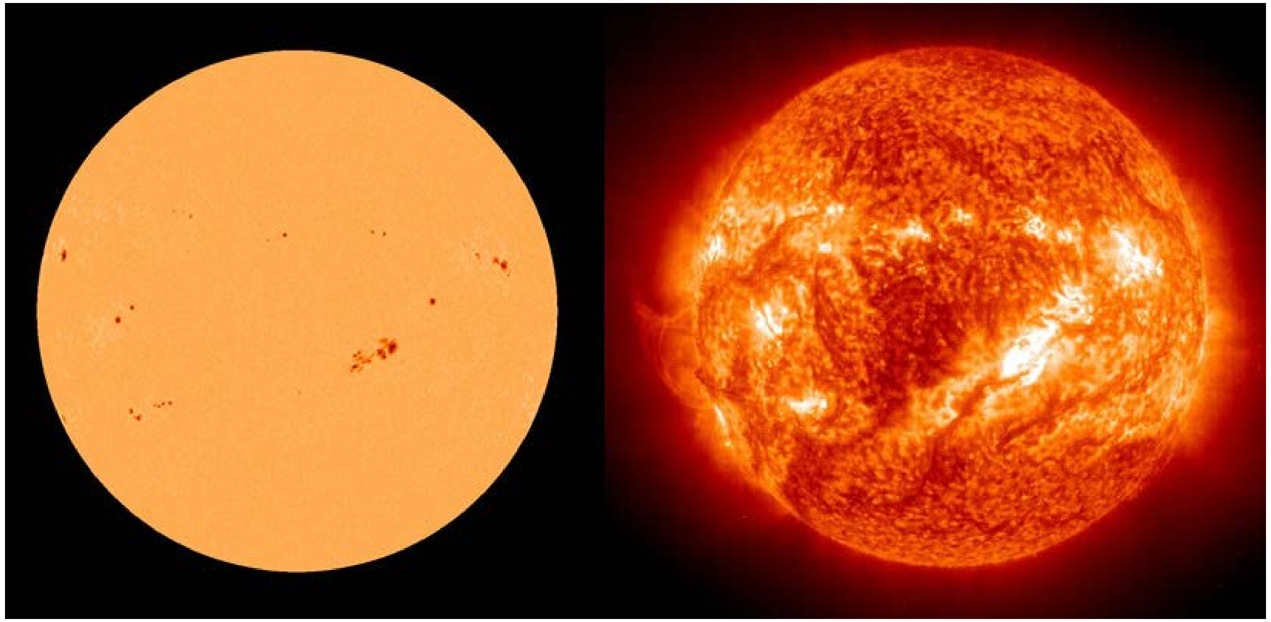
- **SEE may be caused by nuclear reaction products**
  - **Usually the case for incident protons**
- **Metric for single event rate is still charge collected in sensitive volume but calculation is more complex**



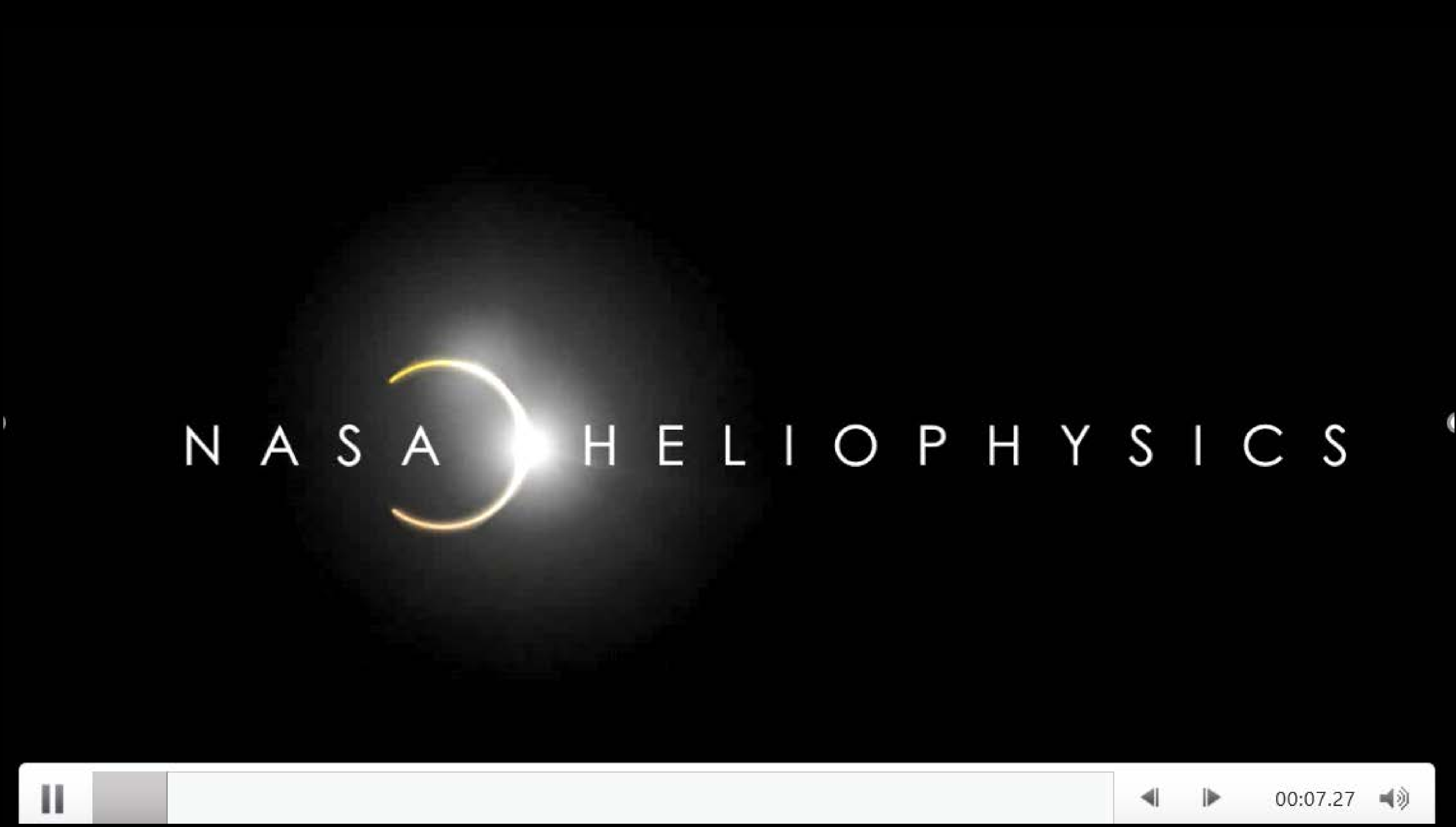
The Solar Cycle
Sunspots

- **Sun's activity has a long-term, periodic behavior**
- **Sunspots are viewed as a proxy to solar activity**
  - **Active regions have twisted magnetic fields that inhibit local convection**
  - **Region is cooler and appears darker when viewed in visible light.**

Images Taken Feb. 3, 2002:



Credit: ESA and NASA (SOHO)


NASA HELIOPHYSICS
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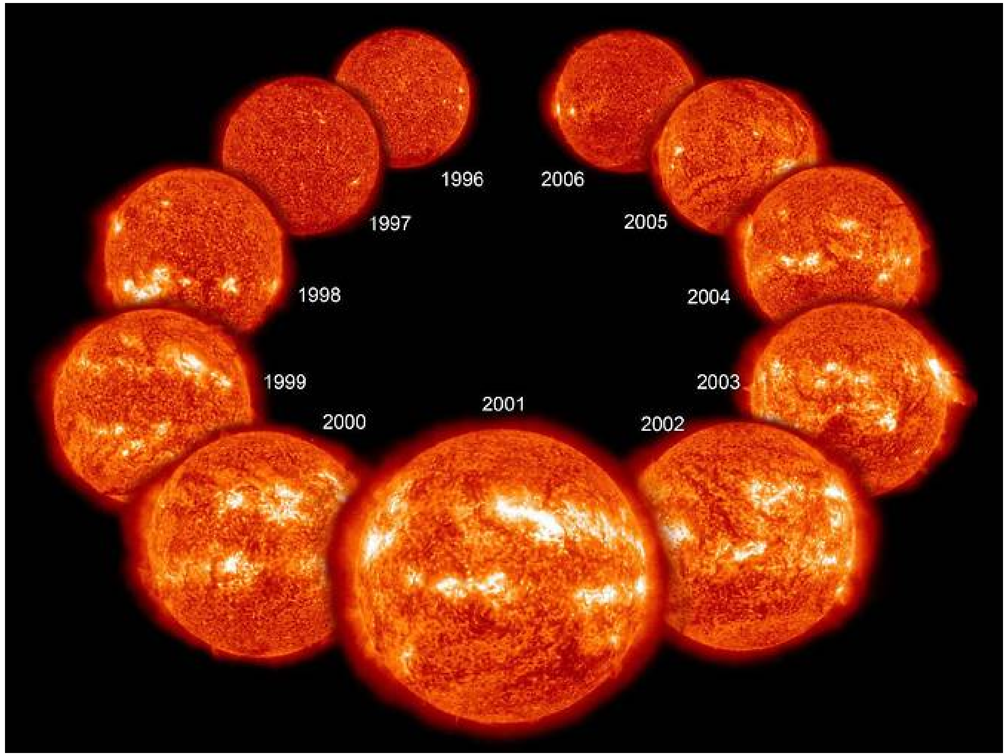
Effects of Sun's Magnetic Activity on Single Event Environment

- The sun is either a source or modulator of all energetic particle radiations in near-Earth region
- Source of:
  - Solar protons and heavy ions
  - Protons (and electrons) in Van Allen belts
- Modulates galactic cosmic ray fluxes entering solar system
  - Main source of atmospheric neutrons

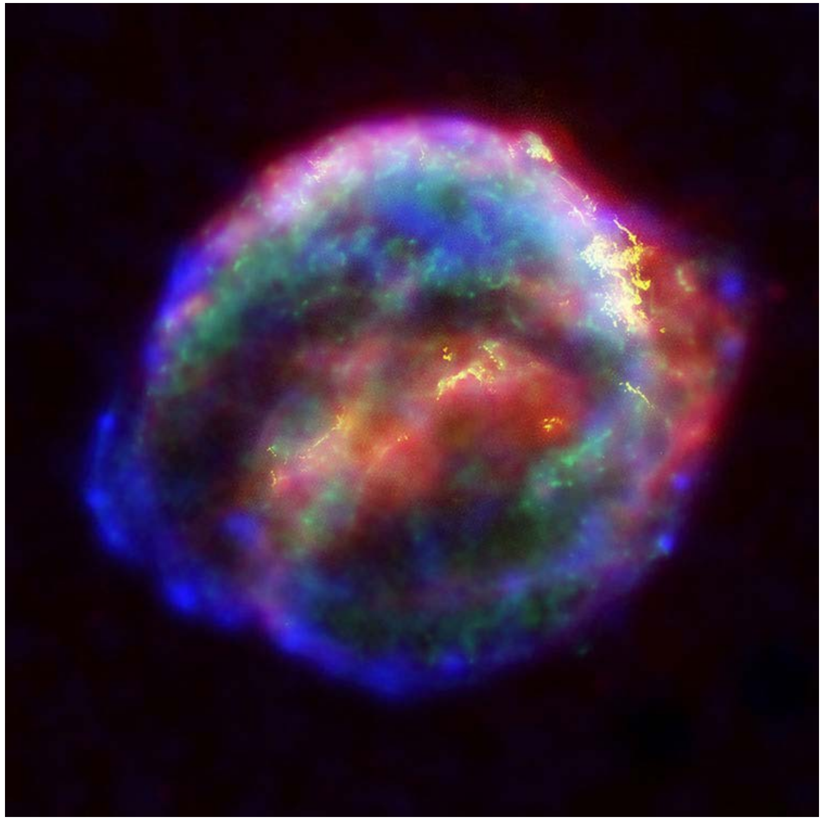


Credit: NASA

Quiet Time Environment
Galactic Cosmic Rays

- **Properties**
- **Models**
  - **Badhwar and O'Neill 2014**
  - **Moscow State University (MSU)**

