Radiation Effects in Semiconductors and Devices Session

The Near-Earth Space Radiation Environment

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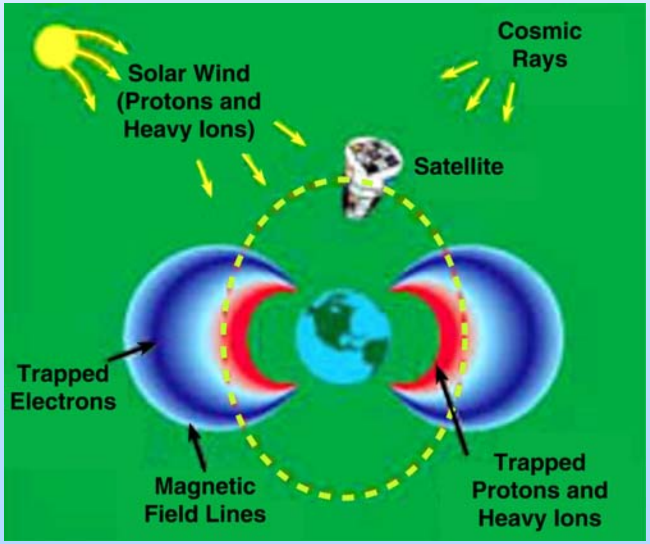
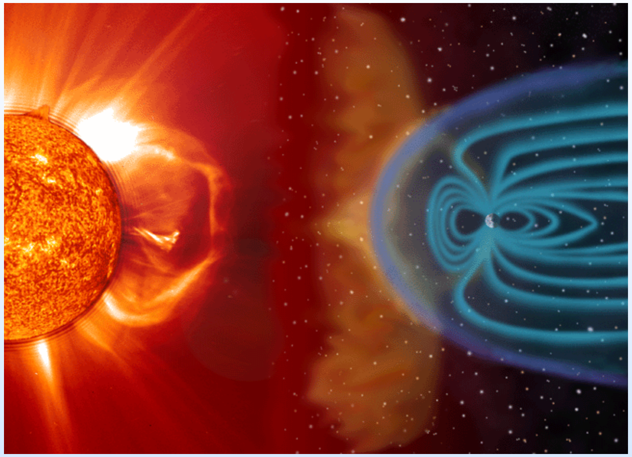
Outline

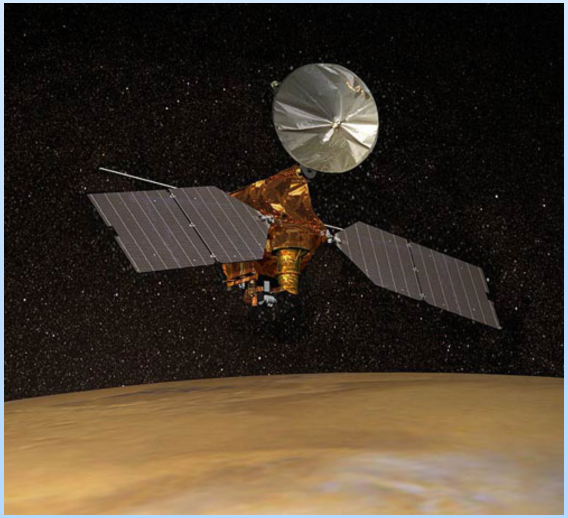
- Background
- The Earth's Trapped Radiation Environment
- Solar Particle Events
- Galactic Cosmic Rays
- Comparison to Accelerator Facilities



Introduction

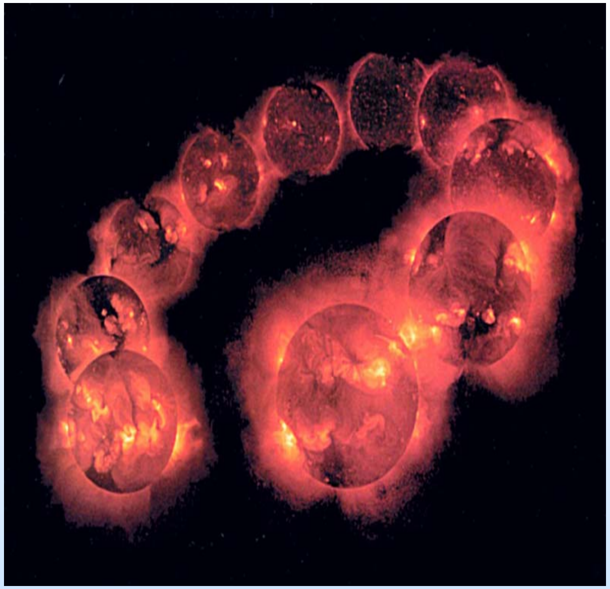
- **Understanding the space radiation environment is important for**
  - **reliable, cost-effective microelectronic system designs**
  - **implement new space technologies**
- **Underestimating radiation levels leads to**
  - **excessive risk**
  - **degraded system performance**
  - **loss of mission lifetime**
- **Overestimating radiation levels leads to**
  - **excessive shielding**
  - **reduced payloads**
  - **over-design**
  - **increased cost**

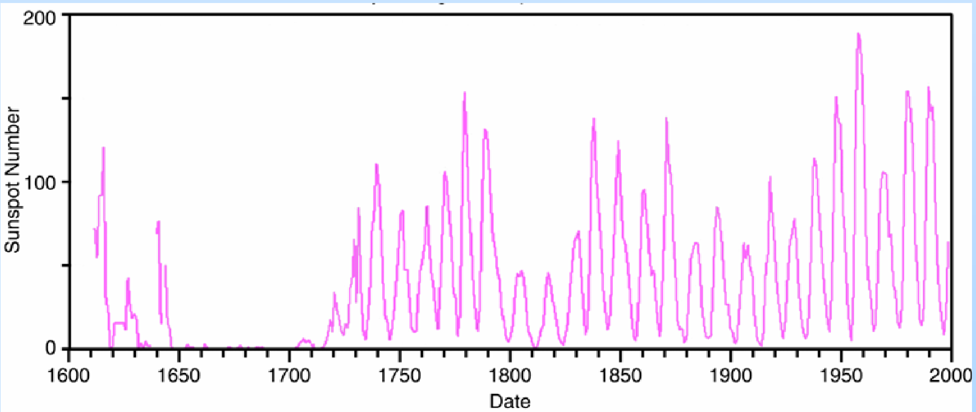




The Solar Activity Cycle

- **The sun is a source and modulator of space radiations.**
- **Many characteristics of space radiations follow the cyclical behavior of solar activity.**
- **Its approximately 11-year cycle typically consists of**
  - **7 years of solar maximum**
  - **4 years of solar minimum**
- **Sunspot numbers are commonly used indicators of solar activity.**





