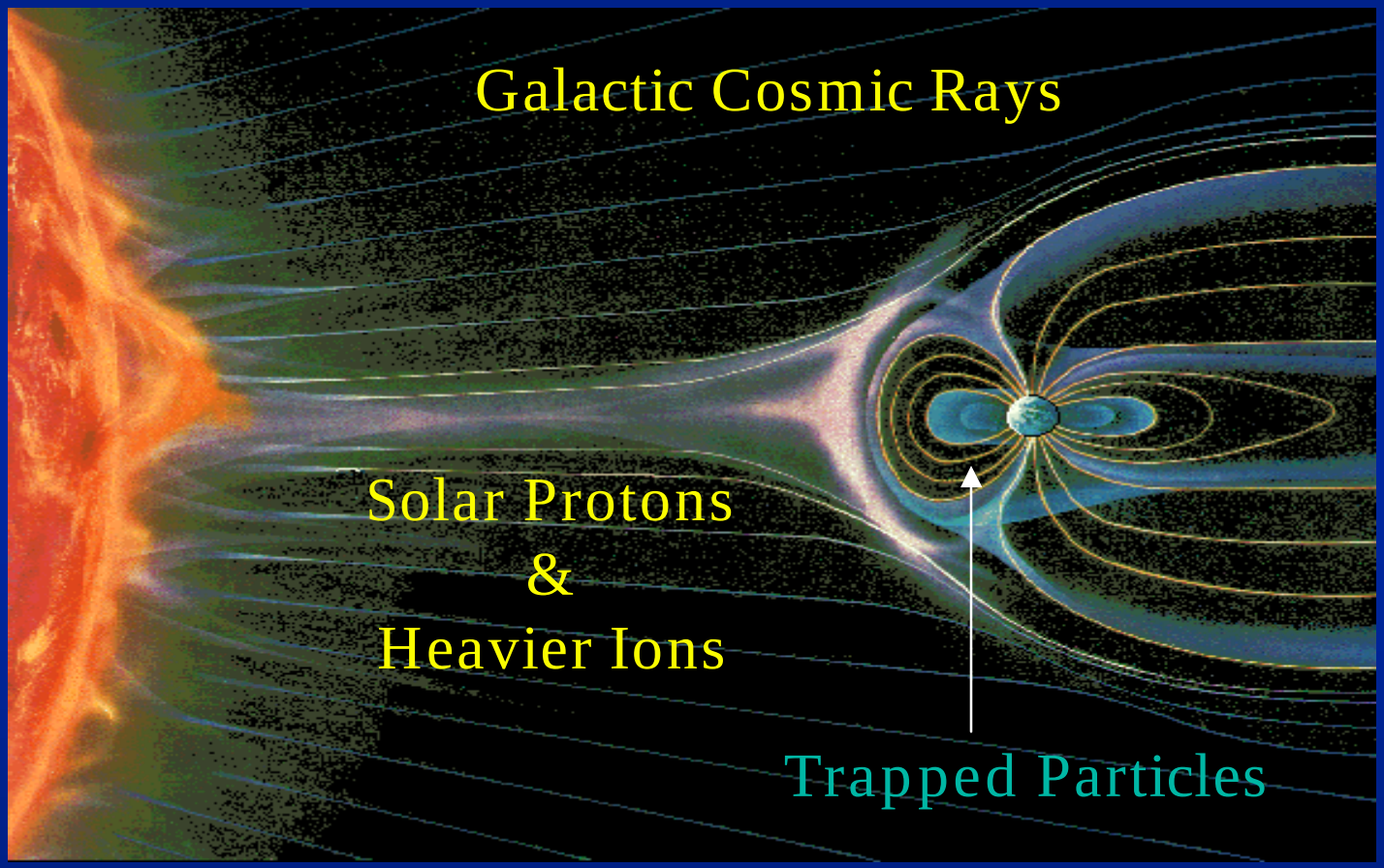
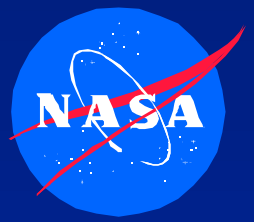
The Radiation Environment



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

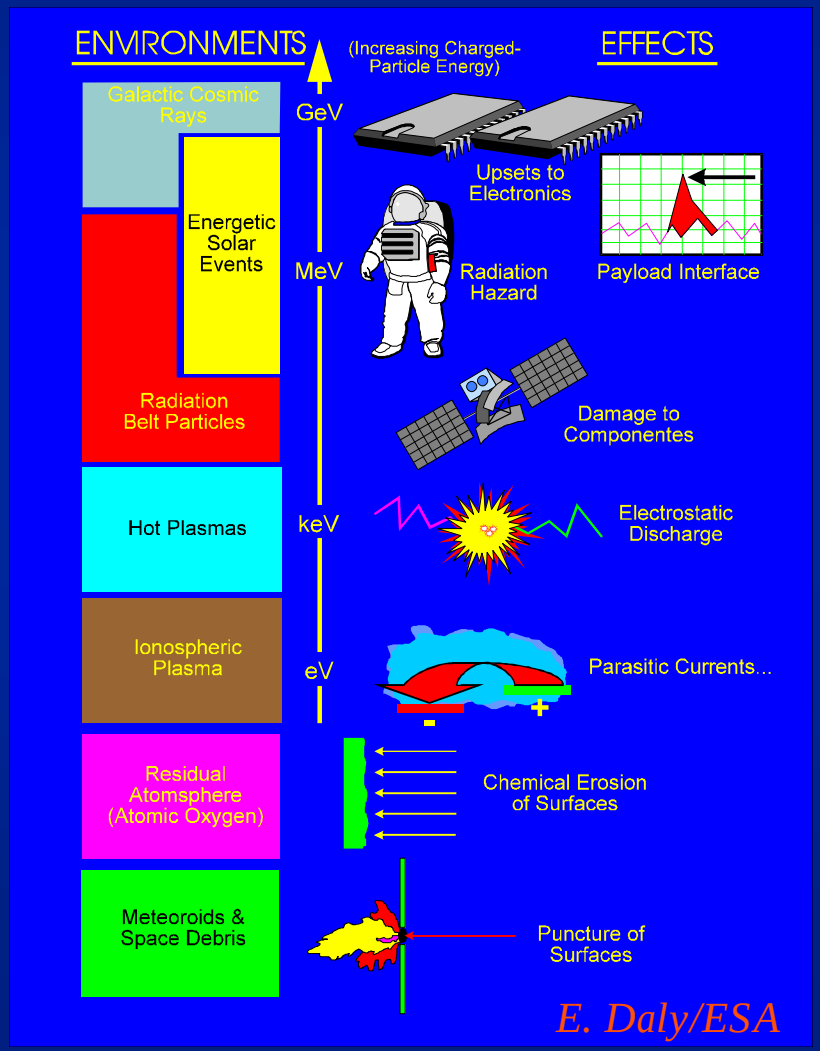


Components of the Natural Environment

- Transient
  - » Galactic Cosmic Rays
    - – Protons & Heavier Ions
  - » Solar Particle Events
    - – Protons & Heavier Ions
- Trapped
  - » Electrons, Protons, & Heavier Ions
- Atmospheric & Terrestrial Secondaries
  - » Neutrons