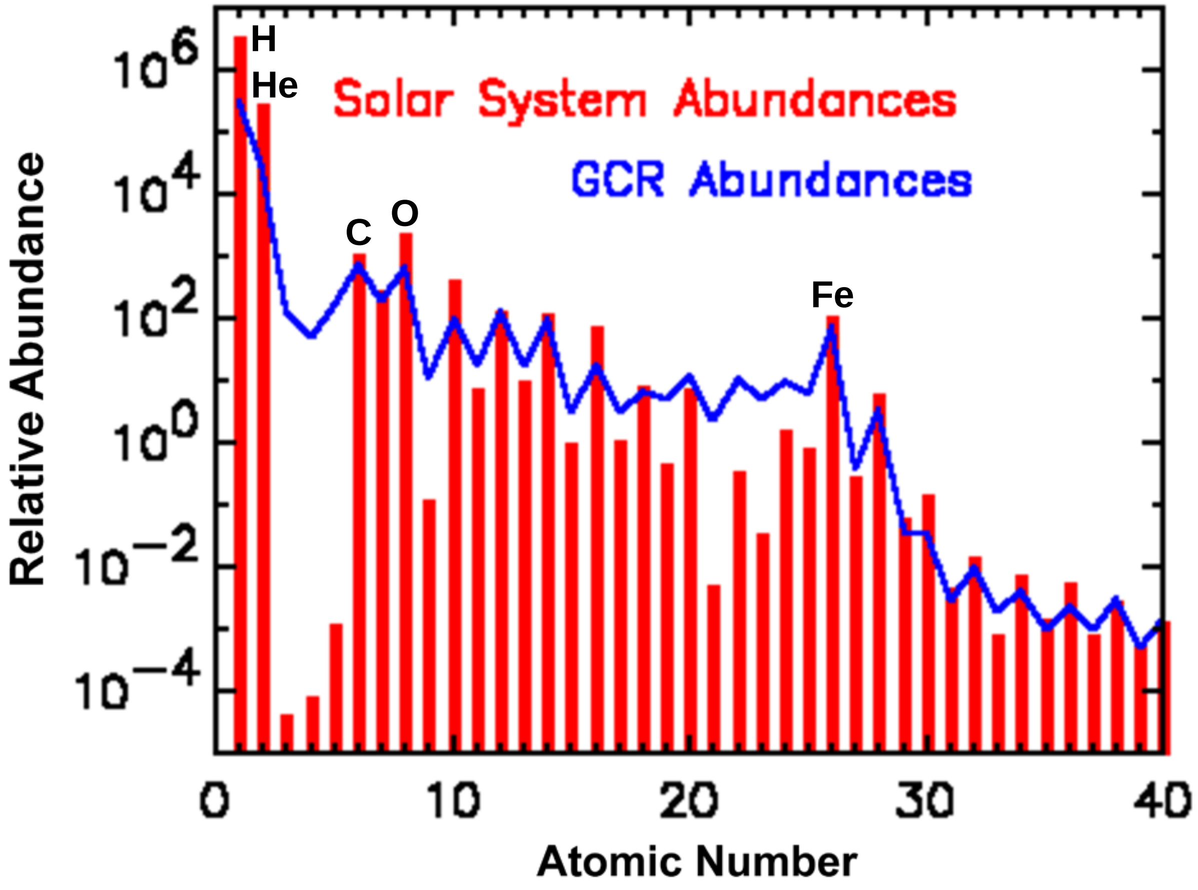
Kepler's 1604 Supernova Remnant



Credit: NASA, ESA & JHU APL (Chandra, Hubble and Spitzer)

Composition

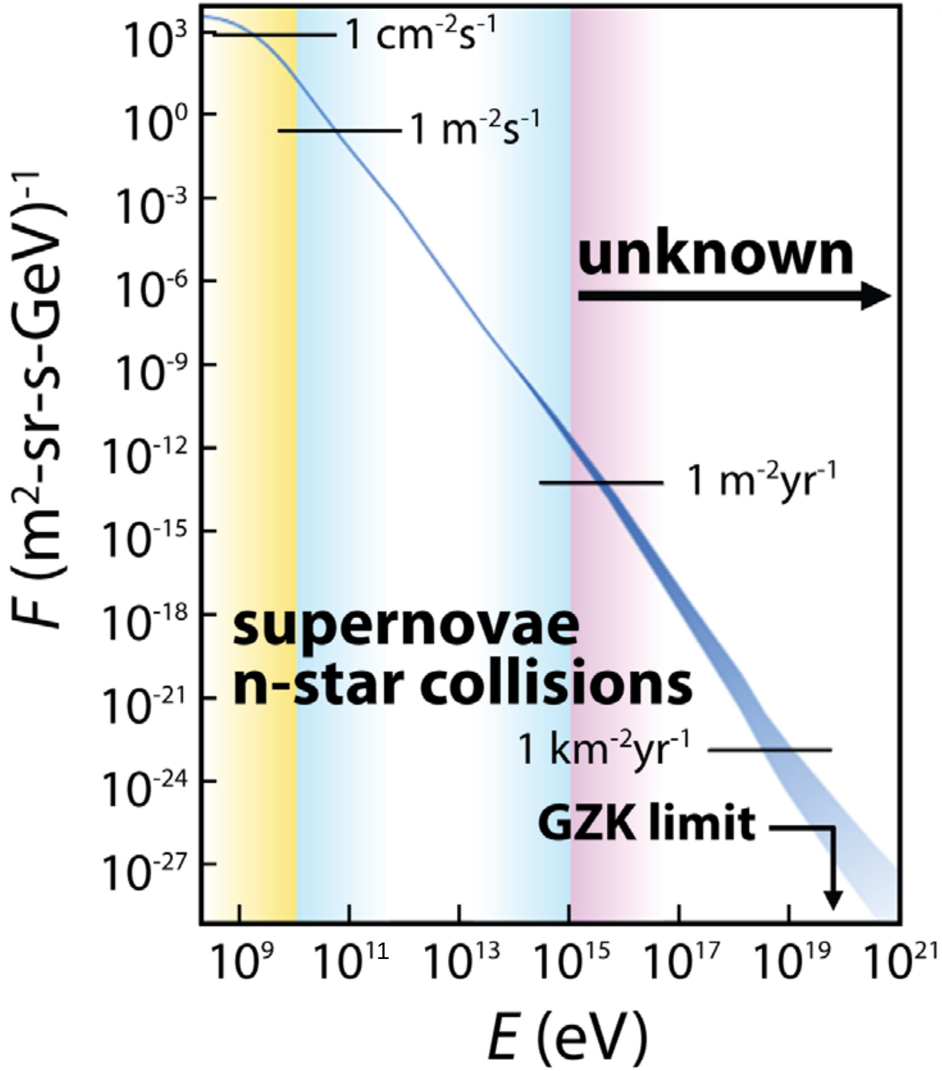
- Galactic Cosmic Rays (GCR) are high energy, low flux charged particles that originate outside our solar system.
- Composed of all naturally occurring elements
  - 90% hydrogen
  - 9% helium
  - 1% heavier ions
- Generally similar to solar abundances but secondary products due to interstellar GCR fragmentation smooths out abundances



https://imagine.gsfc.nasa.gov/

Energy Spectra

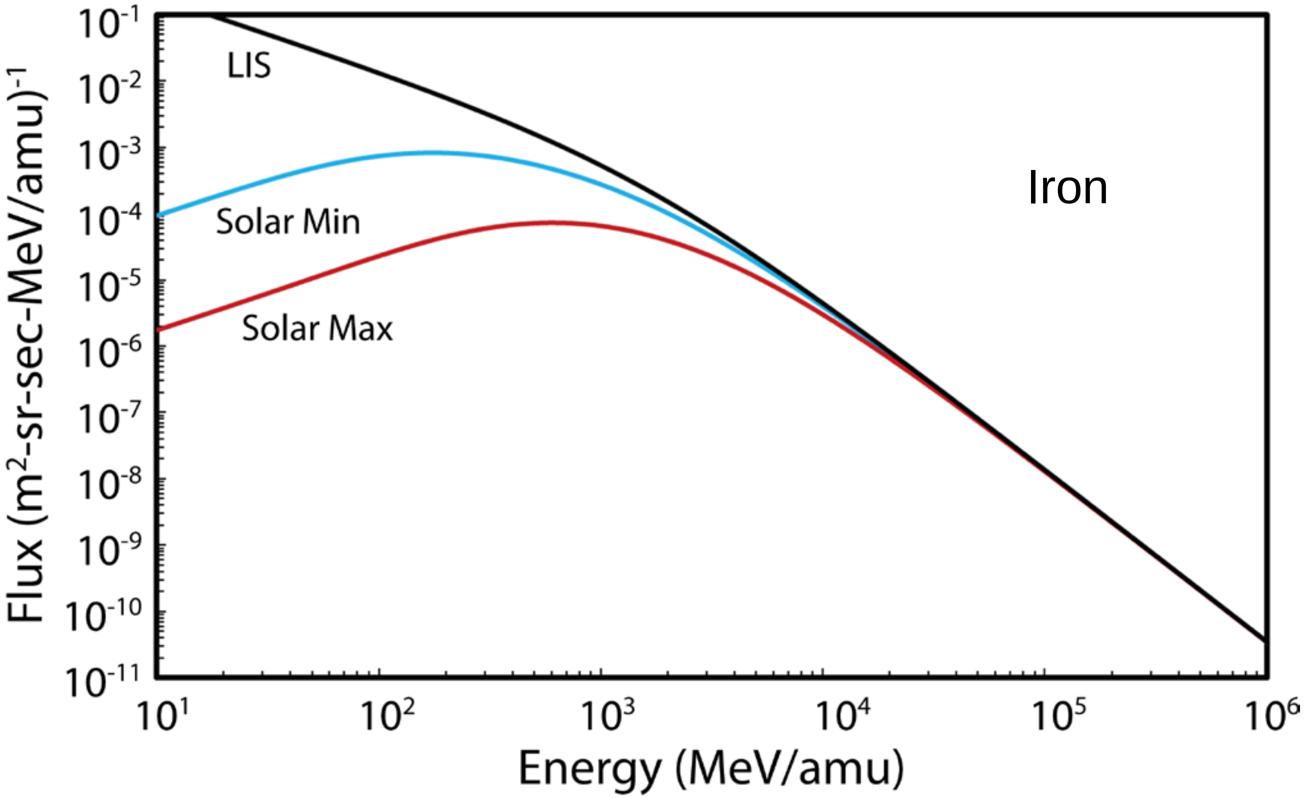
- For GCR energies < 10^{15} eV:
  - Mainly attributed to supernovae within Milky Way galaxy and neutron star collisions
  - Integral fluxes ~ 1 $cm^{-2}s^{-1}$, dependent on solar cycle
  - Most significant for SEE
- For GCR energies > 10^{15} eV:
  - Unknown origin, especially highest energies
  - More a scientific than SEE problem
- Recall charge collected is key metric
  - Directly related to LET