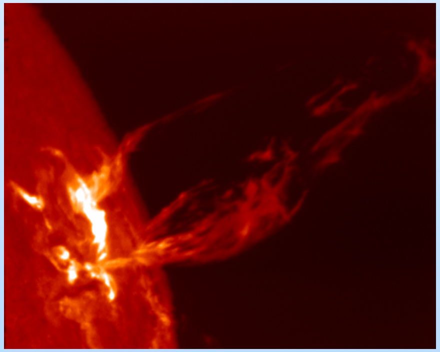
The Space Radiation Environment

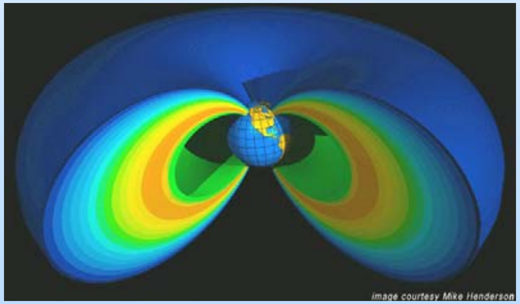
High Energy Particle Radiation

Galactic Cosmic Rays

Solar Particle Events

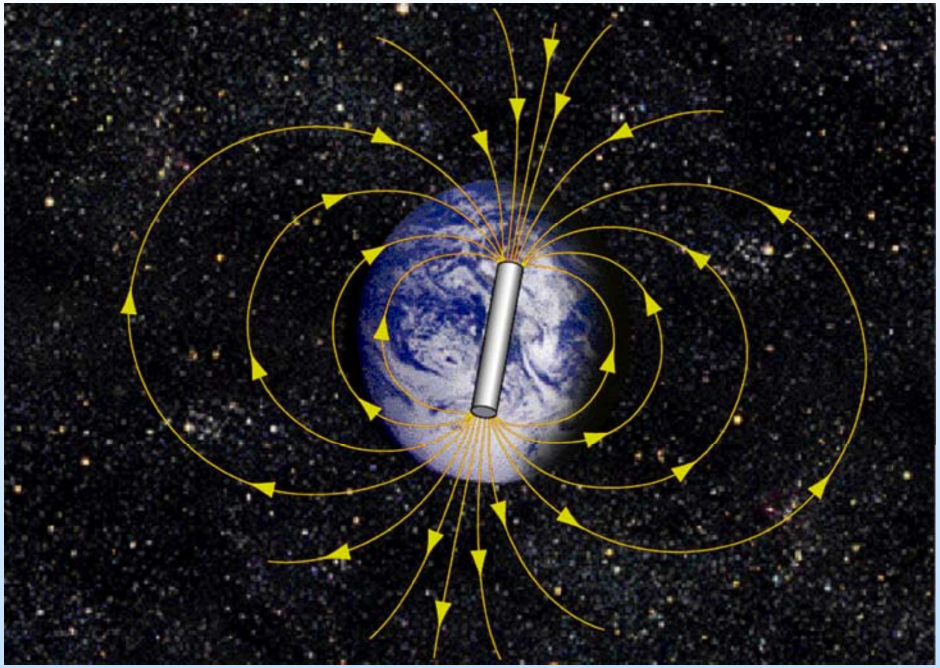
Trapped Particles





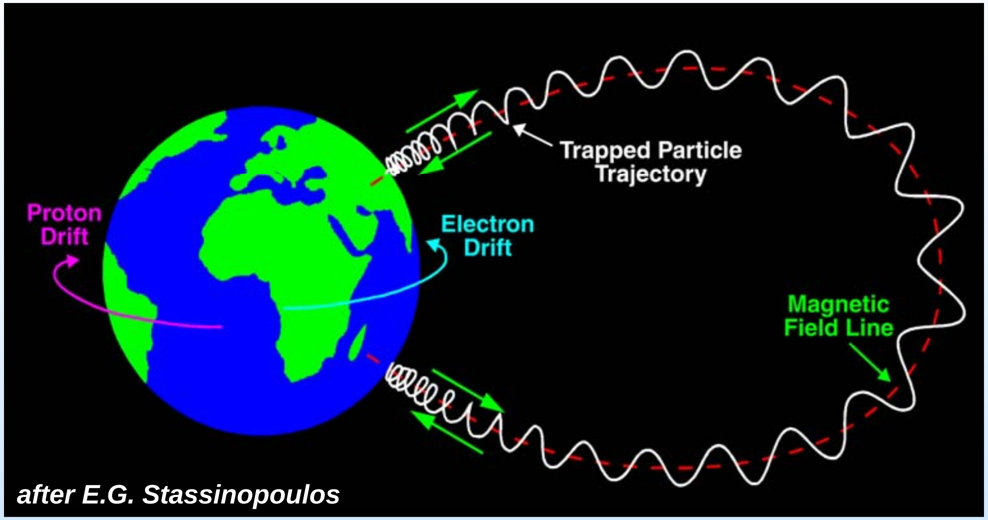
Trapped Particles
Earth's Internal Magnetic Field

- **Geomagnetic field is approximately dipolar for altitudes up to about 4 to 5 earth radii.**
- **Dipole axis not same as geographic North-South axis**
  - **11^{o} tilt**
  - **> 500 km displacement**
- **Trapped particle populations conveniently mapped in terms of dipole coordinate systems.**



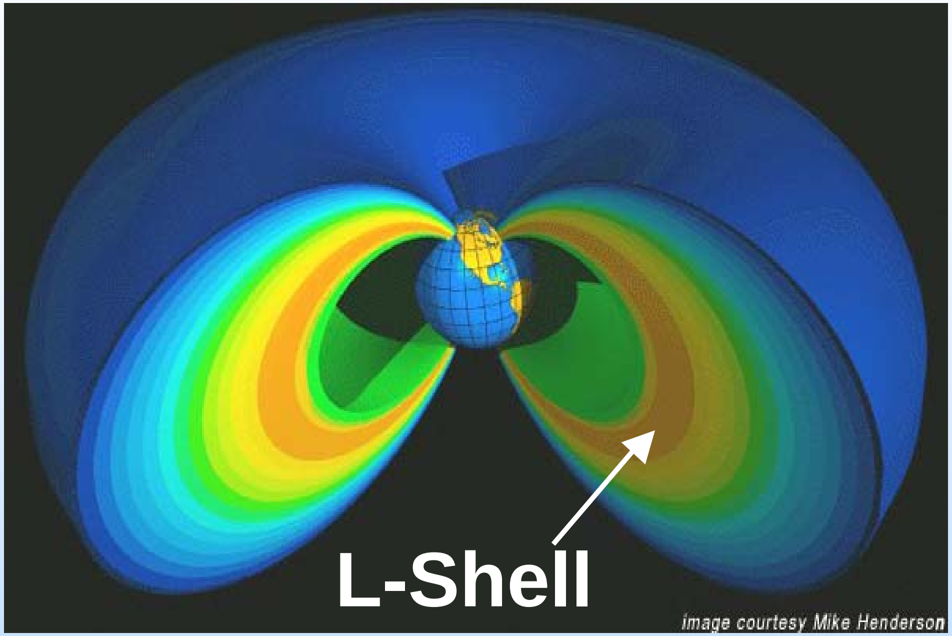
Trapped Charged Particle Motion

- In earth's magnetic field
  - Particles spiral along magnetic field lines
  - Increased field strength in polar region causes spiral to tighten and eventually the particle reverses direction.
  - Additionally, there is a slower longitudinal drift around the earth.
  - A complete azimuthal rotation of the trajectory traces out a drift shell or L-shell.