Radiation & Effects

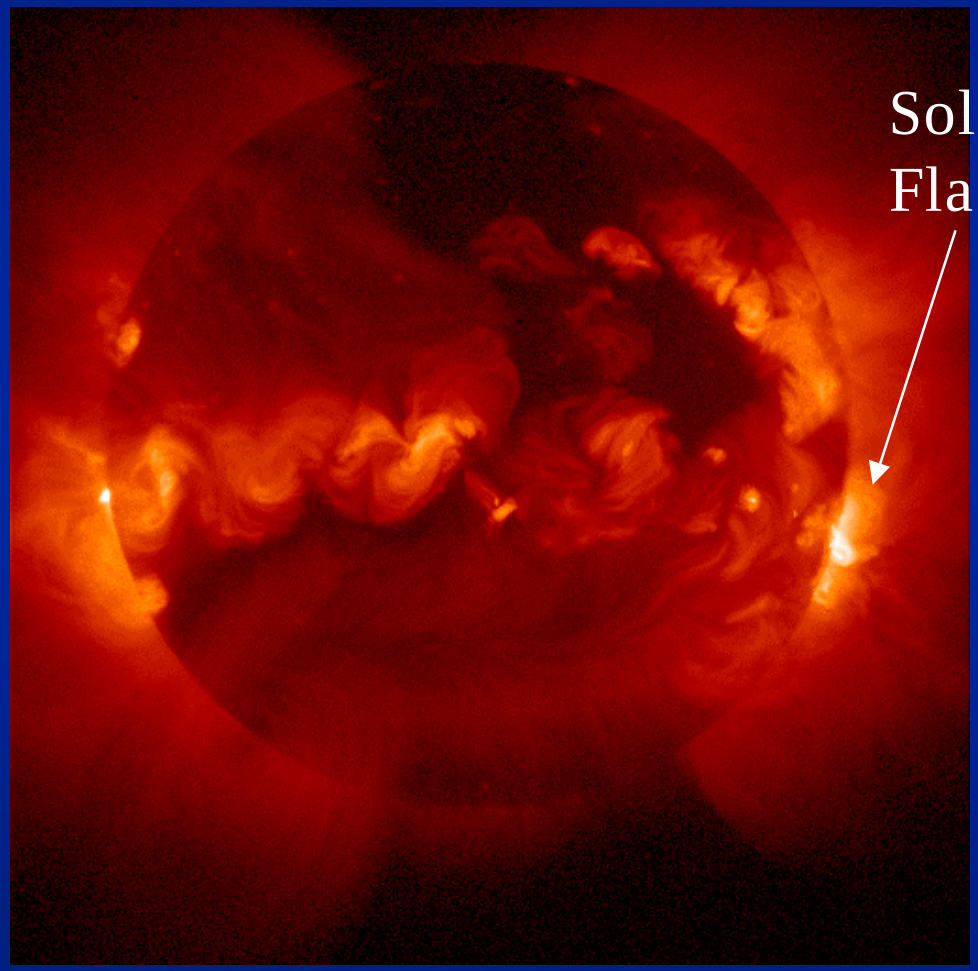
- Total Ionizing Dose
  - » Cumulative long term ionizing damage due to protons & electrons
- Displacement Damage
  - » Cumulative long term non-ionizing damage due to protons, electrons, & neutrons
- Single Event Effects
  - » Event caused by a single charged particle - heavy ions & protons for some devices



J. Barth/Code 562

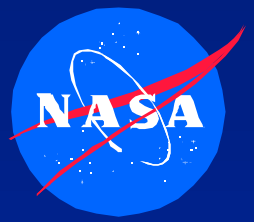
Sun

- Dominates the Radiation Environment
  - » Source
  - » Modulator
- Structure
  - » Photosphere
  - » Chromosphere
  - » Corona



Yohkoh/SXT

J. Barth/Code 562

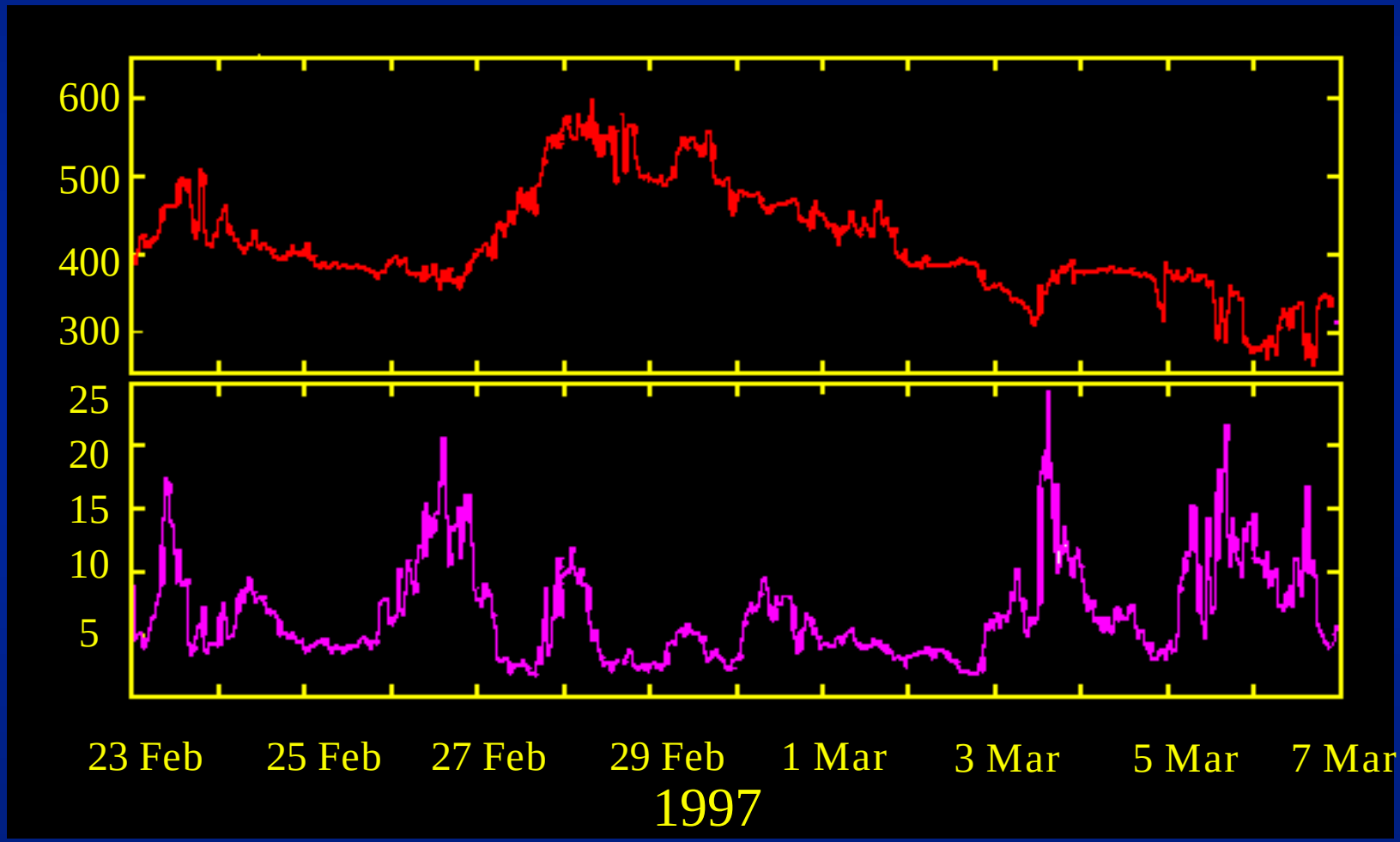


Solar Wind

- Stream of Charged Particles from Sun's Corona
  - » Electrons
  - » Protons
  - » Heavy Ions

  } Density ~ 1 - 30 / cm^3
- Magnetized Plasma
- Detected Out to 10 billion km from Earth by Pioneer 10
- Velocity ~ 300 - 900 km / s
- Energy ~ .5 - 2.0 keV / nuc