Data from S. Swordy, Space Sci. Rev., Oct. 2001

Models
Variation with Solar Cycle

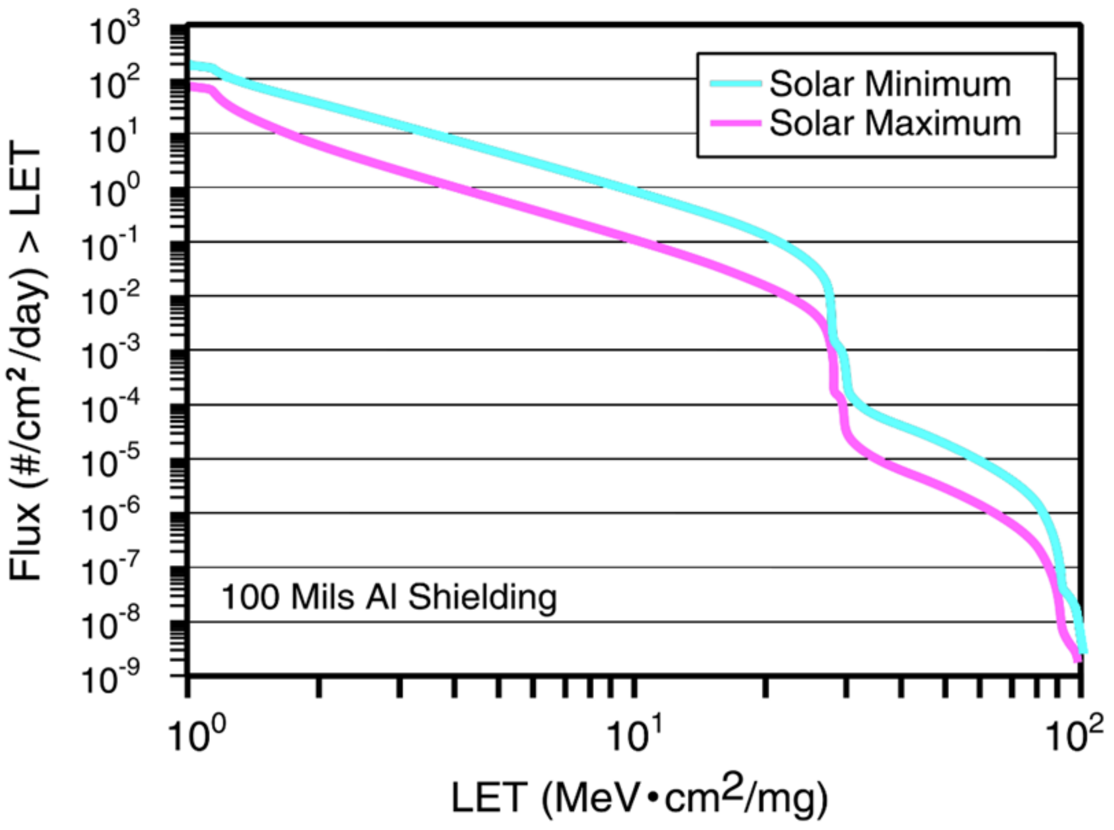
- **Models based on theory of solar modulation of GCR fluxes**
- **Describe penetration of GCR Local Interstellar Spectra (LIS) into heliosphere and transport to near Earth**
- **Variation over the solar cycle results from sun’s magnetic activity**
  - **Higher activity during solar maximum results in lower flux.**



P.M. O’Neill, S. Golge and T.C. Slaba, NASA Tech. Paper, March 2015

Models
Variation with Solar Cycle

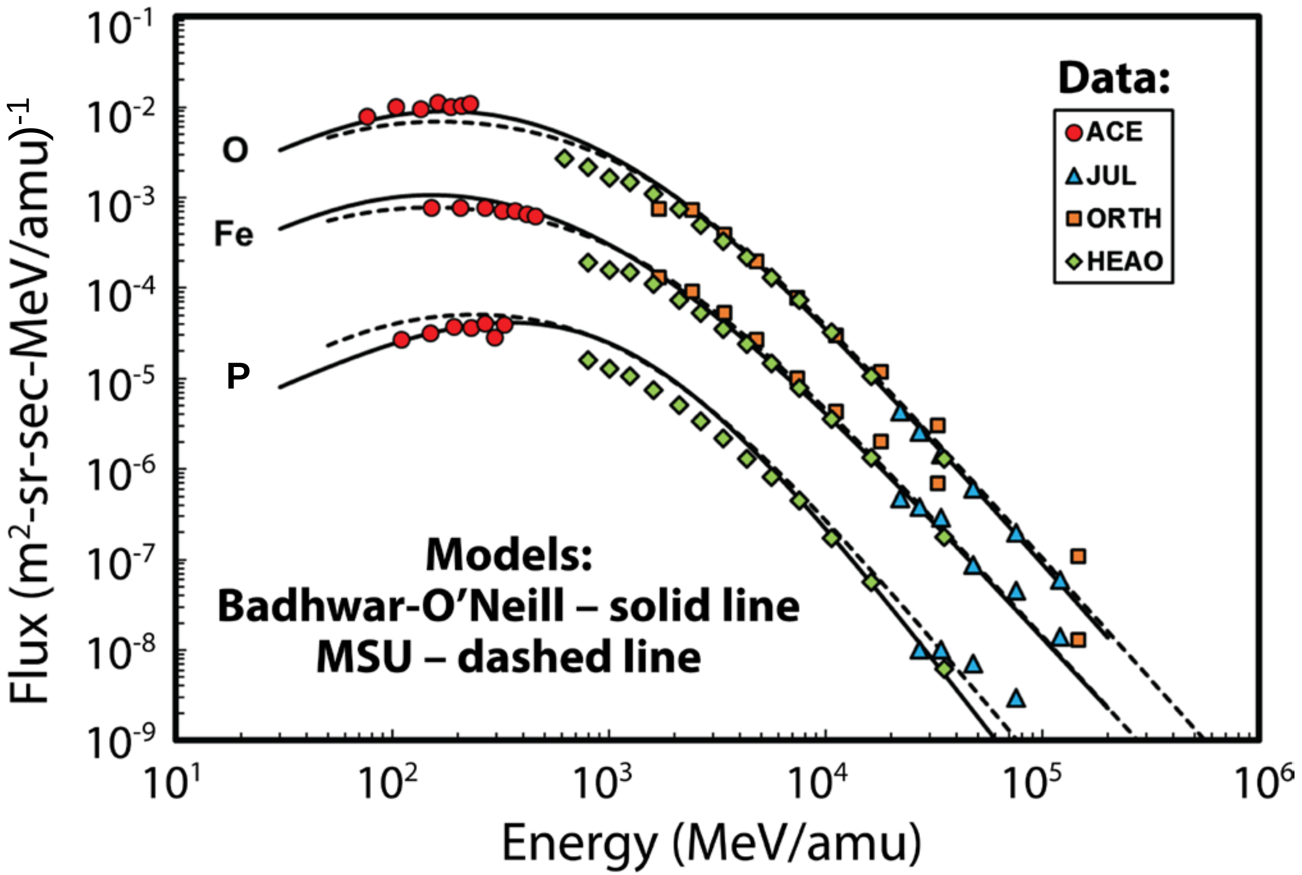
- **Energy spectra can be transformed to LET spectra**
- **LET is directly related to charge deposited in circuit**
- **Bragg Peak (maximum LET) of iron is 29 MeV-cm²/mg in silicon**
  - **Rapid decrease in flux at this point**



From CREME96, https://creme.isde.vanderbilt.edu/

Models

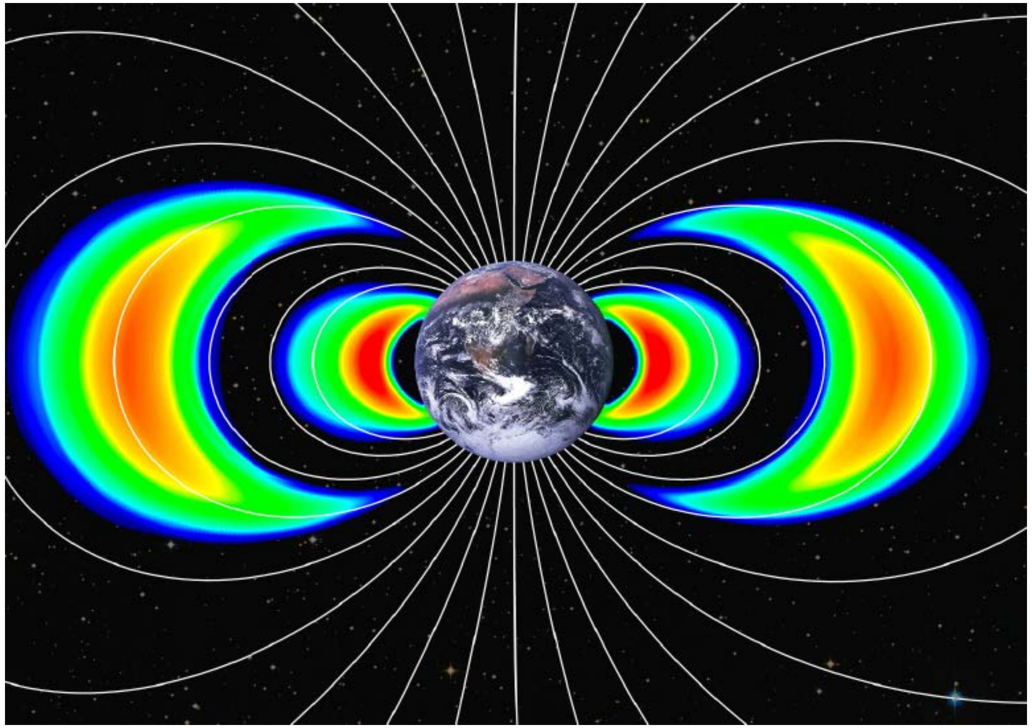
- **Two popular models are used for SEE that parameterize solar modulation using sunspot numbers**
- **Badhwar – O'Neill 2014 Model**
  - **Incorporates broader and more recent data base**
- **MSU (Nymmik) model used in Cosmic Ray Effects in MicroElectronics-1996 (CREME96)**
  - **Integrated with suite of programs for SEE rate calculation, including spacecraft orbit dependence**