The L-Shell Parameter

- **L-shell parameter indicates magnetic equatorial distance from center of earth in number of earth radii but represents the entire drift shell.**
- **An L-shell contains a subset of trapped particles that are peaked at a certain energy moving throughout this shell.**

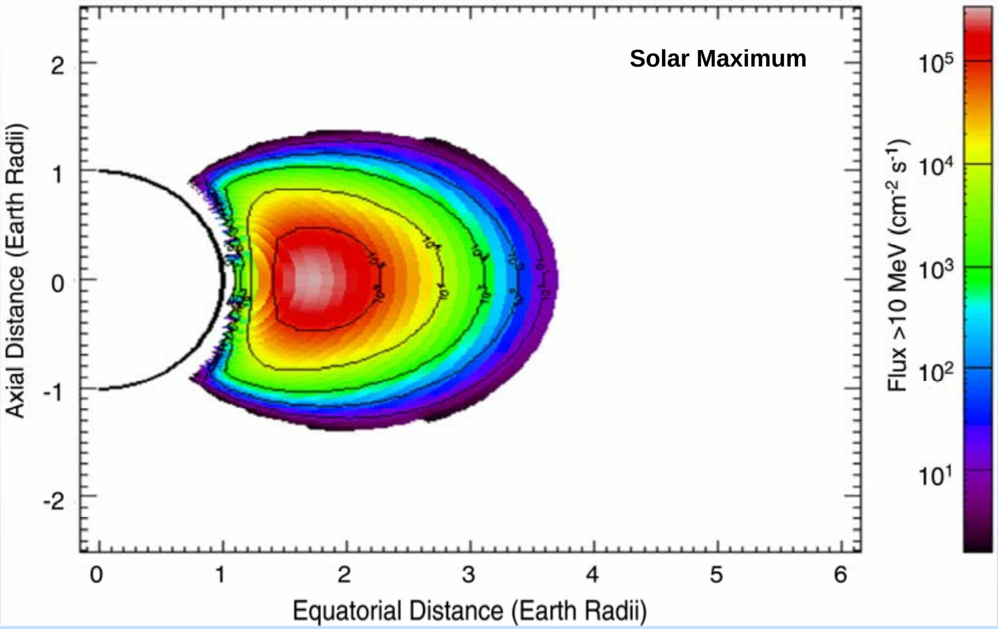


Characteristics of Trapped Protons

- **Single trapped proton region under "quiet" conditions**
  - **L-shell values: 1.15 to 10**
  - **Energies: up to a few 100's of MeV**
    - **> 10 MeV energies confined to altitudes below 20,000 km**
  - **Fluxes: up to ~ 10^5 $cm^{-2}s^{-1}$, near L = 1.8**
- **Energies and Fluxes similar to what can be obtained at accelerator facilities**

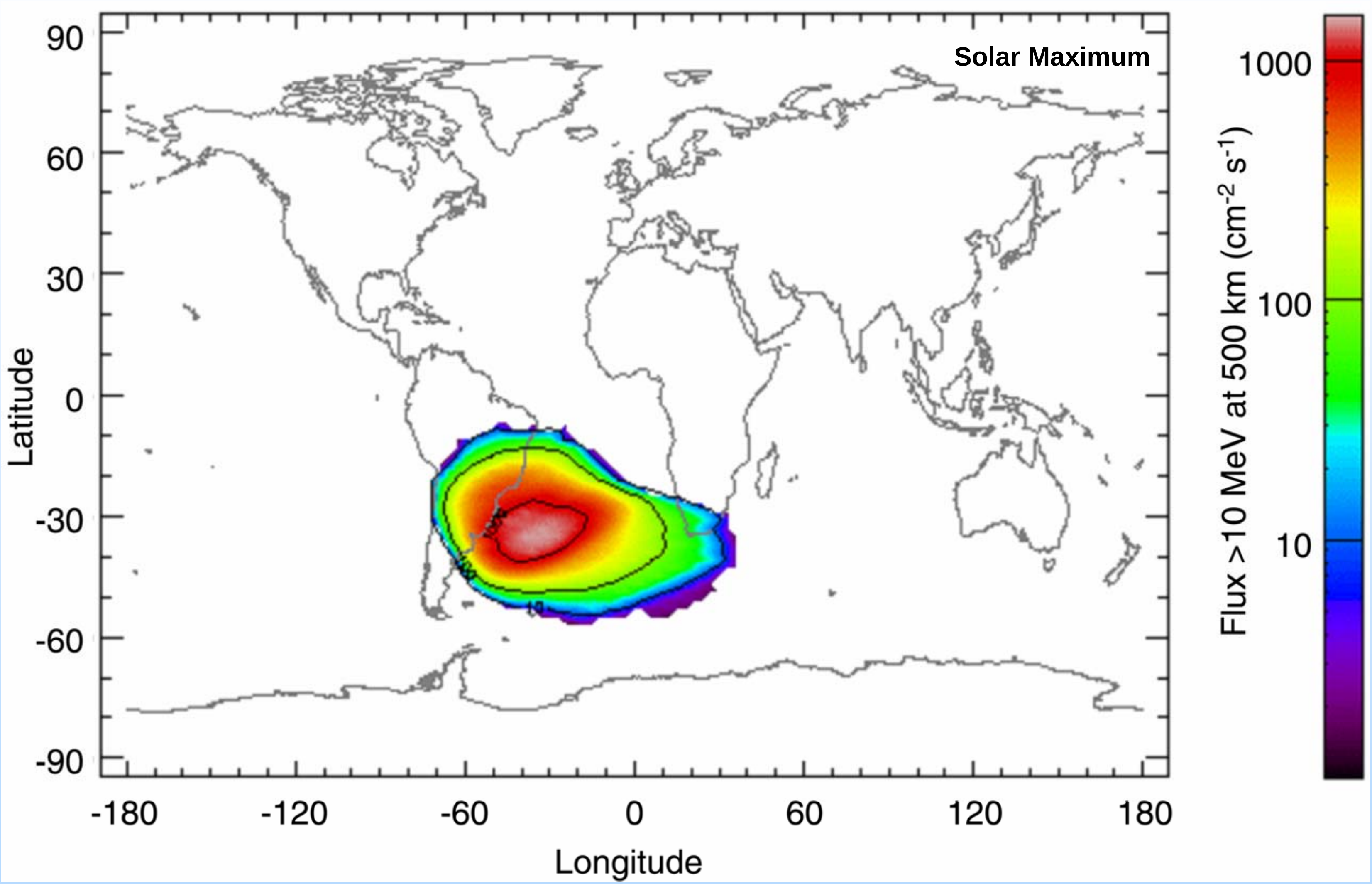
AP-8 Model

- **Eighth version of trapped proton modeling effort led by James Vette.**
- **Static map of proton population for**
  - **Solar maximum**
  - **Solar minimum**
- **Data taken in 1960s and 70s**
- **Example shown in dipole coordinates**
  - **X-axis is distance along geomagnetic equator**
  - **Y-axis is distance along geodipole axis**



From SPENVIS, http://www.spenvis.oma.be/

South Atlantic Anomaly



From SPENVIS, http://www.spenvis.oma.be/

Characteristics of Trapped Electrons

- **Inner Zone**
  - L = 1 to 2.8
  - Energies up to 4.5 MeV
  - Fairly stable population
  - long-term avg. flux:

    up to 10^6 $cm^{-2}s^{-1}$ (> 1 MeV) near L = 1.5

- **Outer Zone**
  - L = 2.8 to 10
  - Energies up to ~ 10 MeV
  - Very dynamic
  - long-term avg. flux:

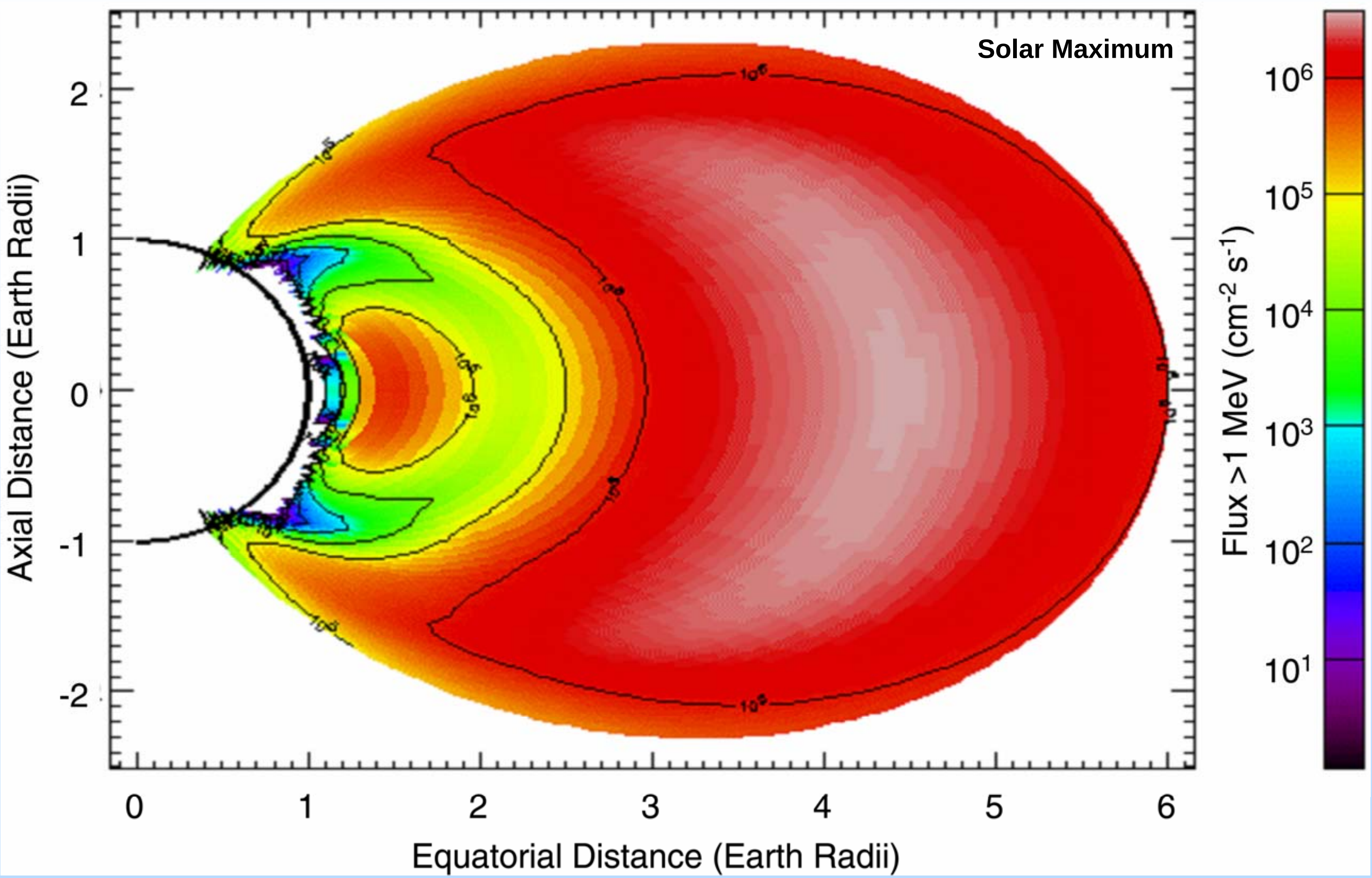
    up to $3x10^6$ $cm^{-2}s^{-1}$

    (> 1 MeV) near L = 4.5

Energies and fluxes similar to what can be produced at accelerator facilities

Slot region – located between the 2 high intensity zones (L = ~2 to 3); region where fluxes at local minimum during quiet periods

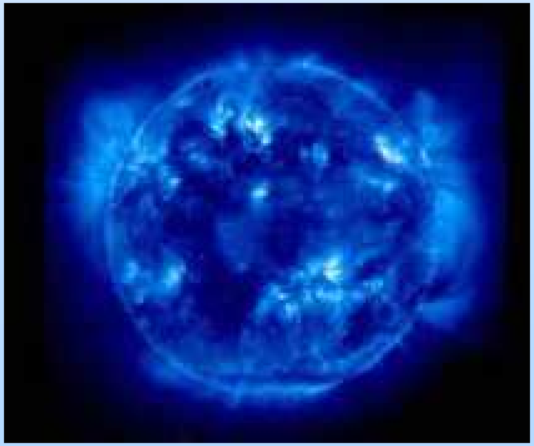
AE-8 Model



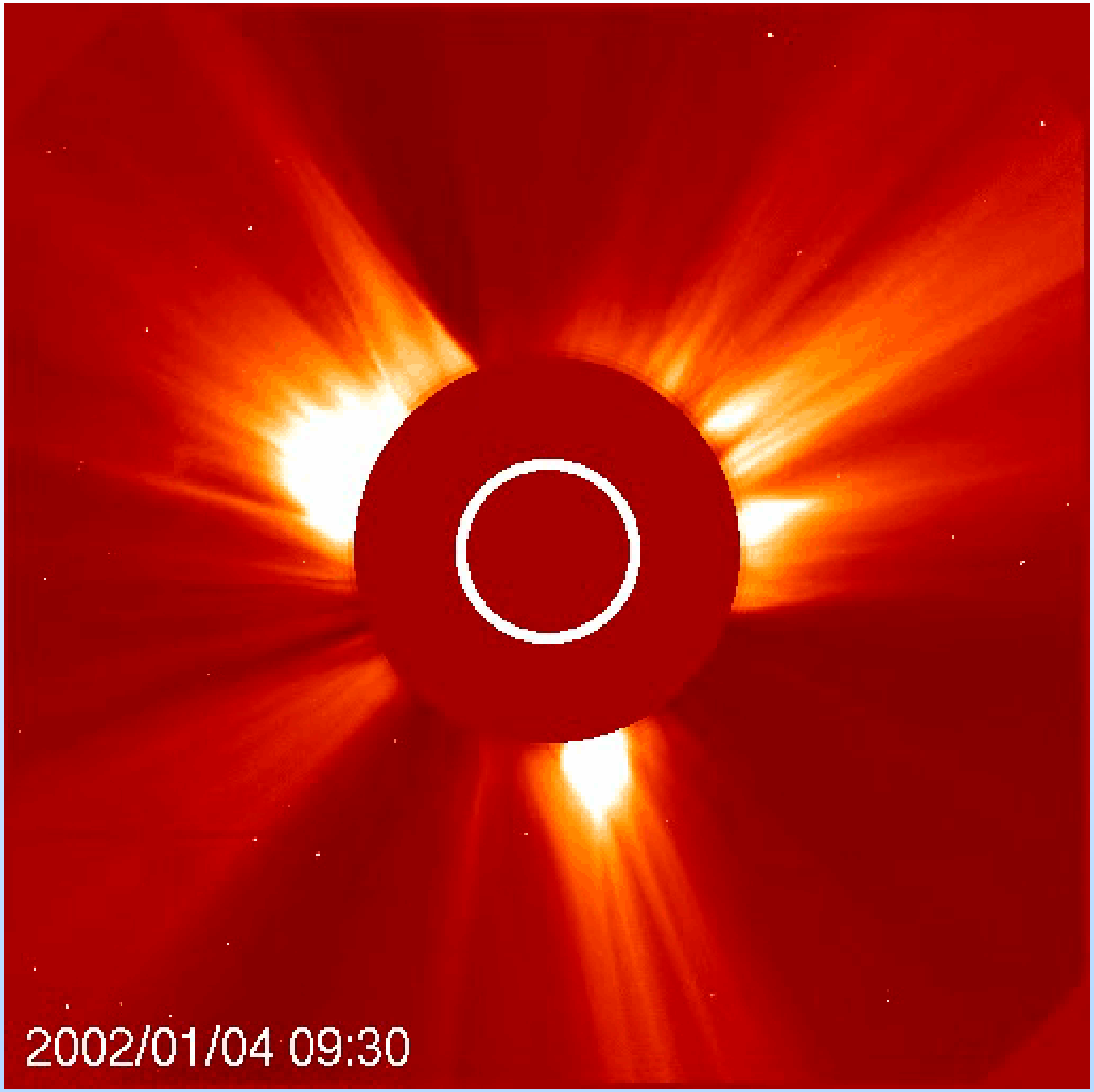
From SPENVIS, http://www.spenvis.oma.be/