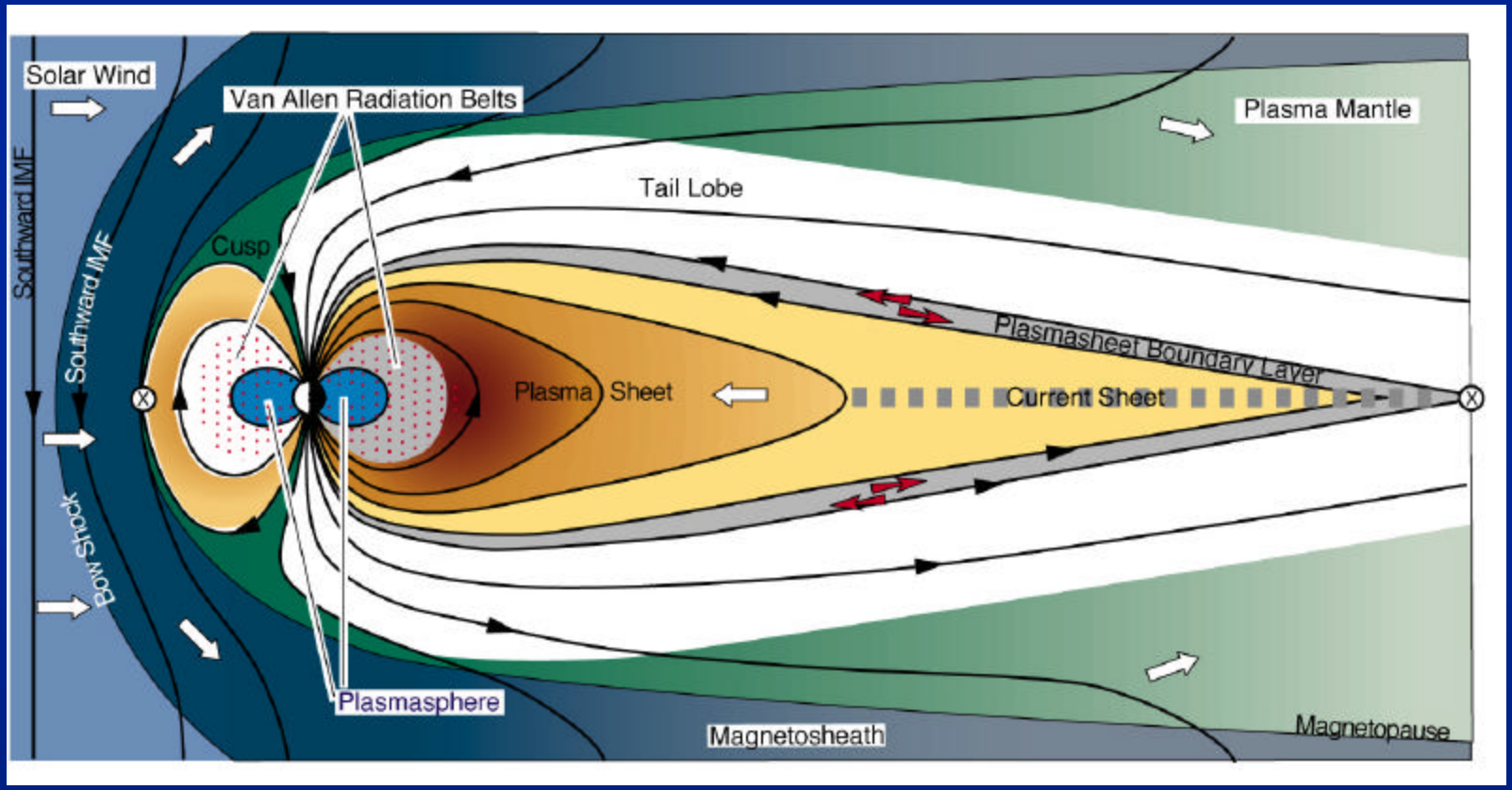
Solar Wind Density & Velocity



University of Maryland, SOHO/CELIAS

J. Barth/Code 562

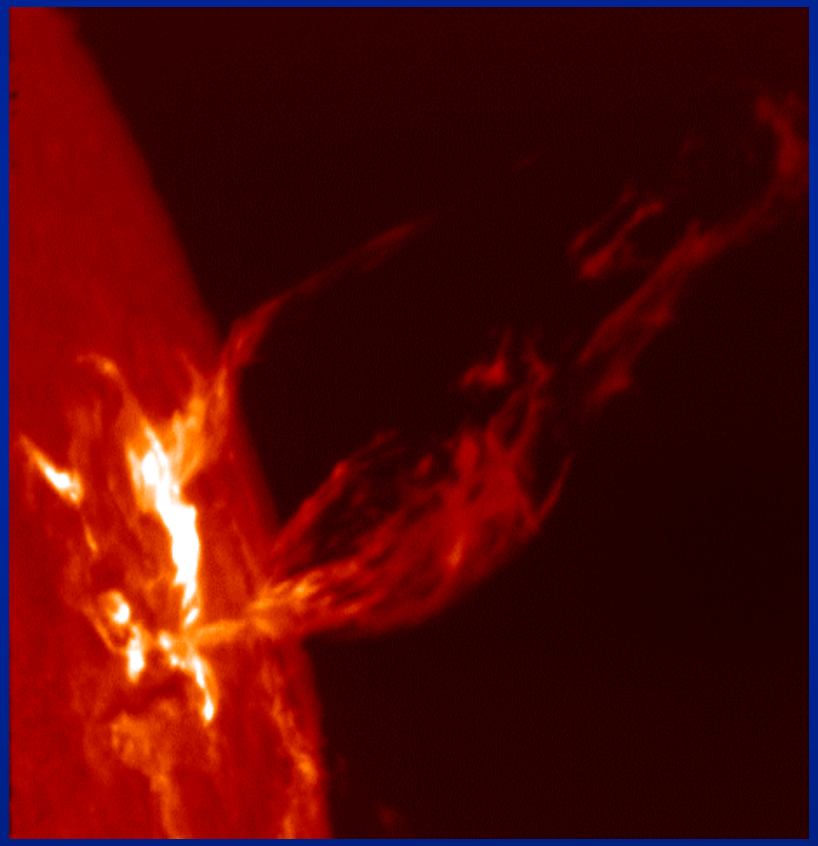
Magnetosphere



J. Barth/Code 562

Coronal Mass Ejections

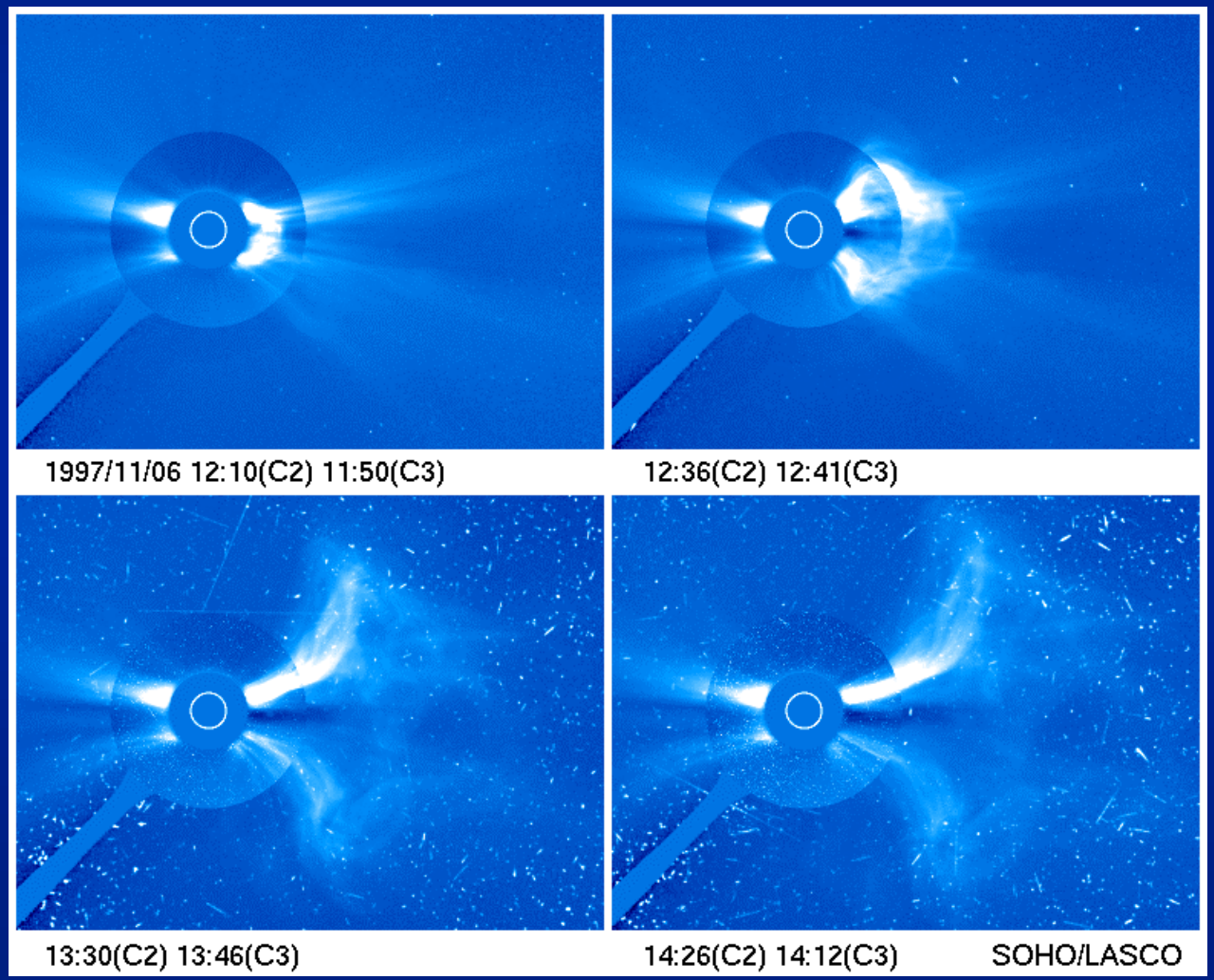
- Bubble of Gas & Magnetic Field
- Ejects ~10^{17} grams of Matter
- Shock Wave Accelerates Particles to Millions of km / hr
- Associated with Magnetic Storms
- Proton Rich Solar Events