P.M. O'Neill, S. Golge and T.C. Slaba, NASA Tech. Paper, March 2015

Quiet Time Environment
Trapped Protons in Van Allen Belts

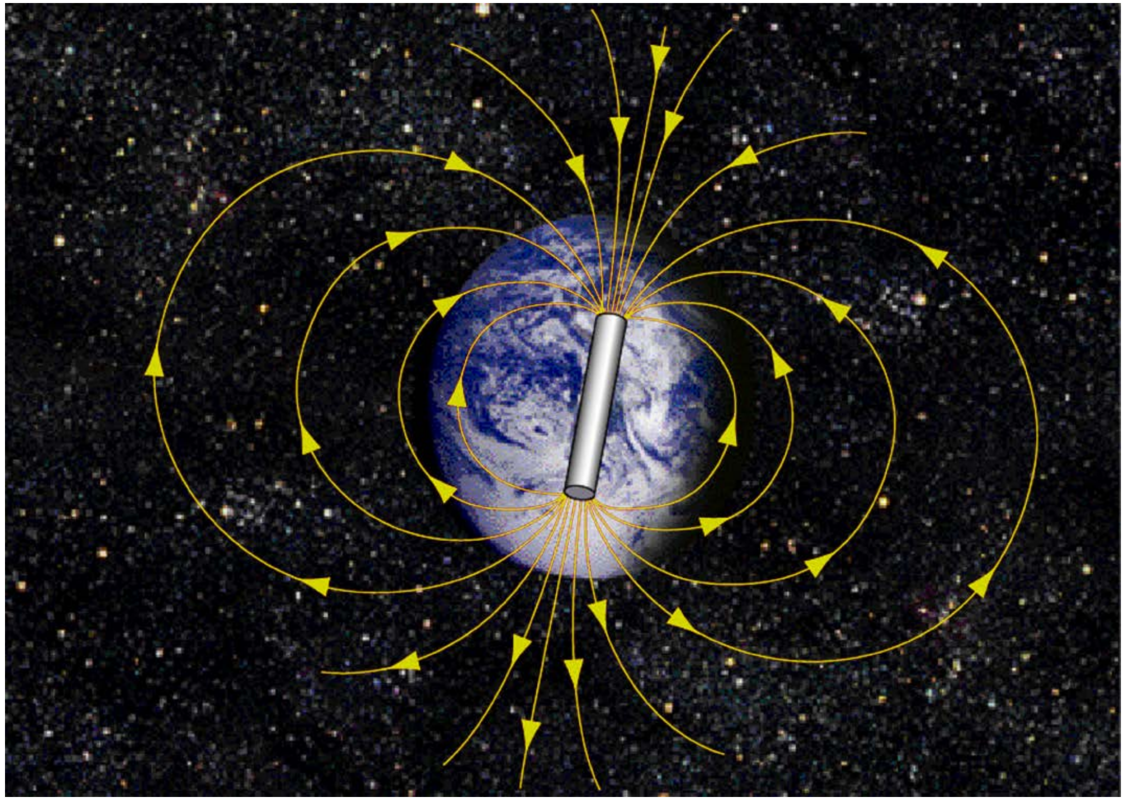
- Trapped Particle Motion in the Geomagnetic Field
  - L-shell Parameter
- Trapped Protons
  - Properties
  - Models – AP8 and AP9/IRENE
- Will not discuss:
  - Trapped electrons
  - Jovian environment



Credit: NASA and Johns Hopkins U. Applied Physics Lab

Earth's Internal Magnetic Field

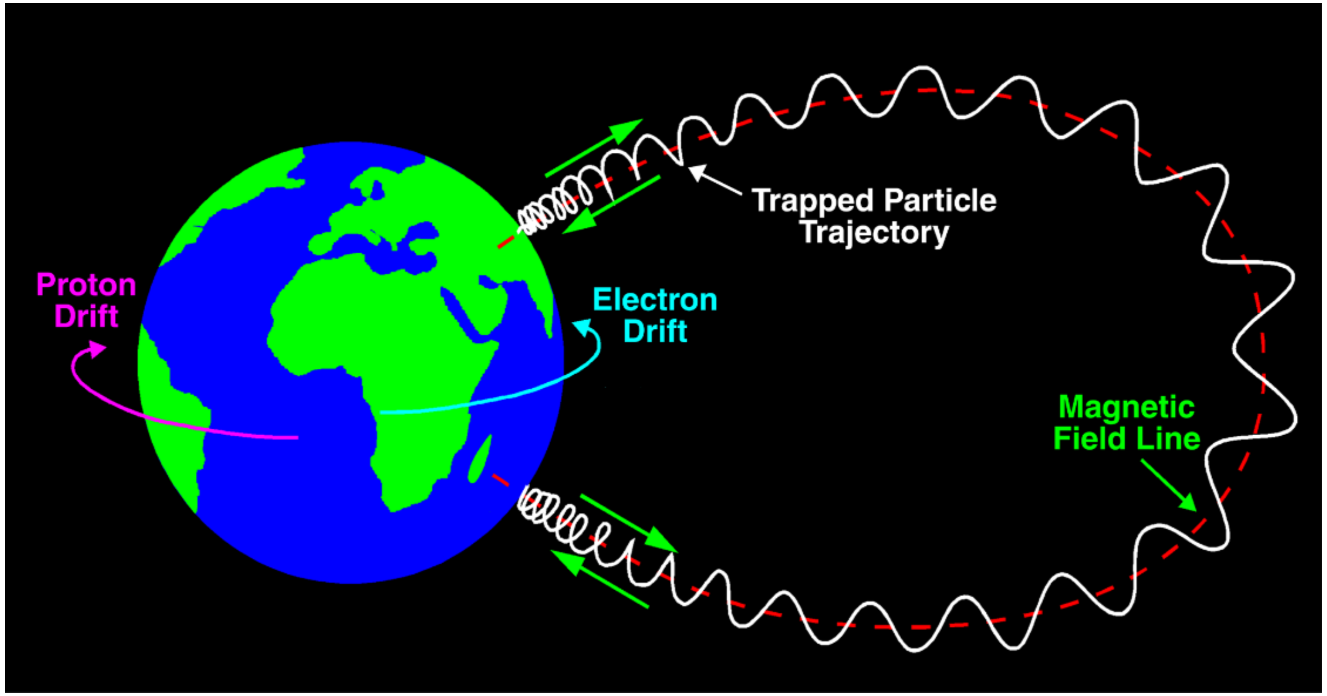
- Geomagnetic field is approximately dipolar for altitudes up to about 4 to 5 Earth radii
- Dipole axis is not same as geographic North-South axis
  - 11.5 degree tilt
  - ~500 km displacement
- Trapped particle populations conveniently mapped in dipole coordinate systems



Credit: ESA

Trapped Charged Particle Motion

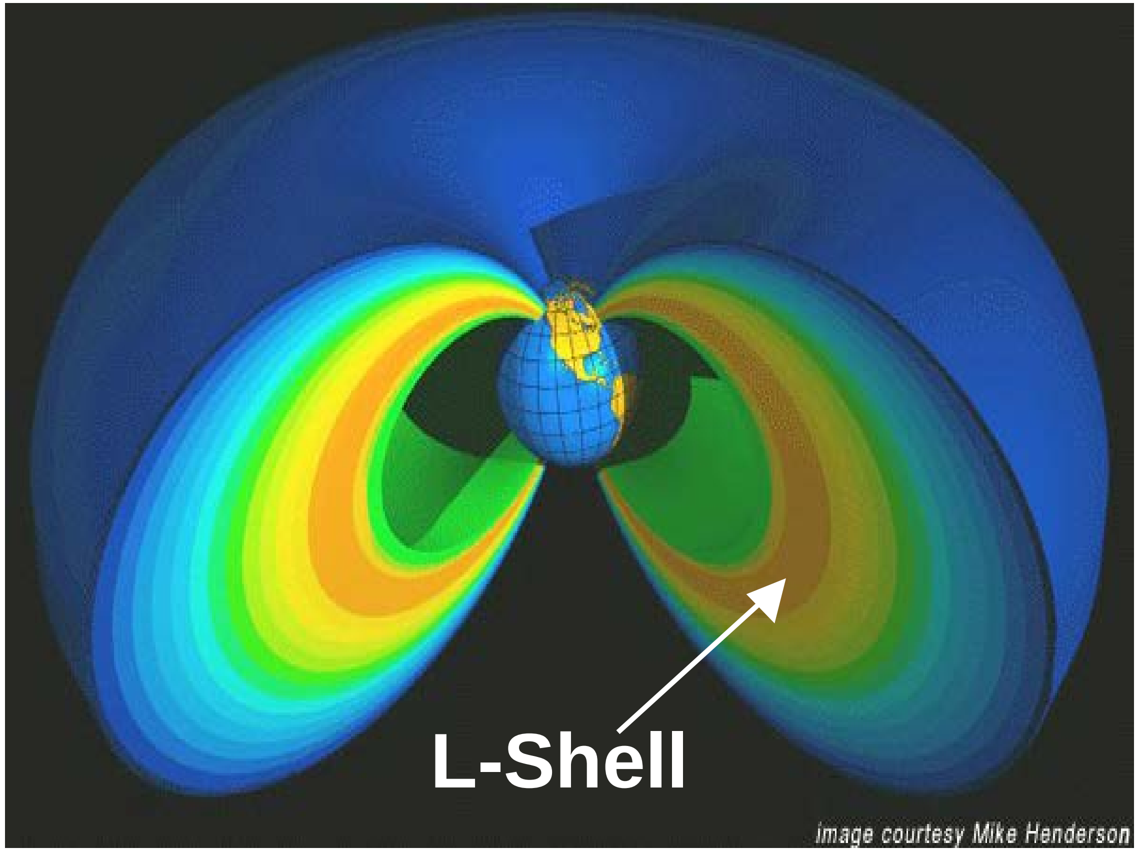
- In Earth's magnetic field
  - Particles spiral along magnetic field lines
  - Increased field strength in polar region causes particle spiral to tighten and eventually reverse direction along magnetic field line at "mirror point"
  - Radial gradient in magnetic field causes slow longitudinal drift around Earth
  - A complete azimuthal rotation of particle trajectory traces out a drift shell or L-shell.