Solar Particle Events

- **Solar flares**
  - Occur when localized energy storage in coronal magnetic field becomes too great and burst of energy is released
- **Coronal Mass Ejections (CMEs)**
  - Large eruption of plasma that drives a shock wave outward and accelerates particles
- **Responsible for major disturbances**
  - Interplanetary space
  - In earth's magnetosphere



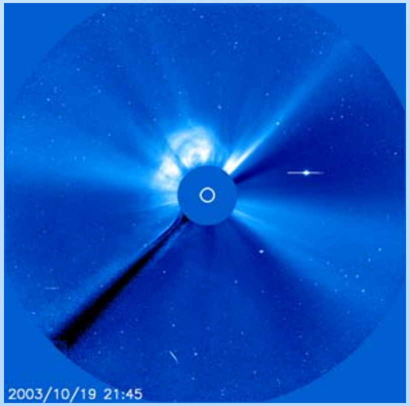
Coronal Mass Ejection

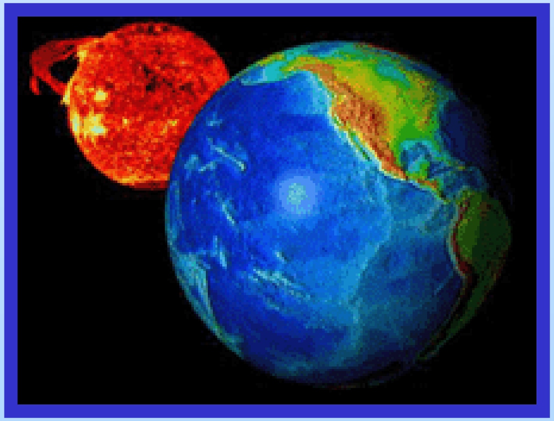


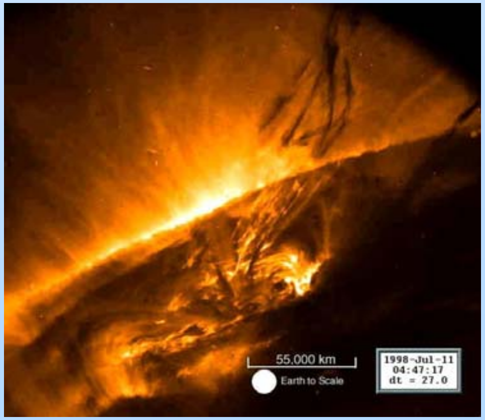
Characteristics of CMEs

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

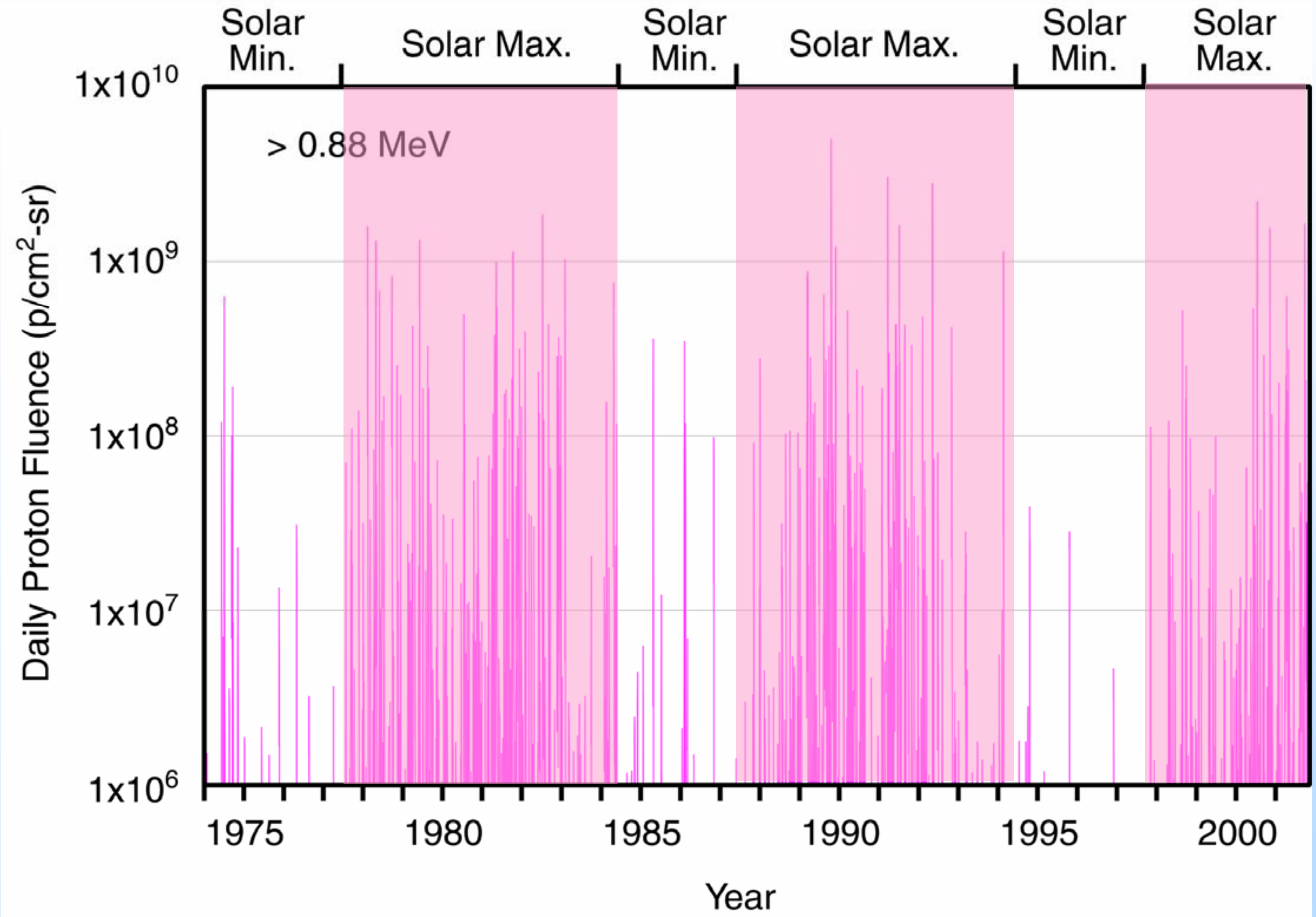
* D.V. Reames, Space Sci. Rev., 1999





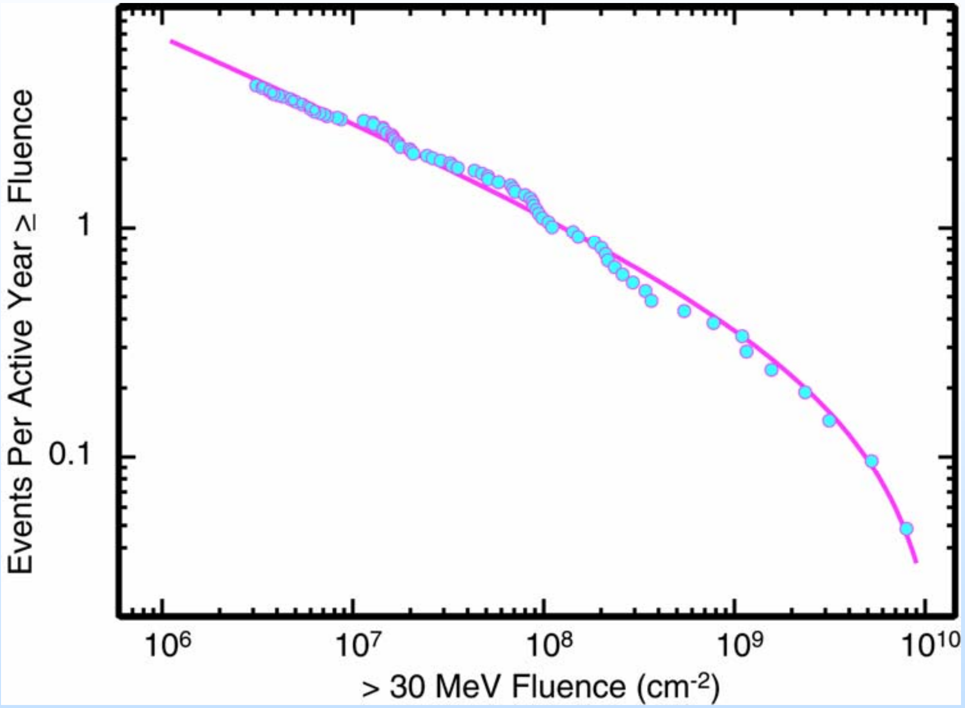


Solar Cycle Dependence



Distribution of Event Magnitudes

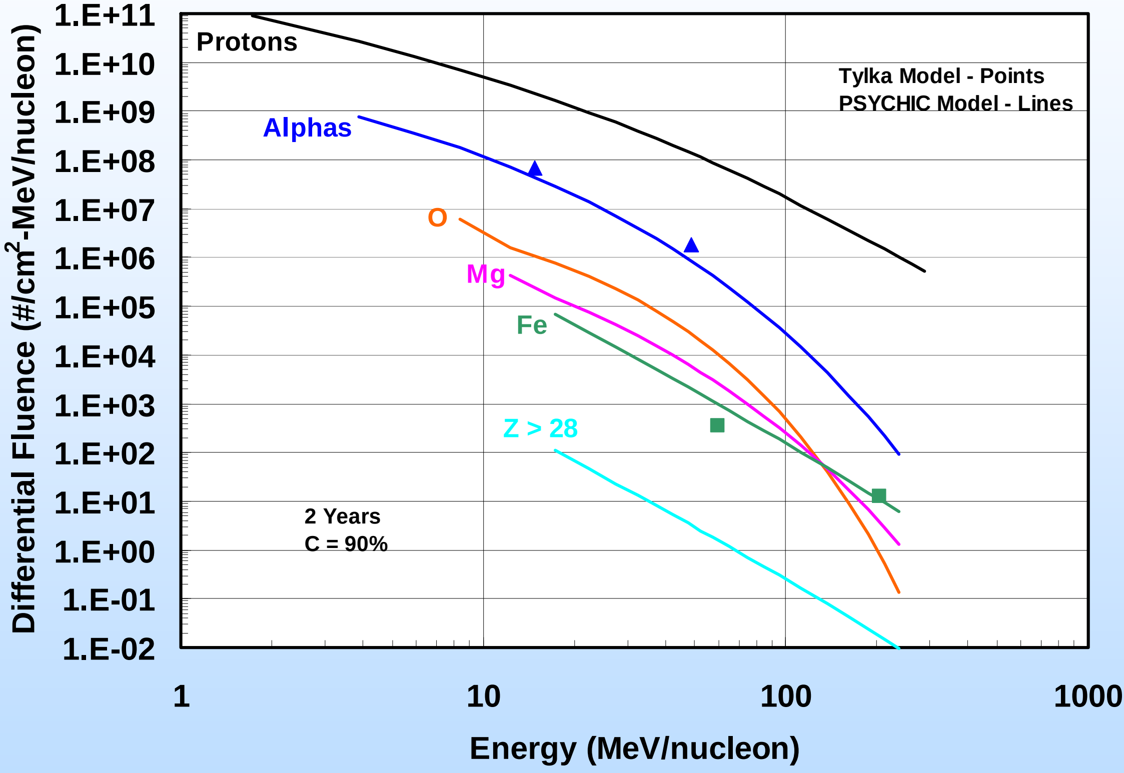
- **Probabilistic phenomena**
- **Truncated power law function describes essential features of distribution of event fluences:**
  - **Sudden bursts of energy released that span orders of magnitude**
  - **Smaller event sizes follow power law function**
  - **Larger event sizes fall off much more rapidly**



M.A. Xapsos et al., IEEE TNS, Dec. 1999

Cumulative Fluence Models
Solar Heavy Ions

- **Preliminary model by Tylka for 2 energy bins each of He, CNO group and Fe**
- **PSYCHIC model of NASA GSFC**
  - **Statistical model of alpha particles based on 28 years of data from IMP-8 and GOES**
  - **Major heavy ions C through Fe determined from ACE instrument measurements.**
  - **Remaining minor elements scaled according to ISEE-3 measurements and corrected photospheric abundance model**