Holloman AFB/SOON

J. Barth/Code 562

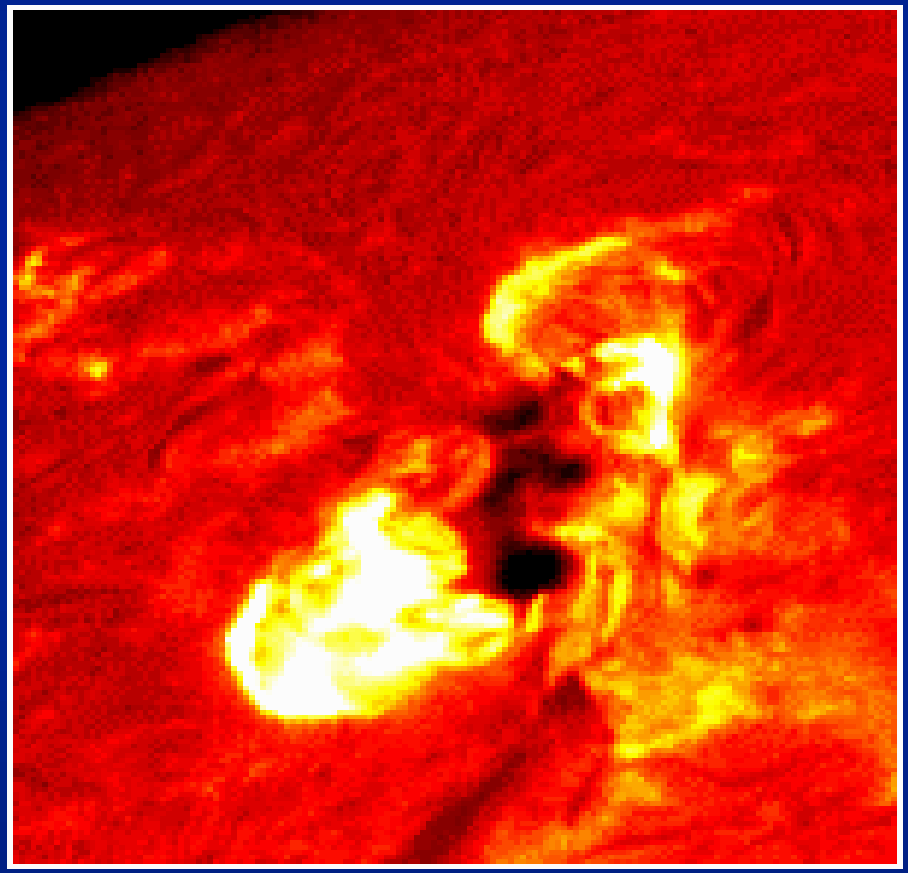
SOHO/LASCO During Solar Particle Event



J. Barth/Code 562

Solar Flares

- Sudden Brightening Near Sunspots
- Solar System's Largest Explosive Events
- Particles Accelerated Directly by Event
- Heavy Ion Rich Solar Events



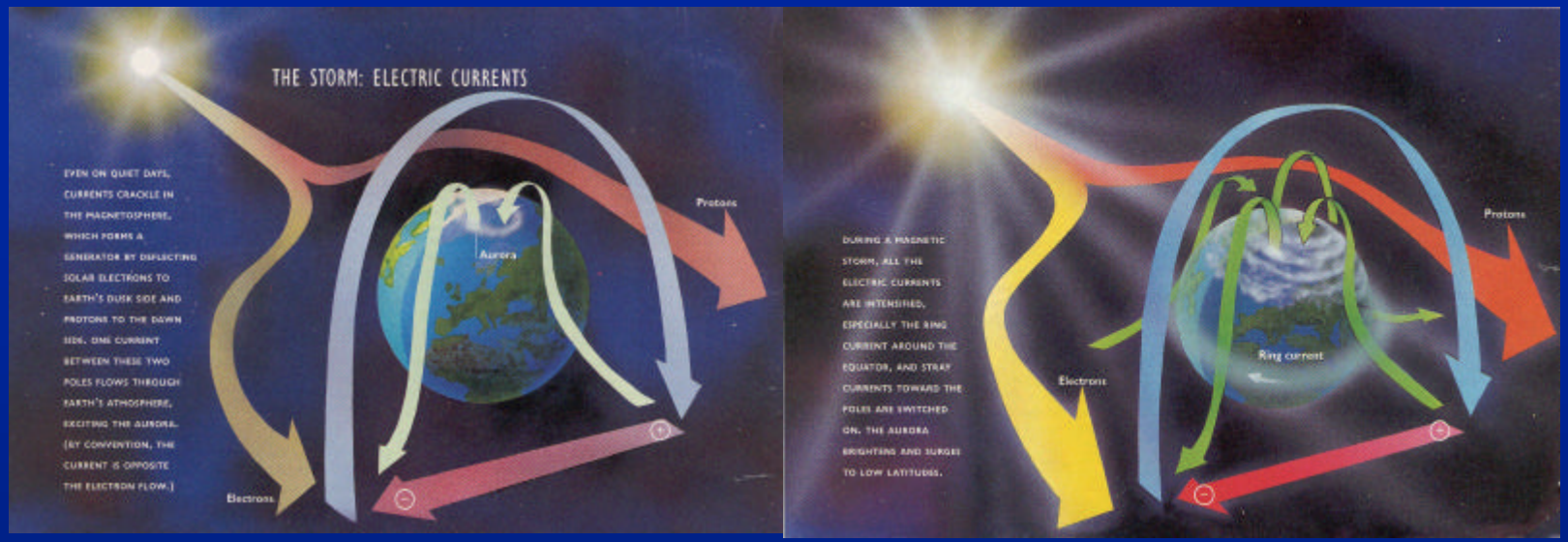
J. Barth/Code 562

Magnetic Storms

- "Gusty" Solar Wind Disturbs the Current Systems in the Magetosphere
- Major Storms Probably the Result of CMEs
  - » Must Be Pointed Toward Earth
  - » Strongest Arrive with Interplanetary Magnetic Field Oriented South
- Cause Increase in Rate & Intensity of Magnetic Sub-storms in the Geotail

Electrical Currents

- Normal Conditions
  - » Currents Present on Quiet Days
- Stormy Conditions
  - » Intensified Currents



J. Barth/Code 562

Discover Magazine - August 1995

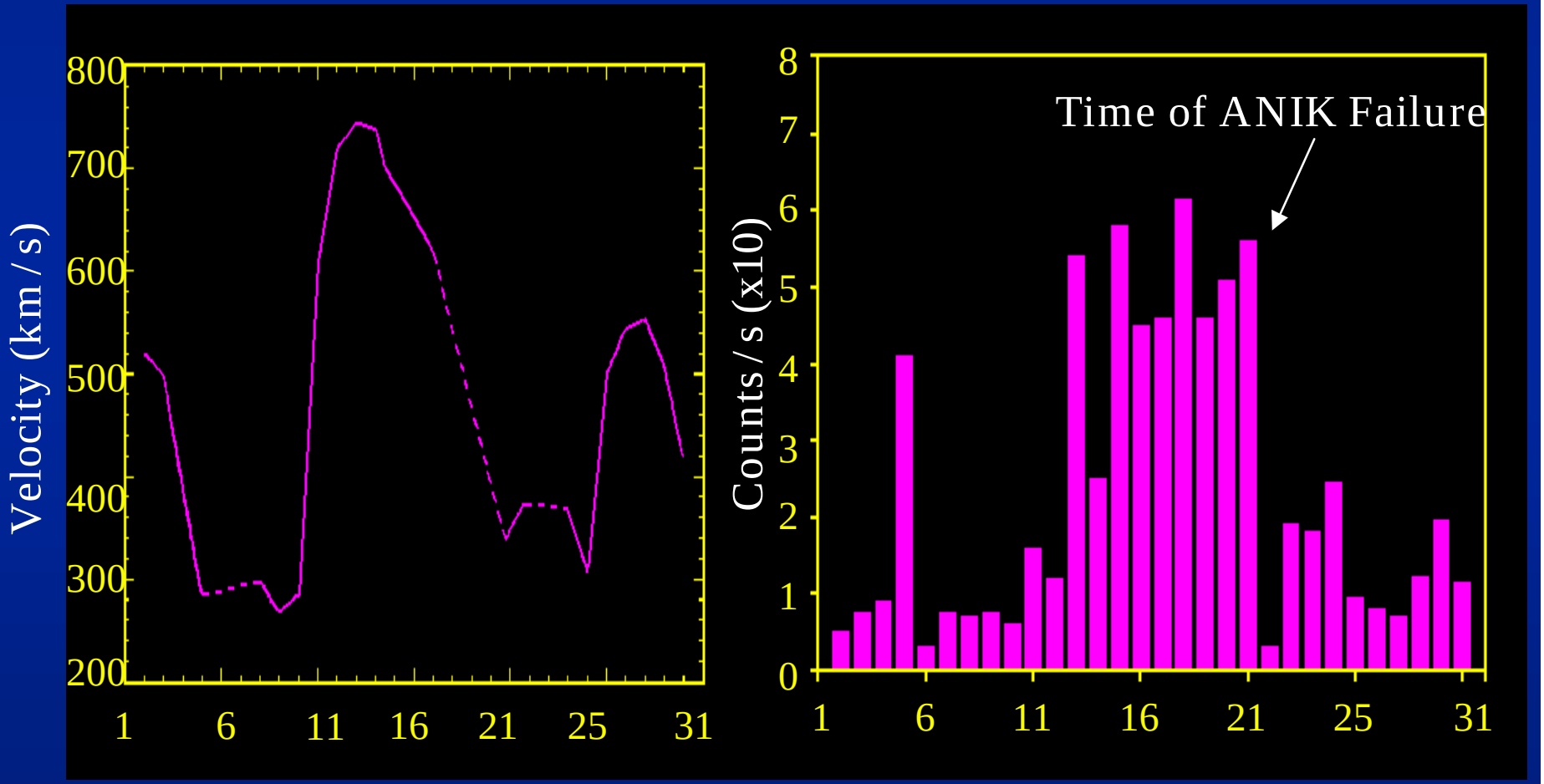
Effects of Solar Storms

- Power Black-outs on Earth
- Block Some Radio Communication
  - » Disturbs electrically charged gases in the ionosphere
- Interfere with Cellular Phone Systems
  - » Ionospheric disturbances & satellite system failures
- Interfere with GPS Navigation (Ships & Airplanes)
- Trigger Phantom Commands on Spacecraft
- Increased Atmospheric Drag on Low Earth Orbit (LEO) Satellites
- Increased Protons & Heavy Ion Particle Counts
- "Pump Up" the Van Allen Belts