After E.G. Stassinopoulos

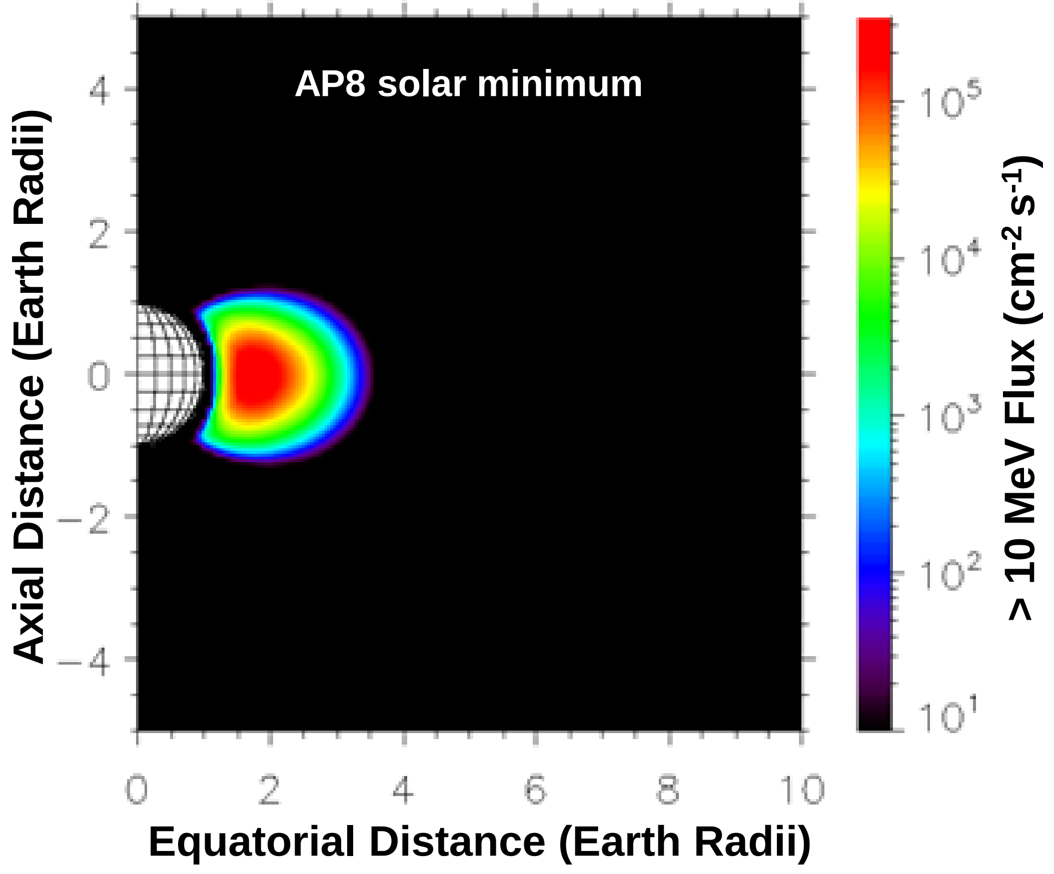
The L-Shell Parameter

- L-shell parameter indicates magnetic equatorial distance from Earth's center in number of Earth radii and represents the entire drift shell.
- An L-shell contains a subset of trapped particles peaked at a certain energy moving throughout this shell.
- Provides convenient global parameterization for a complex population of particles



Trapped Proton Properties

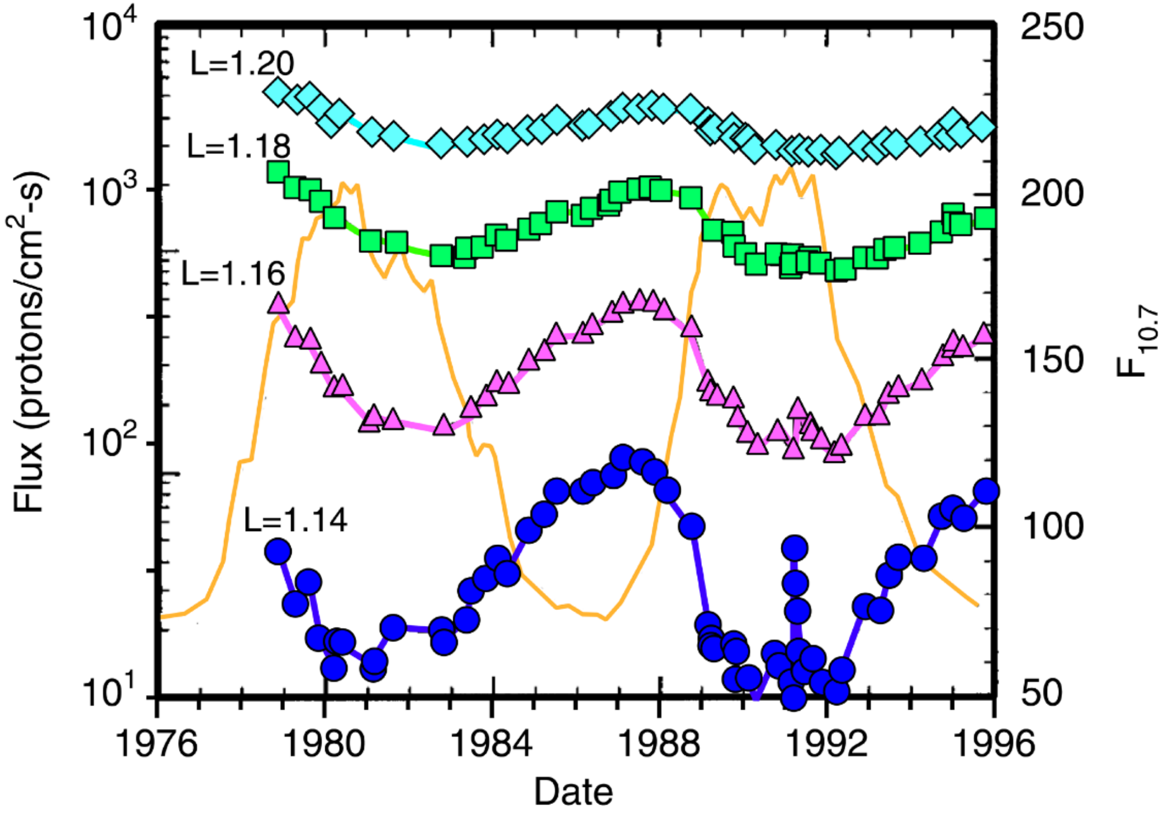
- Nuclear reaction products from incident protons can have LET values up to 20 MeV-cm^2/mg.
- Single trapped proton region for "quiet" conditions
- Earth's atmosphere limits belt to altitudes above ~200 km
- > 10 MeV flux peaks at L-shell = 1.8 and extends to about 4.
- Energies up to ~GeV



S. Bourdarie and M.A. Xapsos, IEEE TNS, Aug. 2008

Solar Cycle Modulation

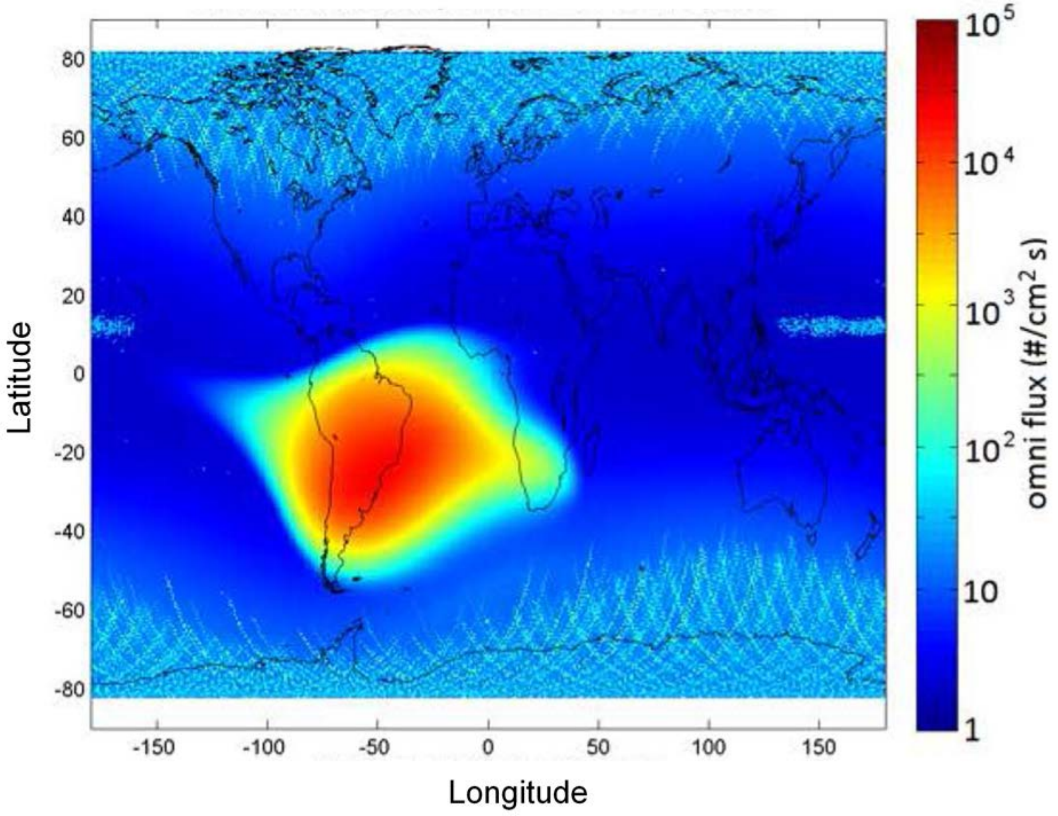
- **Proton fluxes generally anti-correlated with solar cycle activity**
  - **Most pronounced near belt's inner edge**
- **During solar maximum**
  - **Increased loss of protons in upper atmosphere**
  - **Decreased production of protons from Cosmic Ray Albedo Neutron Decay (CRAND) process**



S.L. Huston and K.A. Pfitzer, IEEE TNS, Dec. 1998

South Atlantic Anomaly

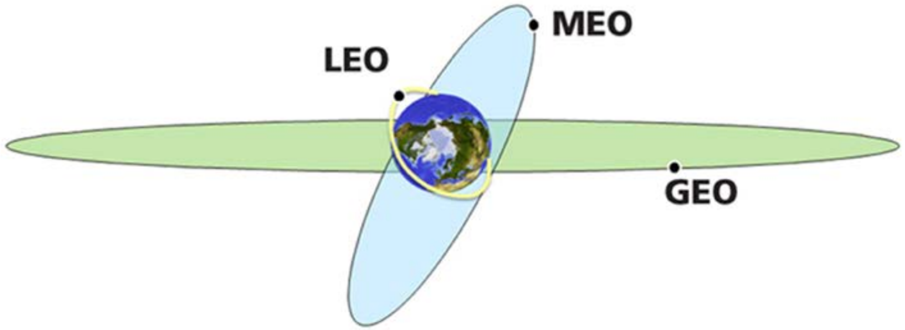
- **Generally dominates the radiation environment for altitudes less than about 1000 km**
- **Caused by tilt and shift of geomagnetic axis relative to rotational axis**
- **Inner edge of proton belt is at lower altitudes in vicinity of South America**



W.R. Johnston et al., IEEE TNS, Dec. 2015

Trapped Particle Models

- General approach
  - Use an orbit generator code to calculate geographical coordinates (latitude, longitude, altitude)
  - Transform the geographical coordinates to dipole coordinate system in which particle population is mapped
  - Determine trapped particle environment external to spacecraft
  - Available in SPace ENVironment Information System (SPENVIS)