M.A. Xapsos et al., IEEE TNS, Dec. 2007

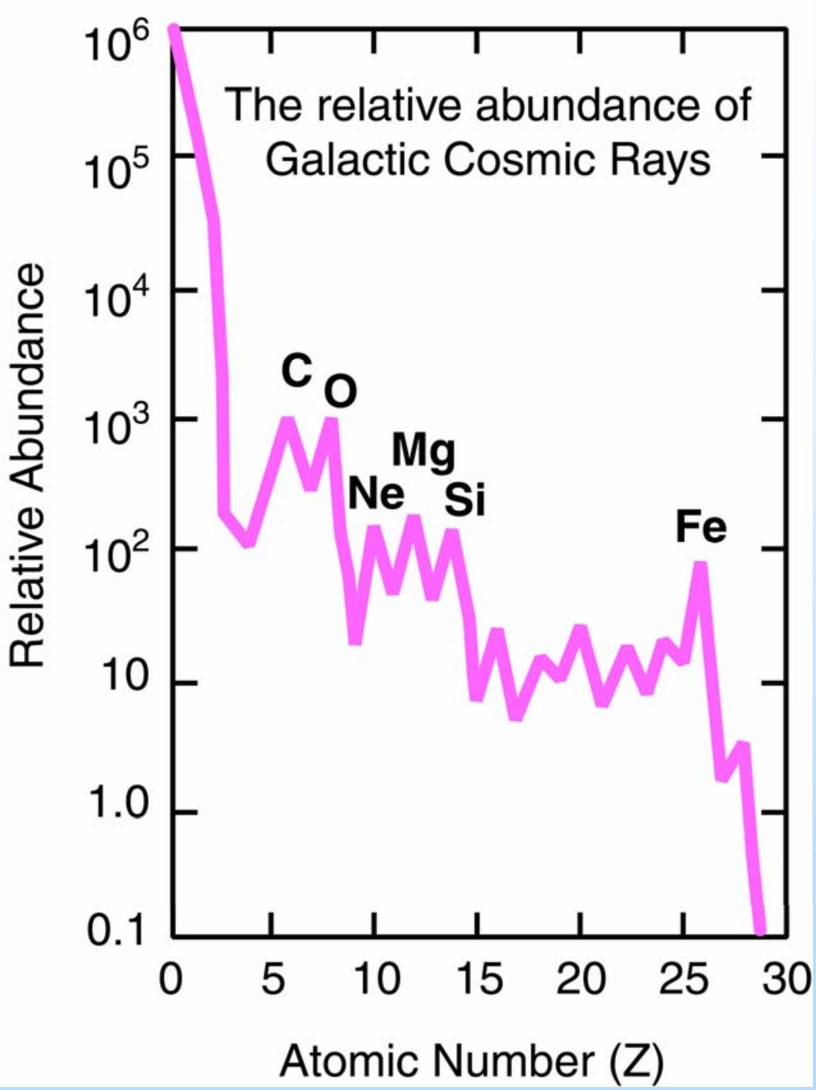
Galactic Cosmic Rays

- **High-energy charged particles that originate outside our solar system**
  - **Supernova explosions are significant source**

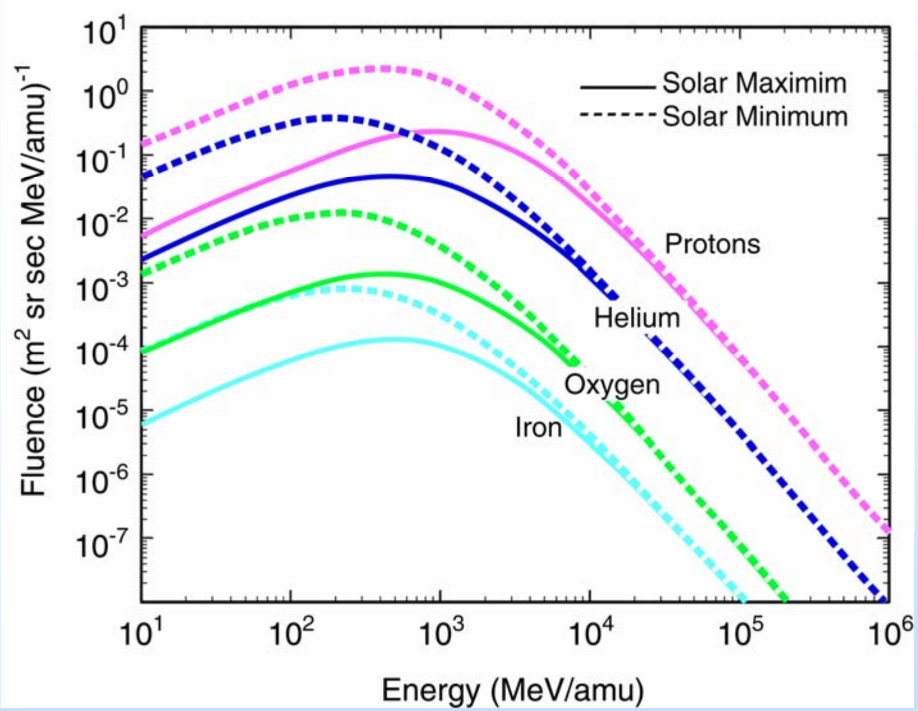
GCR Properties

- **Consist of all naturally occurring elements***
  - **87% protons**
  - **12% alpha particles**
  - **1% heavier ions**
- **Energies: up to 10^{20} eV!**
  - **Energetically equivalent to tennis ball traveling 250 km/hr**
- **Fluxes: 1 to 10 $cm^{-2}s^{-1}$**

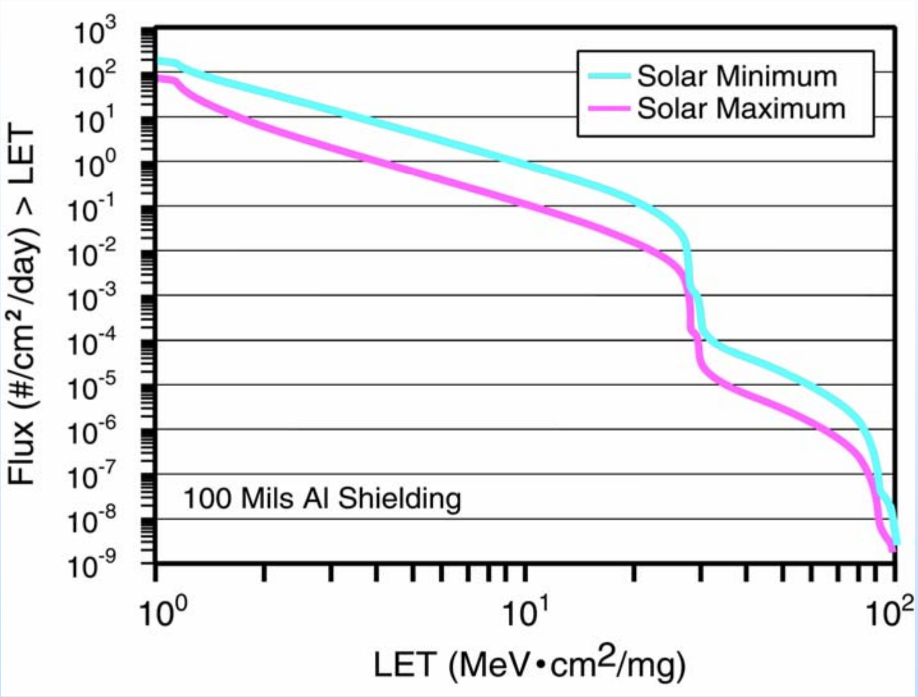
* E.R. Benton and E.V. Benton, NIM B, Sept. 2001