ANIK E1: Magnetic Storm

Solar Wind Velocity (IMP-8 MIT)

SAMPEX Electrons E > 1 MeV

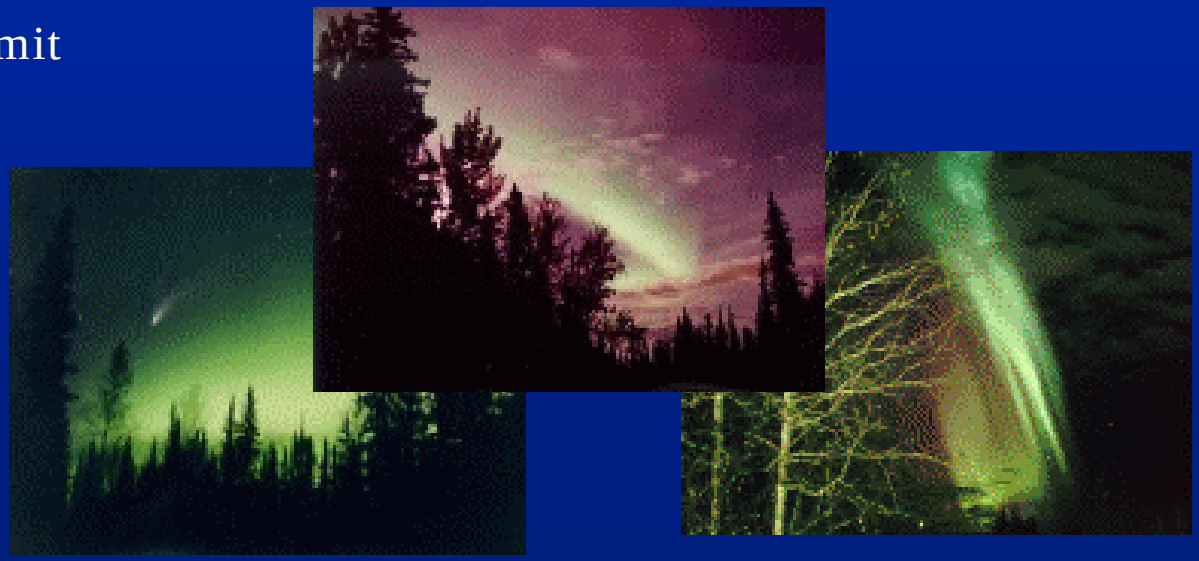


January 1994

J. Barth/Code 562

Aurora

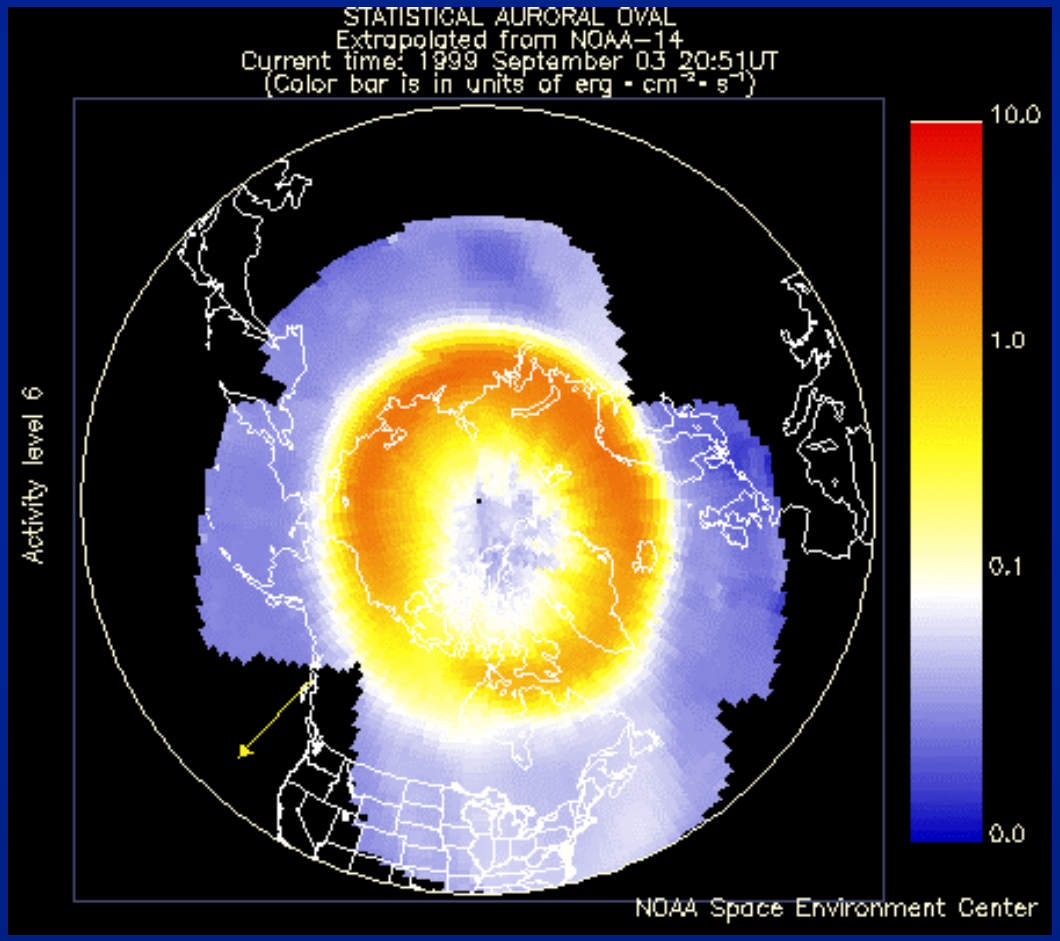
- Particles stream down on magnetic field lines from the geomagnetic tail forming an auroral belt
- Electrons collide with atmospheric gases
- Electrons give energy to atoms and molecules which emit energy as light
- Oxygen ---> Green
- Nitrogen ---> Red



J. Barth/Code 562

Aurora Borealis

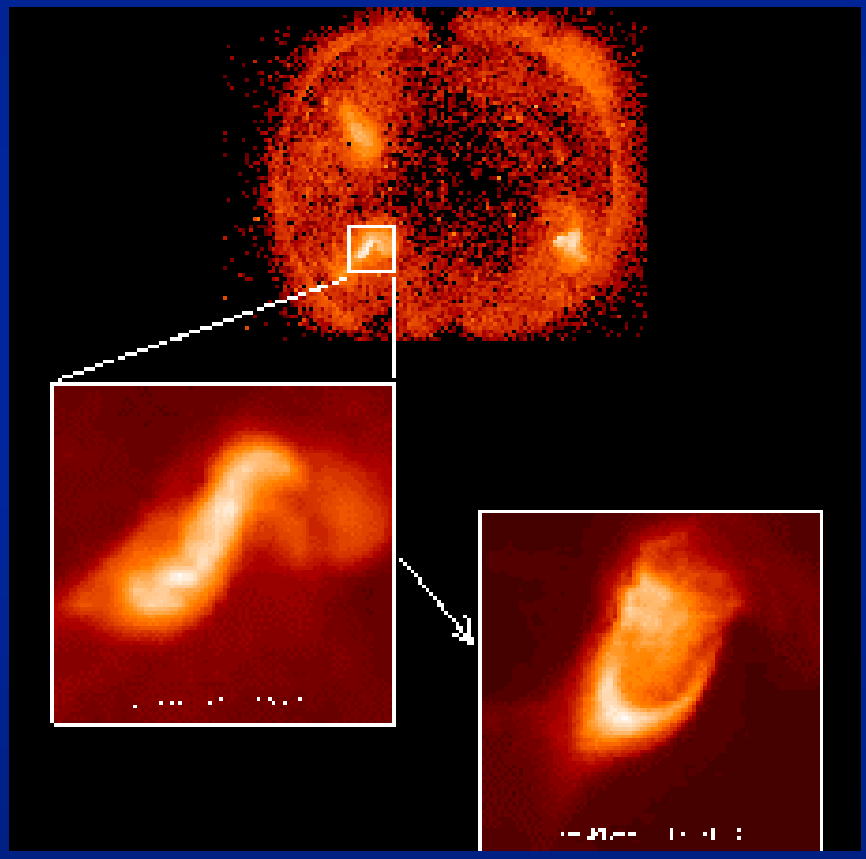
- Northern lights oval as measured by NOAA-14
- Centered on Magnetic Pole