Credit: http://www.intelsat.com/

Trapped Particle Models
SEE Application

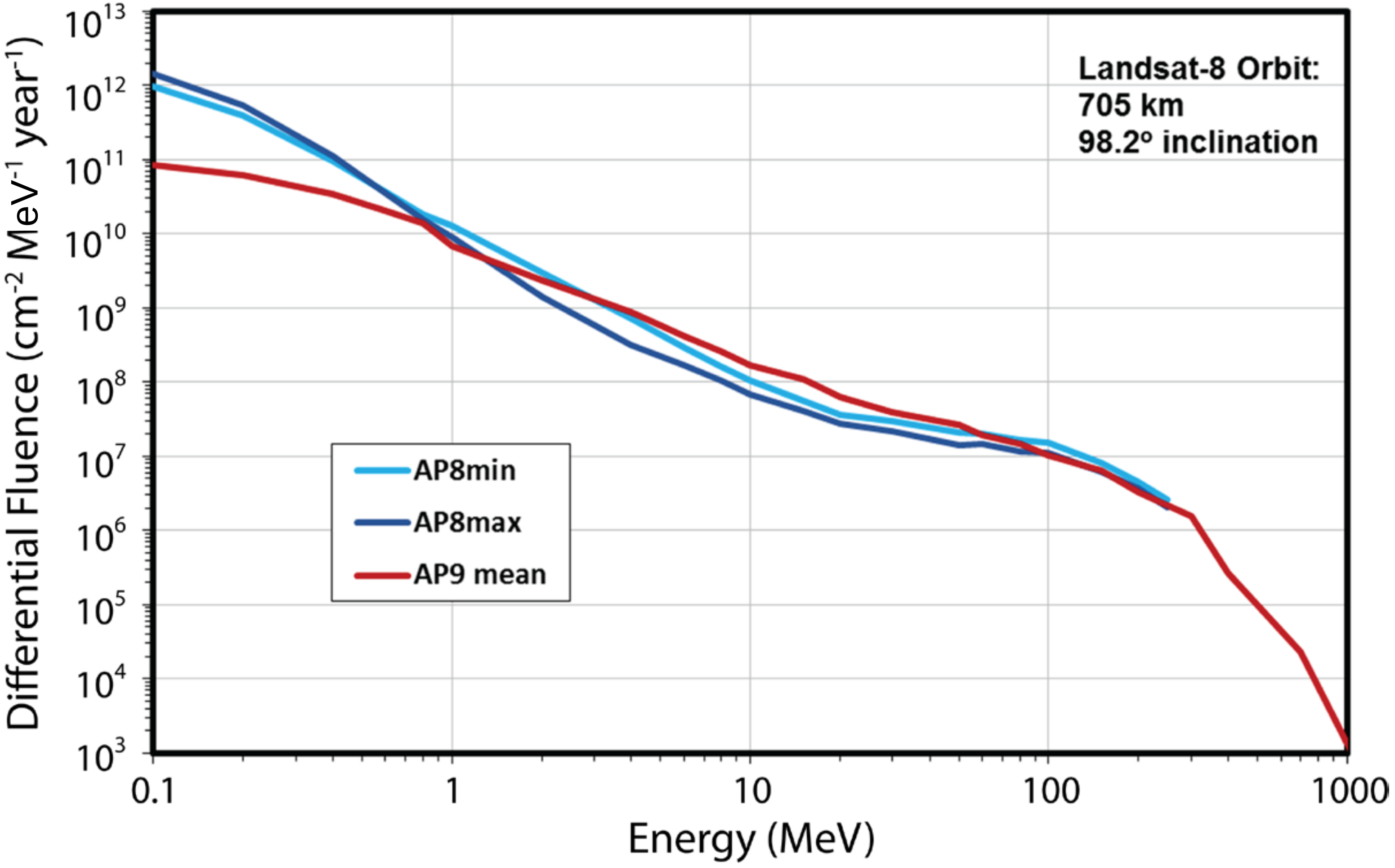
- AP8
  - Static model for mean environment
  - Based on data from 1960s and 1970s
  - Approximate solar cycle dependence
    - Solar maximum
    - Solar minimum

- AP9/IRENE
  - Statistical model for mean or percentile environment
  - Perturbed model adds measurement uncertainty and gap-filling errors
  - Monte Carlo adds space weather variations
  - Based on data from 1976 – 2016
    - ~10x that of AP8 based on instrument years
  - Output averaged over solar cycle

There is another comprehensive trapped particle model, the Global Radiation Earth ENvironment (GREEN) model, from ONERA now available.

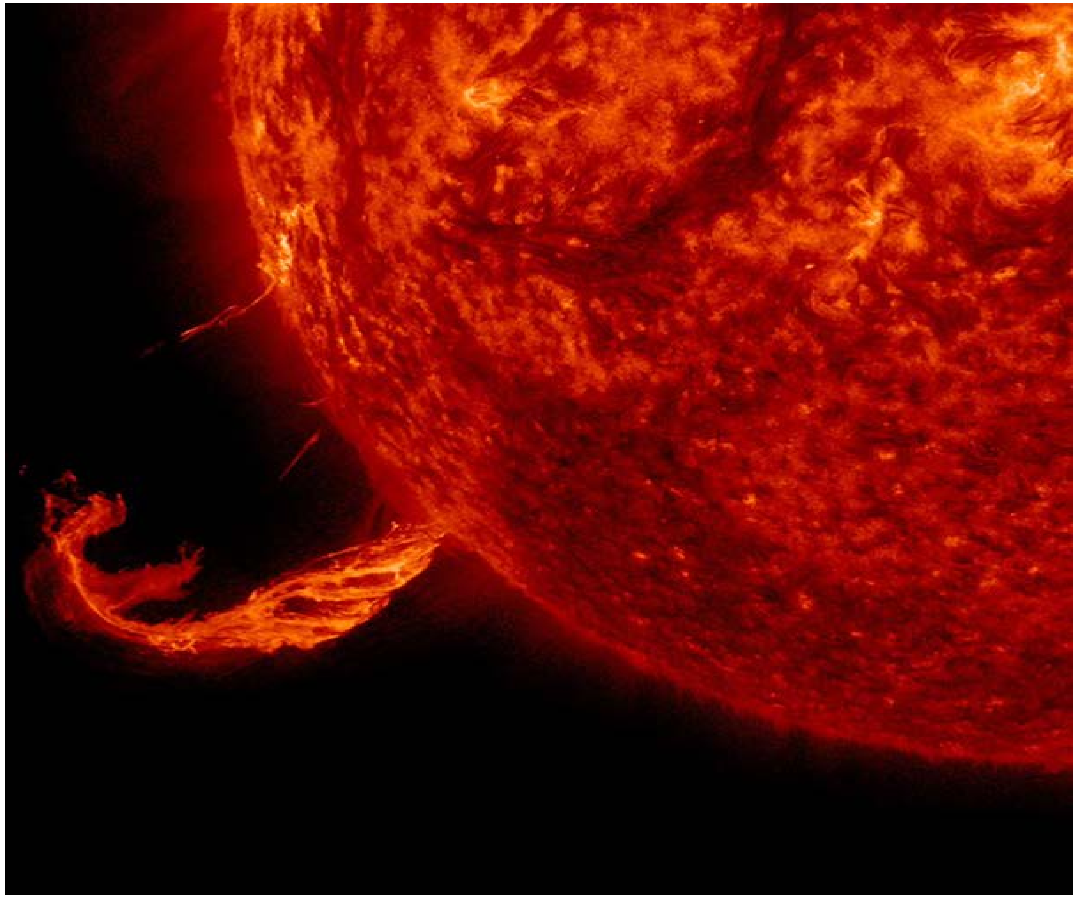
Comparison of AP8 and AP9/IRENE

Polar Low Earth Orbit



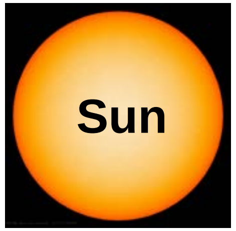
Worst Case Environment
Solar Particle Events

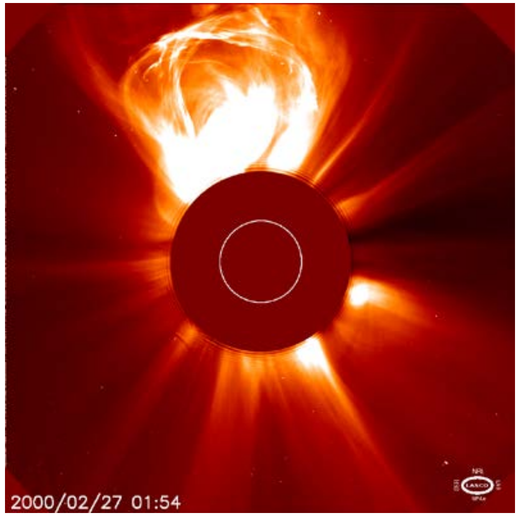
- Properties
  - Coronal Mass Ejections (CME)
  - Solar Flares
- Model
  - CREME96



Credit: NASA (SDO)

Solar Energetic Particle Production





Mass Emission

Electromagnetic Emission

CMEs

Solar Wind

Irradiance

Solar Flares

Solar Energetic Particles

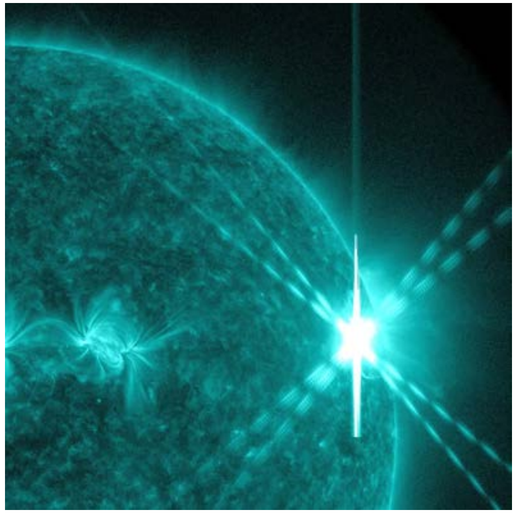
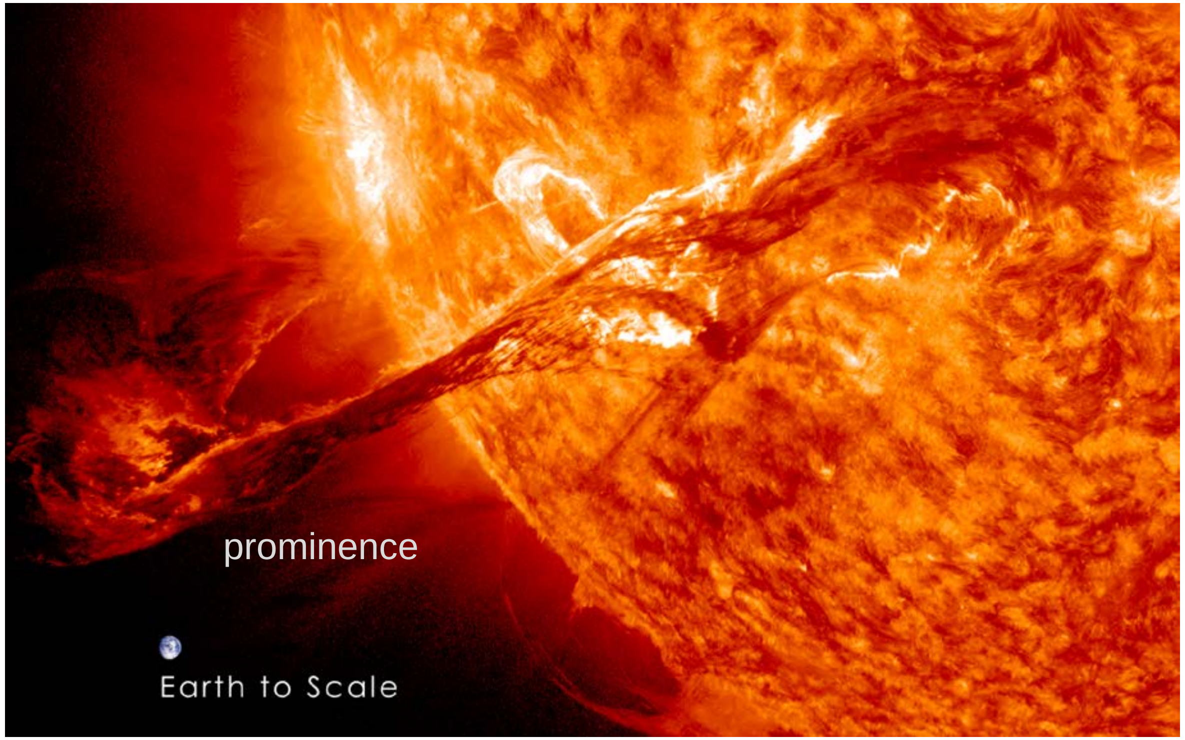