Variation with Solar Cycle



G.D. Badhwar and P.M. O'Neill, Adv. Space Res., 1996



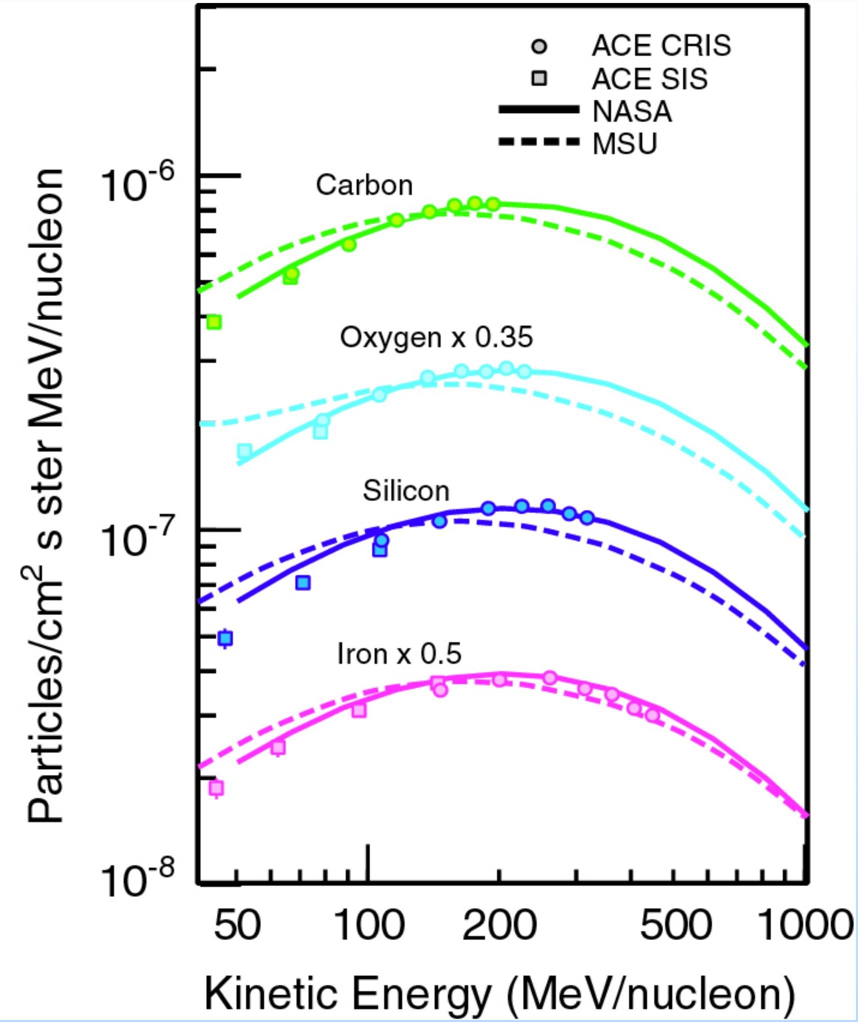
From CREME96, https://creme96.nrl.navy.mil/

GCR Models

- NASA and MSU models originated independently
  - Both based on theory of solar modulation
  - Describes penetration of GCR into heliosphere from outside and transport to near earth
  - Solar modulation results in variation of GCR fluxes over solar cycle
- Implementation of solar modulation differs
  - NASA model determines solar modulation from near earth GCR measurements, including detection of secondary neutrons with ground-based monitors.
  - MSU model uses multi-parameter fits to ultimately relate GCR intensities to observed sunspot numbers.
    - Incorporated in widely used CREME96 program suite

GCR Models

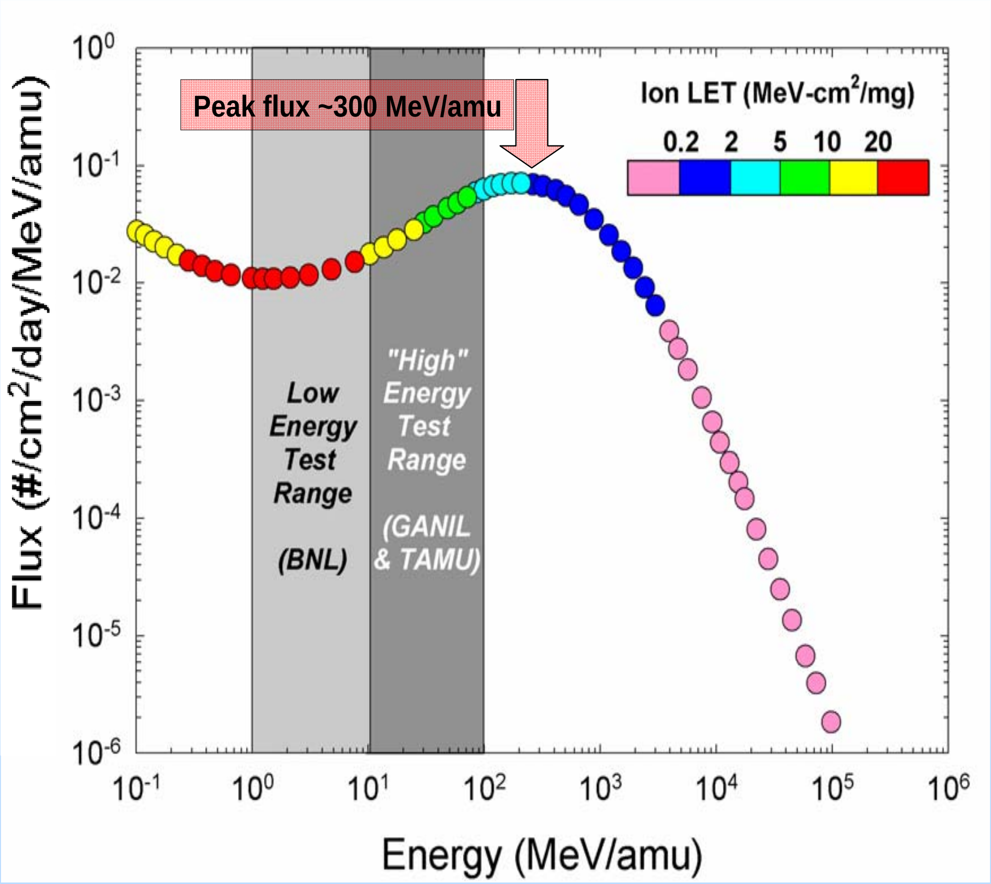
- **Comparisons with modern instrumentation measurements on ACE satellite show good agreement**
  - **1997 solar minimum time period shown**
- **NASA model improved with recent update**



After A.J. Davis et al., J. Geophys. Res., Dec. 2001

GCR Energy vs. Accelerator Ion Energy
Iron behind 100 mils Al Shielding

- **Potential Difficulties**
  - **High energy ions may produce single event effects not observed at lower energies**
    - **Nuclear reactions**
    - **Recoils in metal overlayers**
  - **Ion track size relative to device and circuit dimensions**
    - **Charge sharing**
    - **Well collapse**



P. Dodd et al., IEEE TNS, Dec. 1998