J. Barth/Code 562

Early Warning: S-Curves

- Viewed with X-ray Imagery
- Based on Two Years of Observations
- Strong Correlation between Sigmoid Regions and CMEs
- Likely the Result of Twisted Solar Magnetic Fields
- May Provide Early Warning of Particle Events



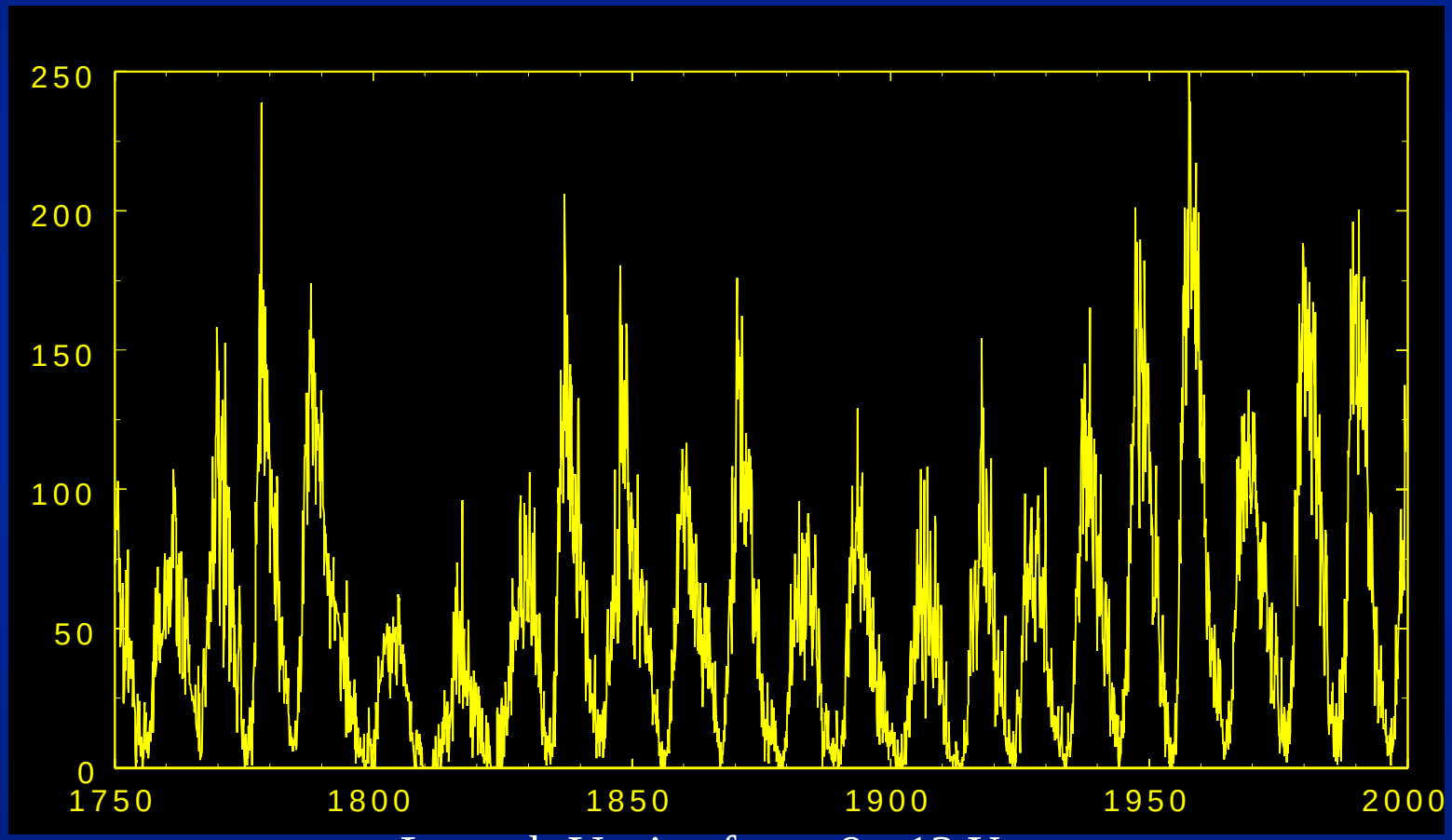
Montana State University

J. Barth/Code 562

Solar Activity: Cyclic Variation

- Sunspot Cycle Discovered in mid 1800s
- Used as Indicator of Solar Activity
- Increased Solar Activity Results in:
  - » Increased Rate of CMEs
  - » Increased Rate of Solar Flares
  - » Increased Rate of Magnetic Storms
  - » Increased Levels of Electrons in Van Allen Belts
  - » Decreased Levels of Protons in Van Allen Belts
  - » Increased Incidence of New Belt Formation
  - » Decreased Levels of Galactic Cosmic Rays
  - » Increased Rate of Solar Particle Events
- Effects on Climate?