Image credits: NASA and ESA (SOHO and SDO)

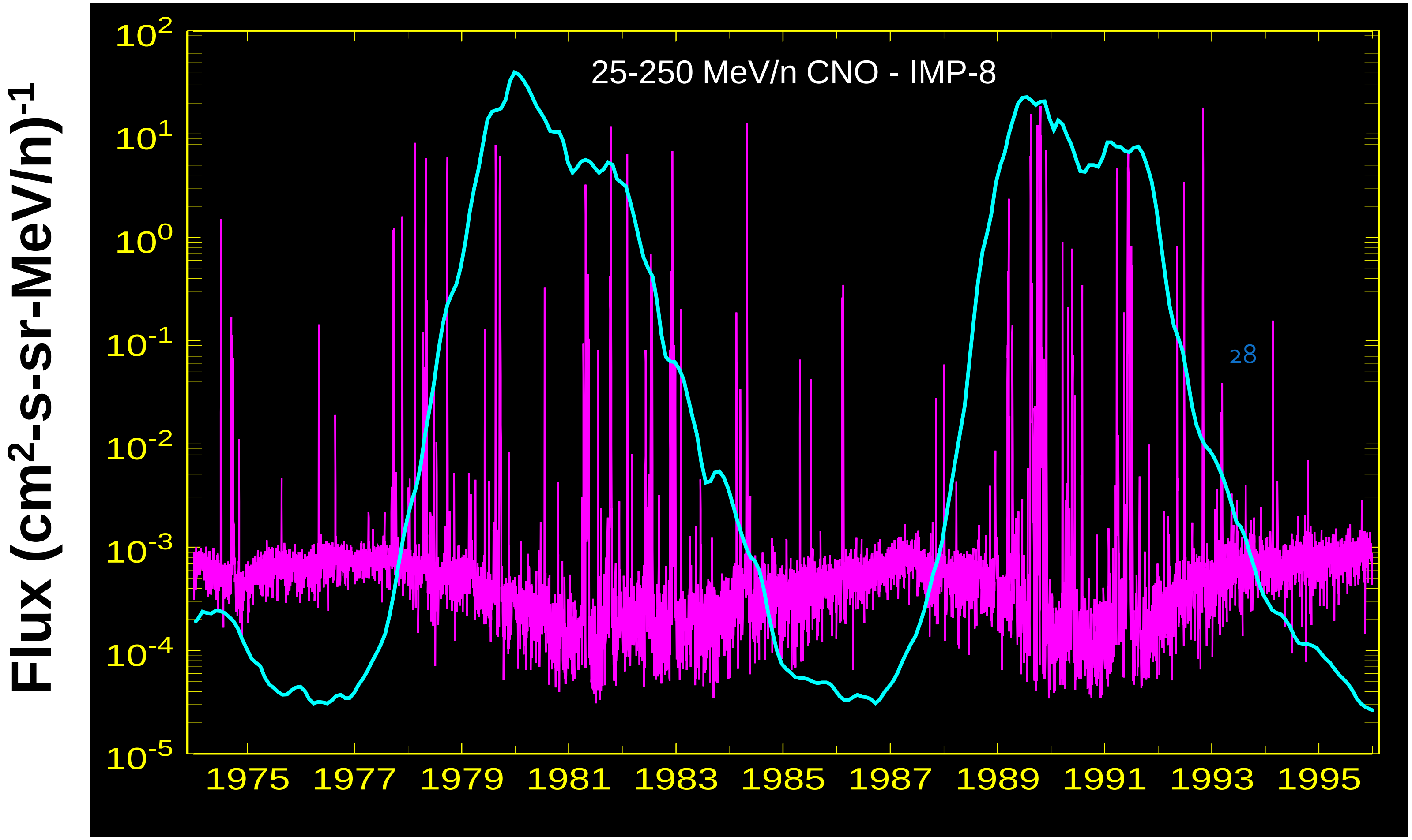
Coronal Mass Ejection Properties

- **Responsible for major disturbances in Earth's magnetosphere and interplanetary space**
- **Typically takes hours to a few days to reach Earth**
- **Very proton rich ~ 96% on average**
- **Energies up to ~ GeV/n**
- **Extreme CME magnitudes**
  - **> 10^{14} kg of magnetized plasma ejected**
  - **> 10 MeV/n fluence can exceed 10^9 cm^{-2}**
  - **> 10 MeV/n peak flux can exceed 10^5 cm^{-2}s^{-1}**



Credit: NASA (SDO)

Solar Cycle Dependence

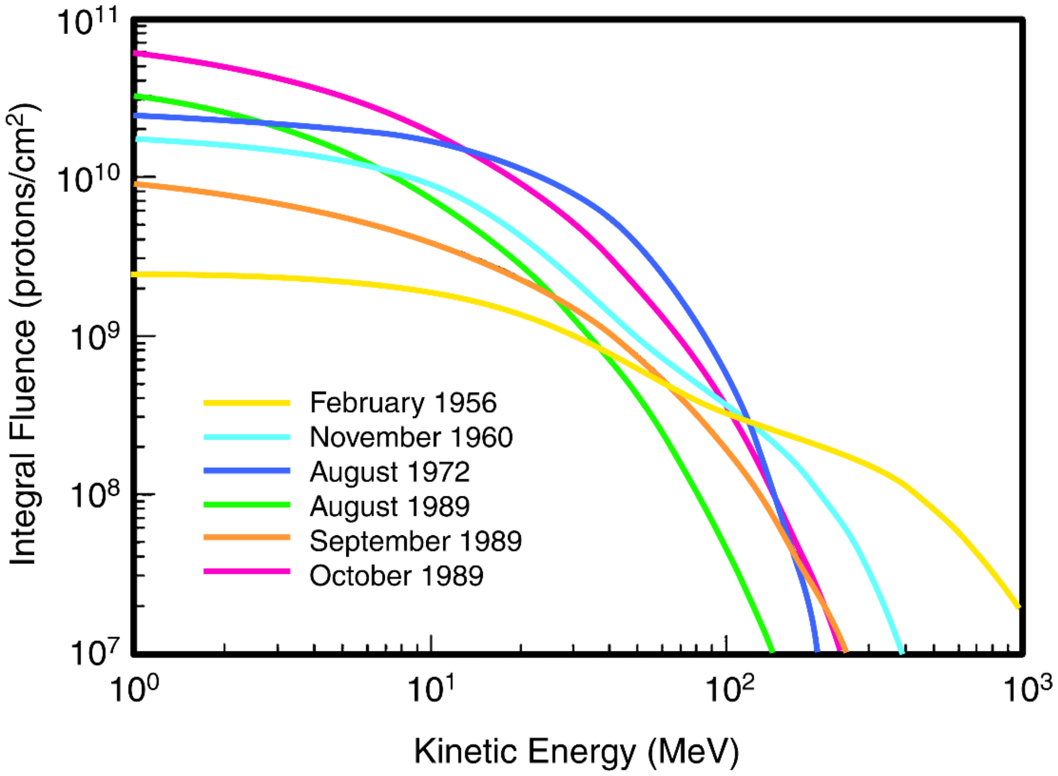


Year

J.L. Barth, 1997 NSREC Short Course

Worst Case Solar Particle Events

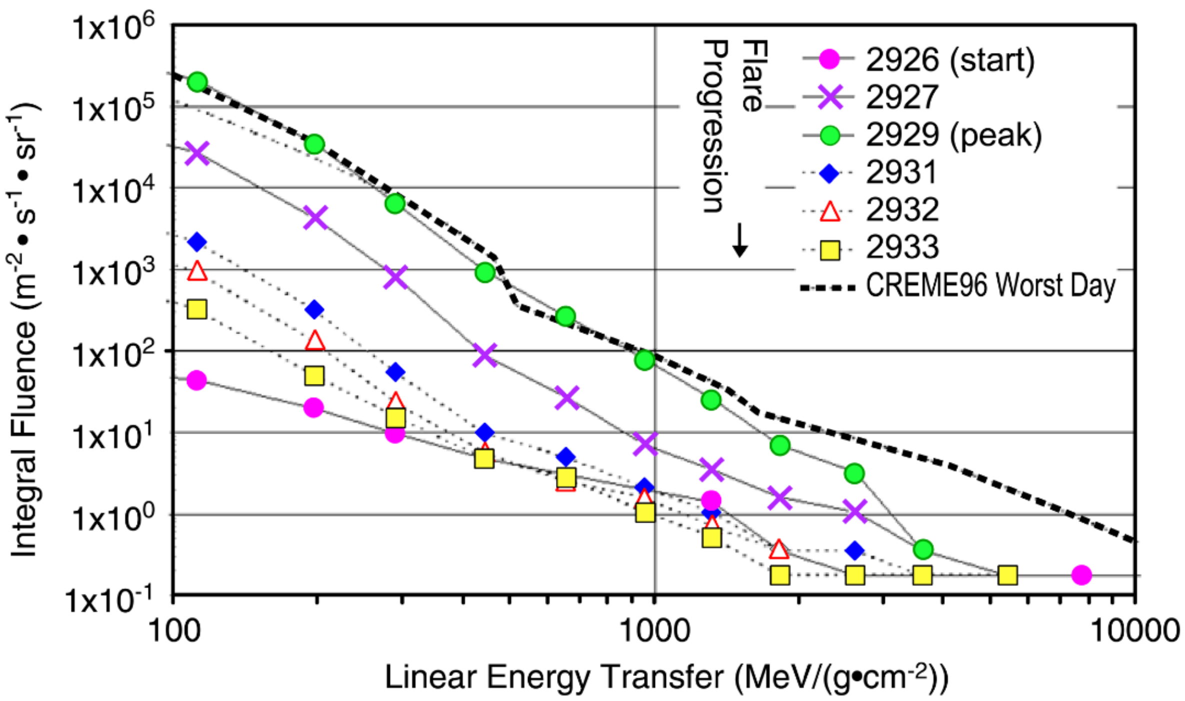
- **Most common approach is to design to a well-known large event**
- **Events most often considered:**
  - **October 1989**
  - **August 1972**
  - **~~Carrington Event 1859~~**
    - **Published ice core data not a reliable indicator of solar proton event magnitudes**