Sunspot Cycle

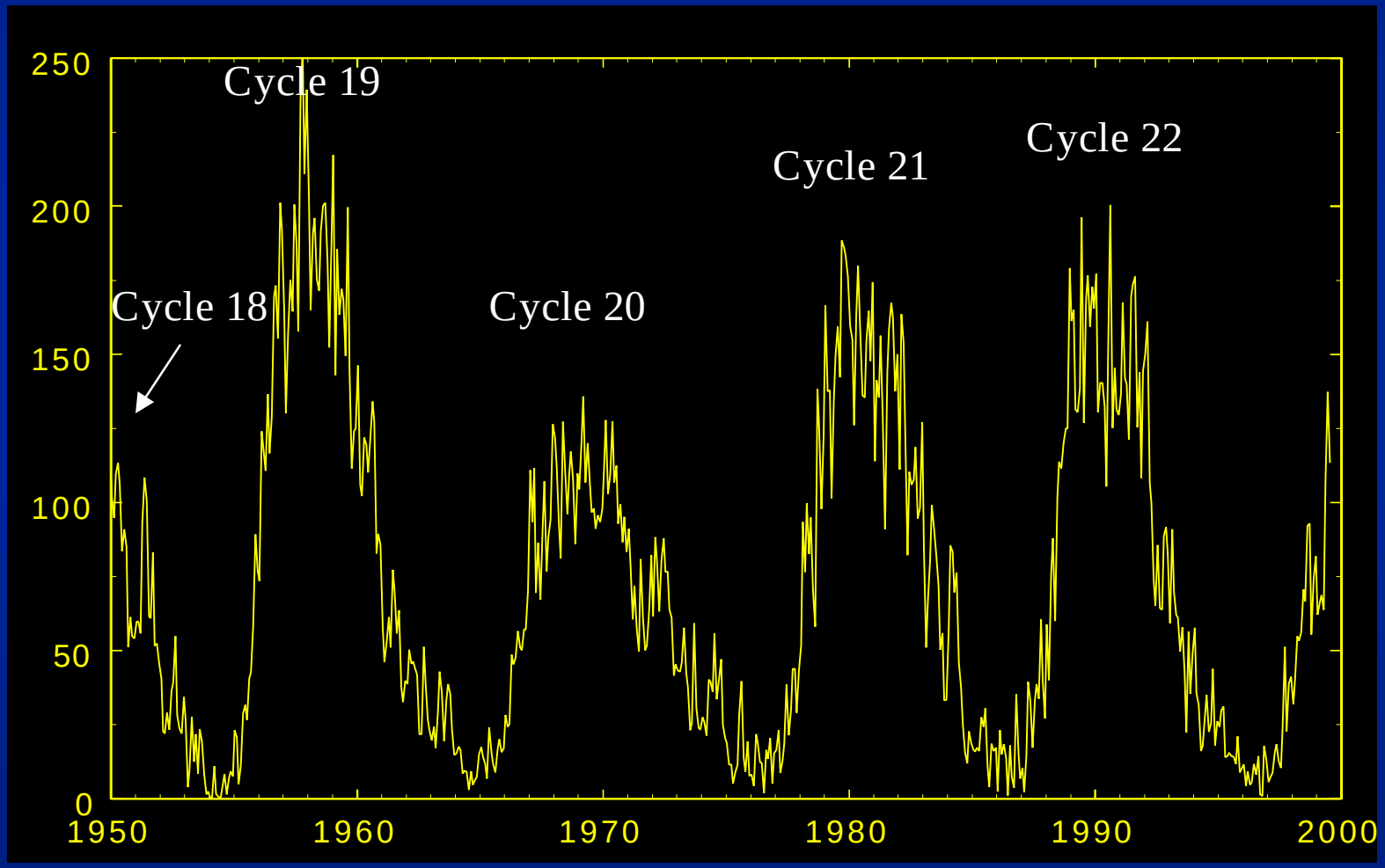


Length Varies from 9 - 13 Years

7 Years Solar Maximum, 4 Years Solar Minimum

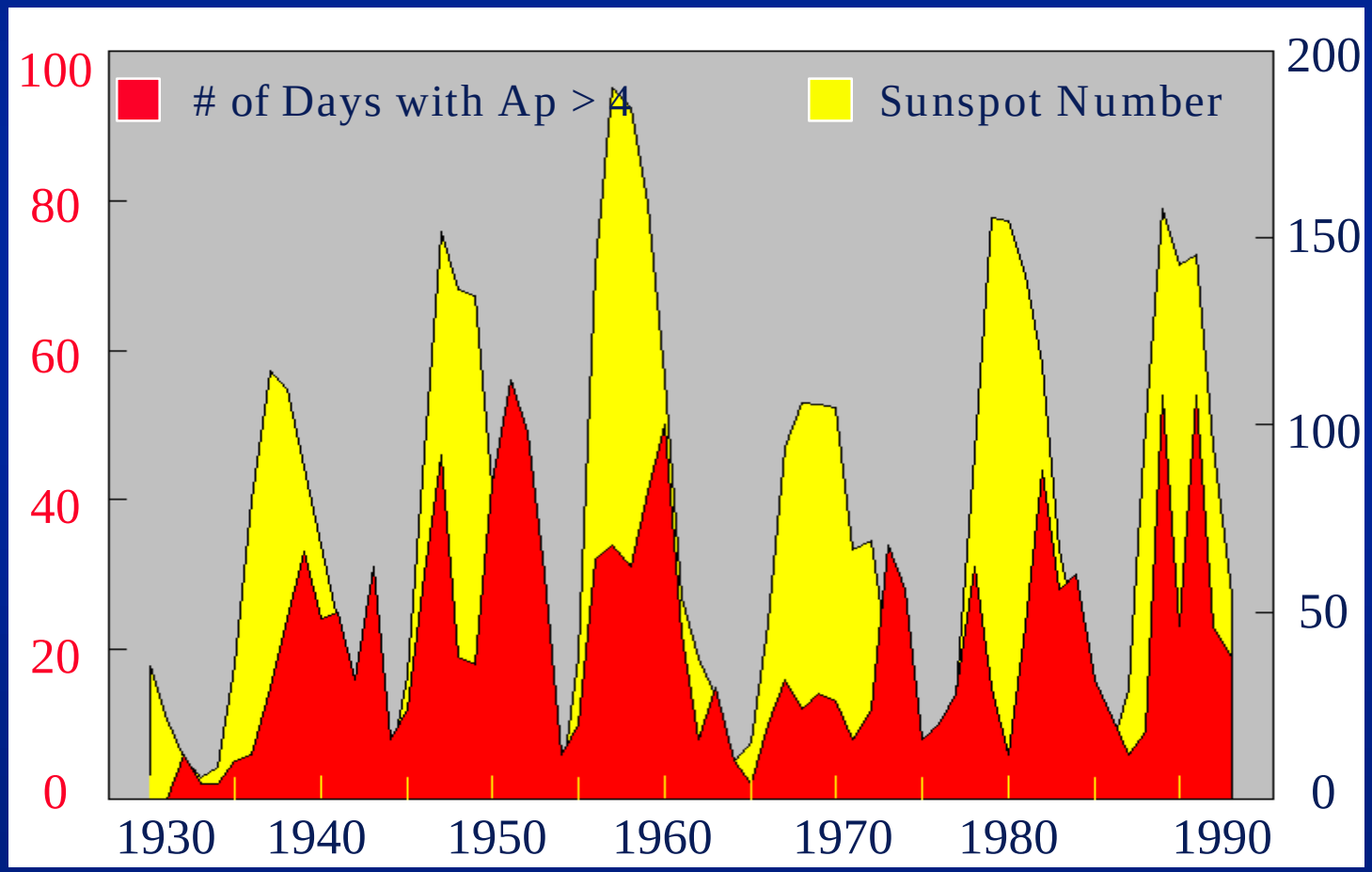
J. Barth/Code 562

Sunspot Cycle



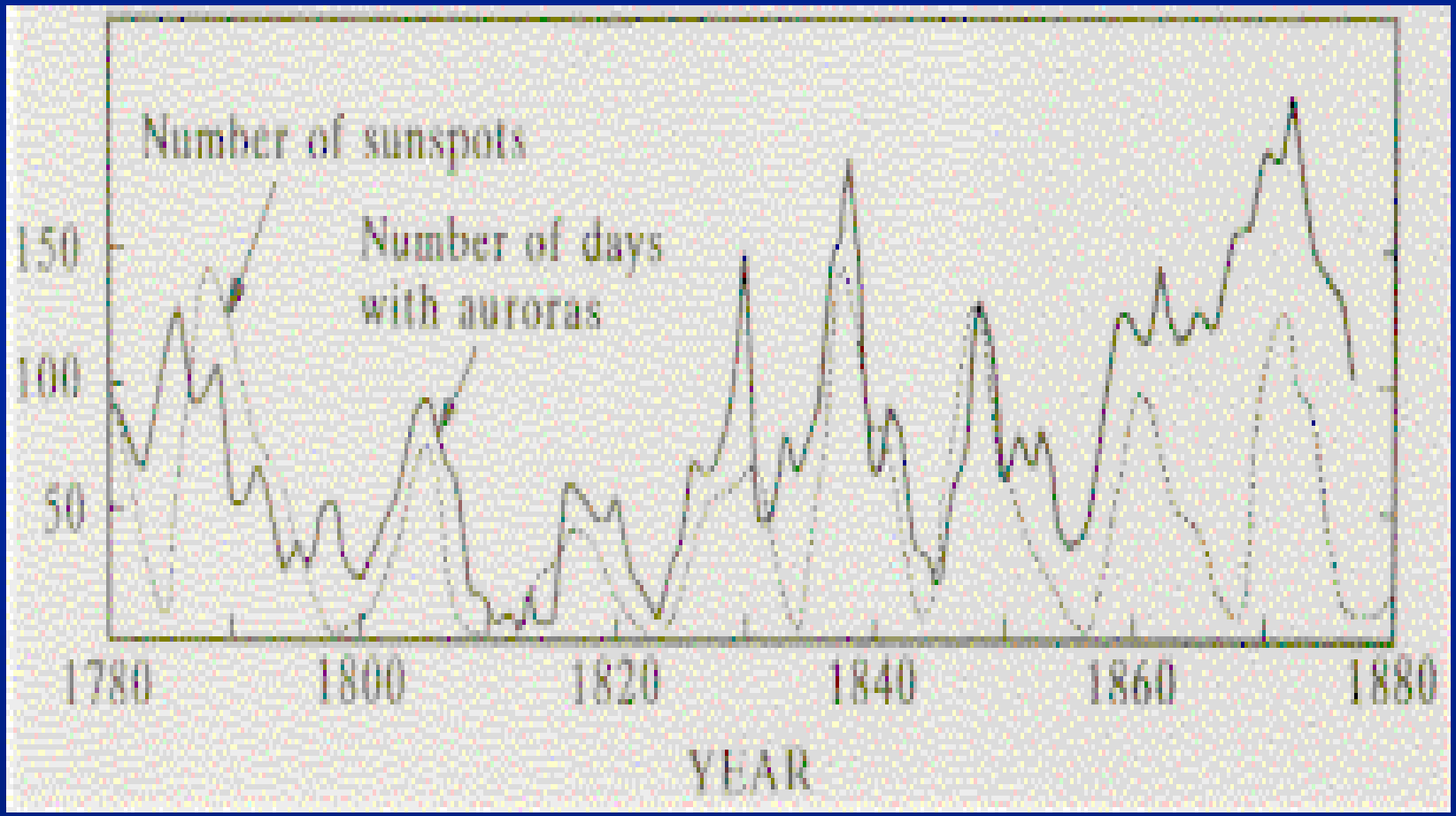
J. Barth/Code 562

Sunspot Cycle with Magnetic Storms



J. Barth/Code 562

Solar Cycle - Aurora Days



From Way North Magazine

J. Barth/Code 562

Discovery of Galactic Cosmic Rays - 1913

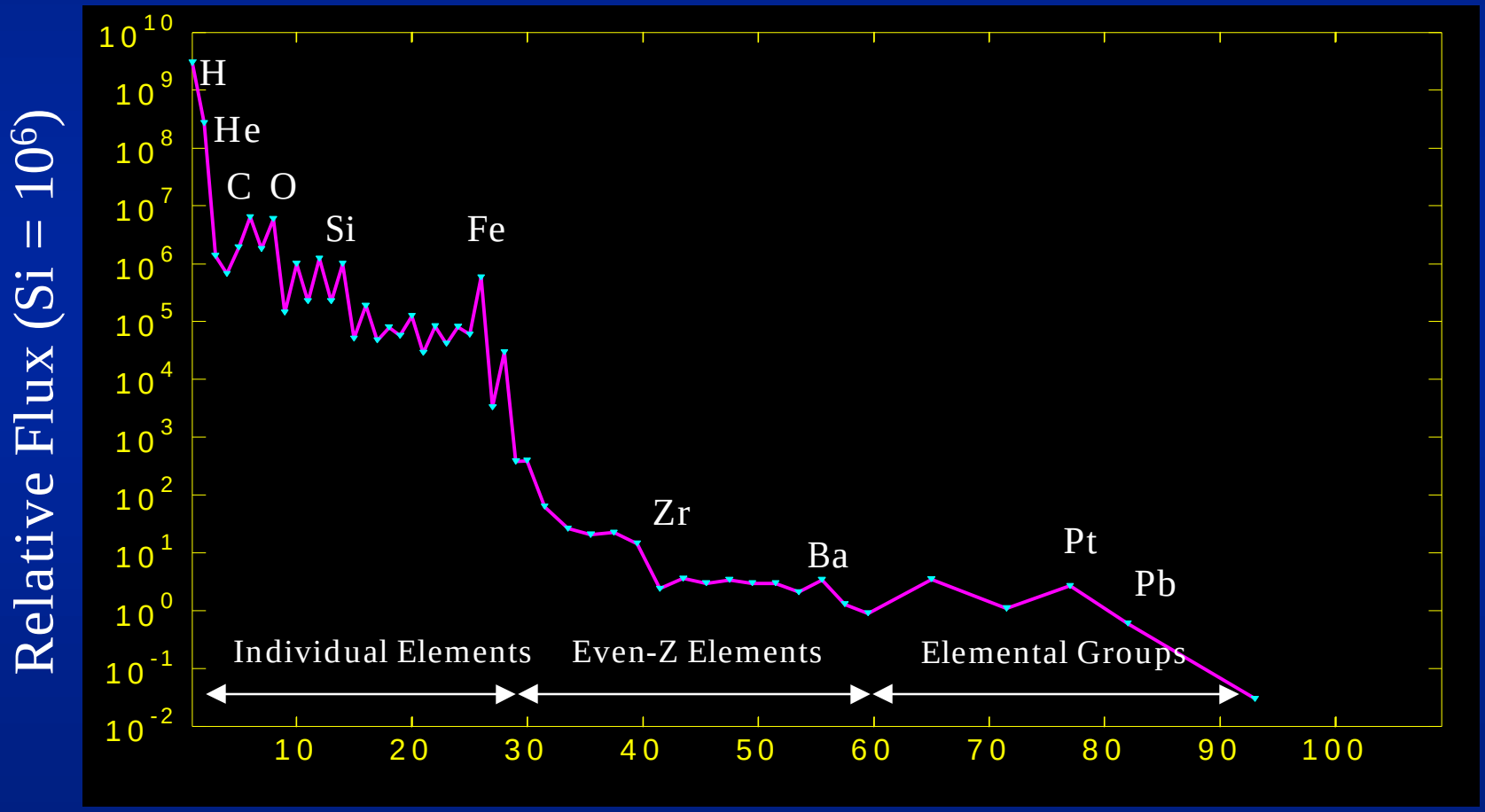
- Electroscope Experiments
  - » Dissipation of Charge on Leaves?
  - » Emissions from Materials on Earth
  - » “Clean” Instruments Did Not Eliminate Dissipation
- Hess
  - » Balloon Experiments with Electroscopes