J.W. Wilson et al., Radiat. Meas., 1999

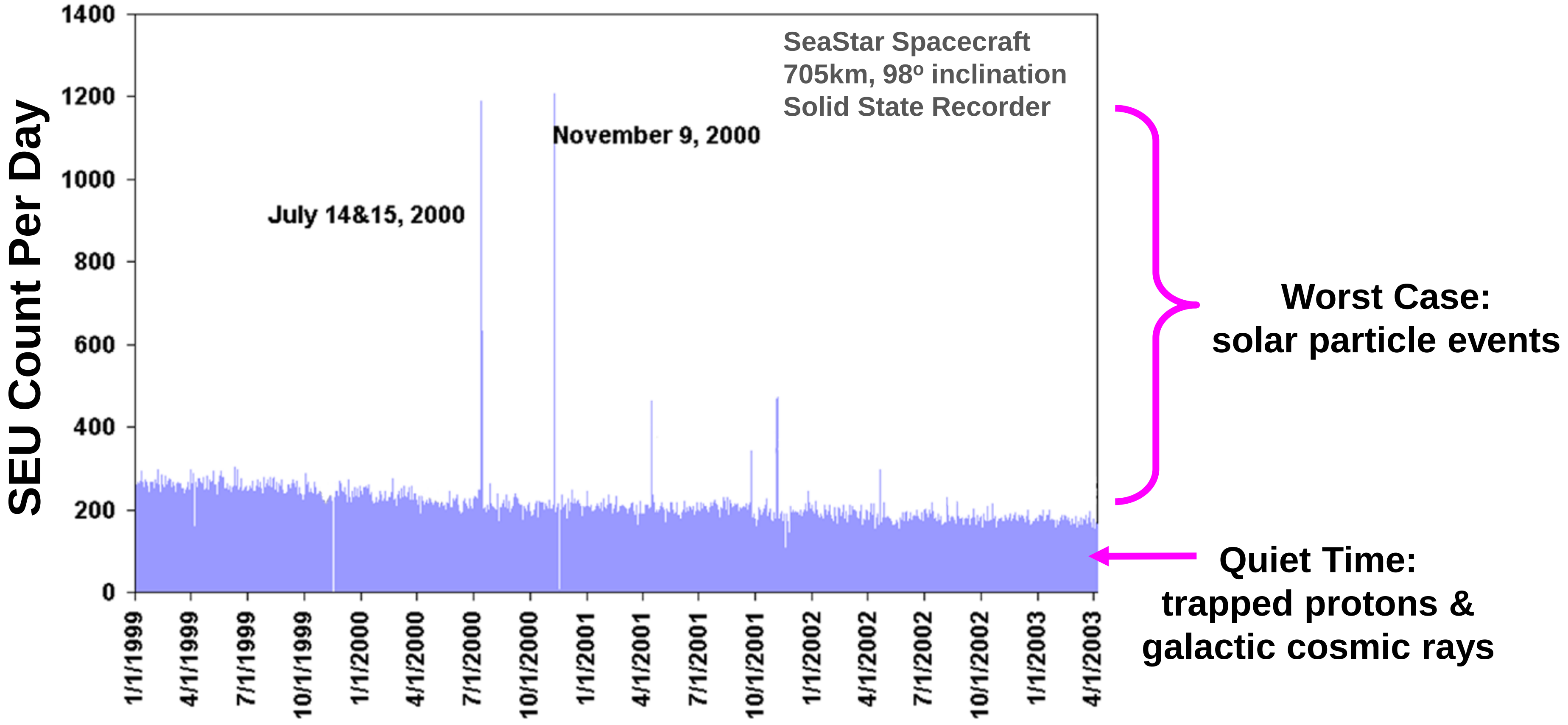
Worst Case Solar Particle Event Model
CREME96

- **Standard CREME96 model based on October 1989 event**
  - **Peak 5 minutes**
  - **Worst day**
  - **Worst week**
- **Incorporated into suite of codes including orbit generator, magnetic and material shielding**
- **Useful for both protons and heavy ions**
- **QinetiQ's CREDO experiment showed "worst day" model bounded severe events during solar cycle 23.**



C.S. Dyer et al., IEEE TNS, Dec. 2002

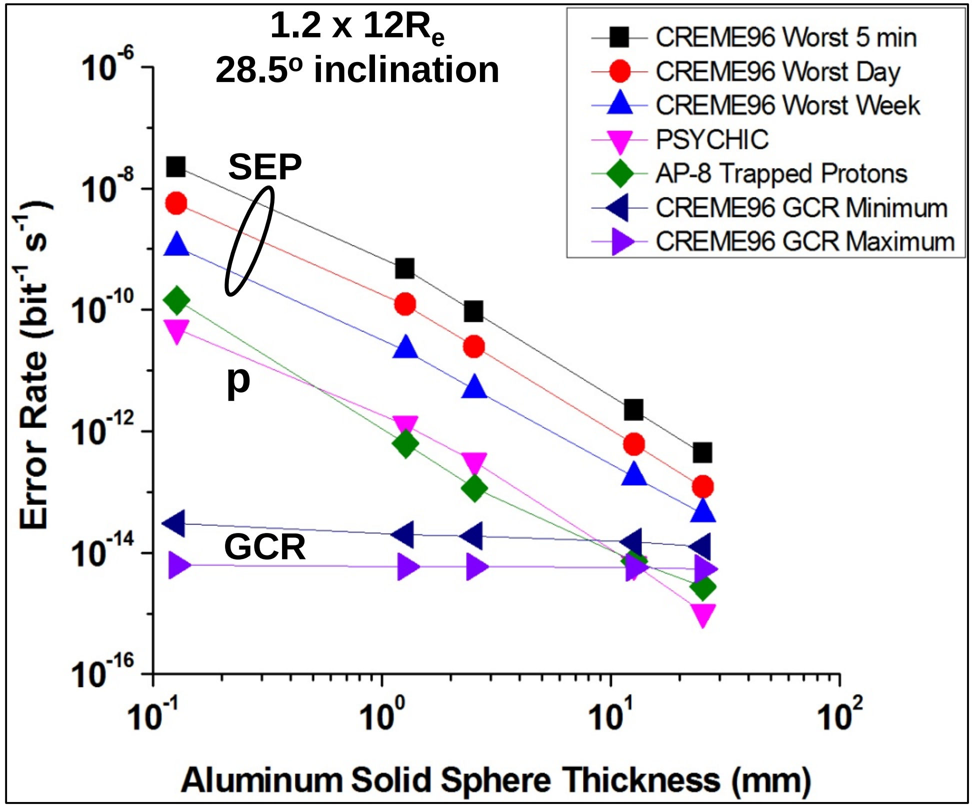
Example Environment
Measured Single Event Upsets



C. Poivey, et al., SEE Symposium, Los Angeles, CA, April 2002

Example Environments
Effect of Shielding on Single Event Upset

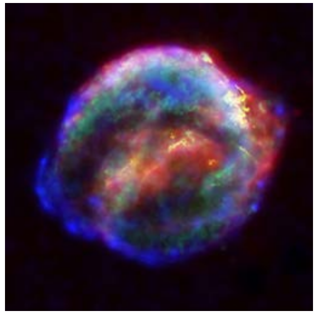
- Consider Highly Elliptical Orbit
  - For SEE must account for solar heavy ions and galactic cosmic rays
  - For sensitive devices must also include solar and trapped protons
- SEU rate calculated for 4 Gbit NAND flash memory
- Shielding can reduce rates during solar events and for trapped protons.
- GCR rate provides a lower limit for SEU not practical to reduce

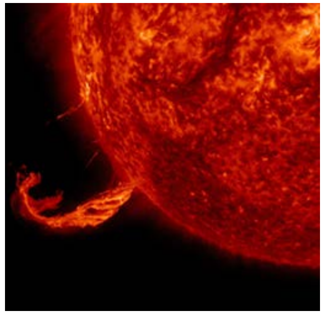


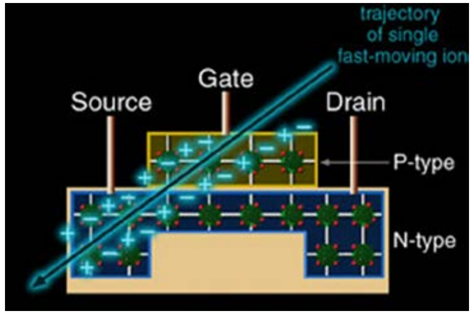
J.A. Pellish et al., IEEE TNS, Dec. 2010

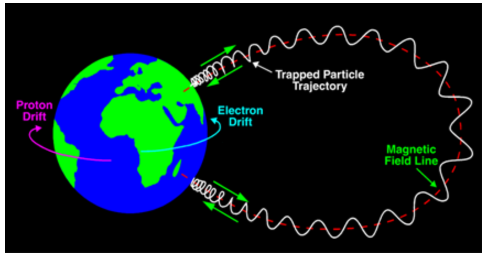
Summary

- The SEE environment of space has been discussed.
- Space radiations that can contribute to SEE during quiet conditions are GCR and trapped protons.
- Solar energetic particles cause worst case SEE rates.
- Models available for public use can be found at the SPENVIS and CREME web sites:
  - https://www.spenvis.oma.be/
  - https://creme.isde.vanderbilt.edu/









Acronyms

- AP8/9 – Aerospace Proton Model 8/9
- CME – Coronal Mass Ejection
- CRAND – Cosmic Ray Albedo Neutron Decay
- CREDO – Cosmic Radiation Environment and Dosimetry Experiment
- CREME96 – Cosmic Ray Effects in Microelectronics 1996
- GCR – Galactic Cosmic Rays
- GREEN – Global Radiation Earth Environment
- IRENE – International Radiation Environment Near Earth
- LASCO – Large Angle and Spectrometric Coronagraph
- LET – Linear Energy Transfer
- LIS – Local Interstellar Spectrum
- MSU – Moscow State University
- NAND – Neither Agree Nor Disagree
- NSREC – Nuclear and Space Radiation Effects Conference
- SEB – Single Event Burnout
- SEE – Single Event Effects
- SEL – Single Event Latchup
- SET – Single Event Transient
- SEU – Single Event Upset
- SOHO – Solar and Heliospheric Observatory
- SPENVIS – Space Environment Information System