  - » Hypothesis: Background Radiation Will Disappear with Increasing Altitude
  - » > 10,000 feet - Background Increased with Altitude
  - » Named “Cosmic Rays” by Hess

Galactic Cosmic Ray Ions

- All Elements in Periodic Table - 200 Million Years Old
- Energies in GeV
- Found Everywhere in Interplanetary Space
- Omnidirectional
- Mostly Fully Ionized - Protons & Bare Nuclei of Heavier Elements
- Cyclic Variation in Fluence Levels
  - » Lowest Levels = Solar Maximum Peak
  - » Highest Levels = Lowest Point in Solar Minimum
- Trajectories Bent by Magnetic Field
- Single Event Effects Hazard
- Model: CREME96

GCRs: Nuclear Composition

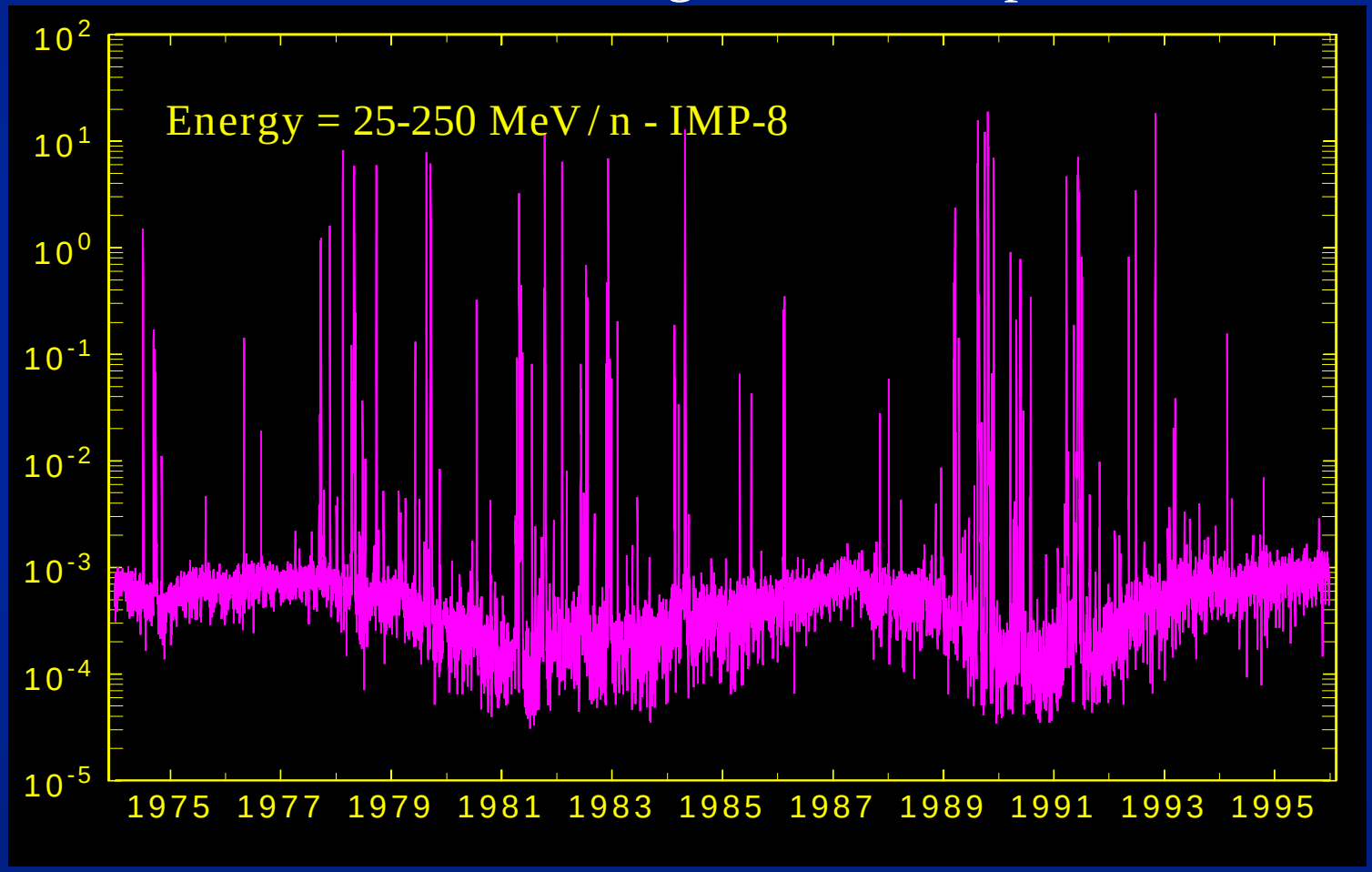
Energy = 2 GeV / n, Normalized to Silicon = 10^6



J. Barth/Code 562

GCRs: Solar Modulation

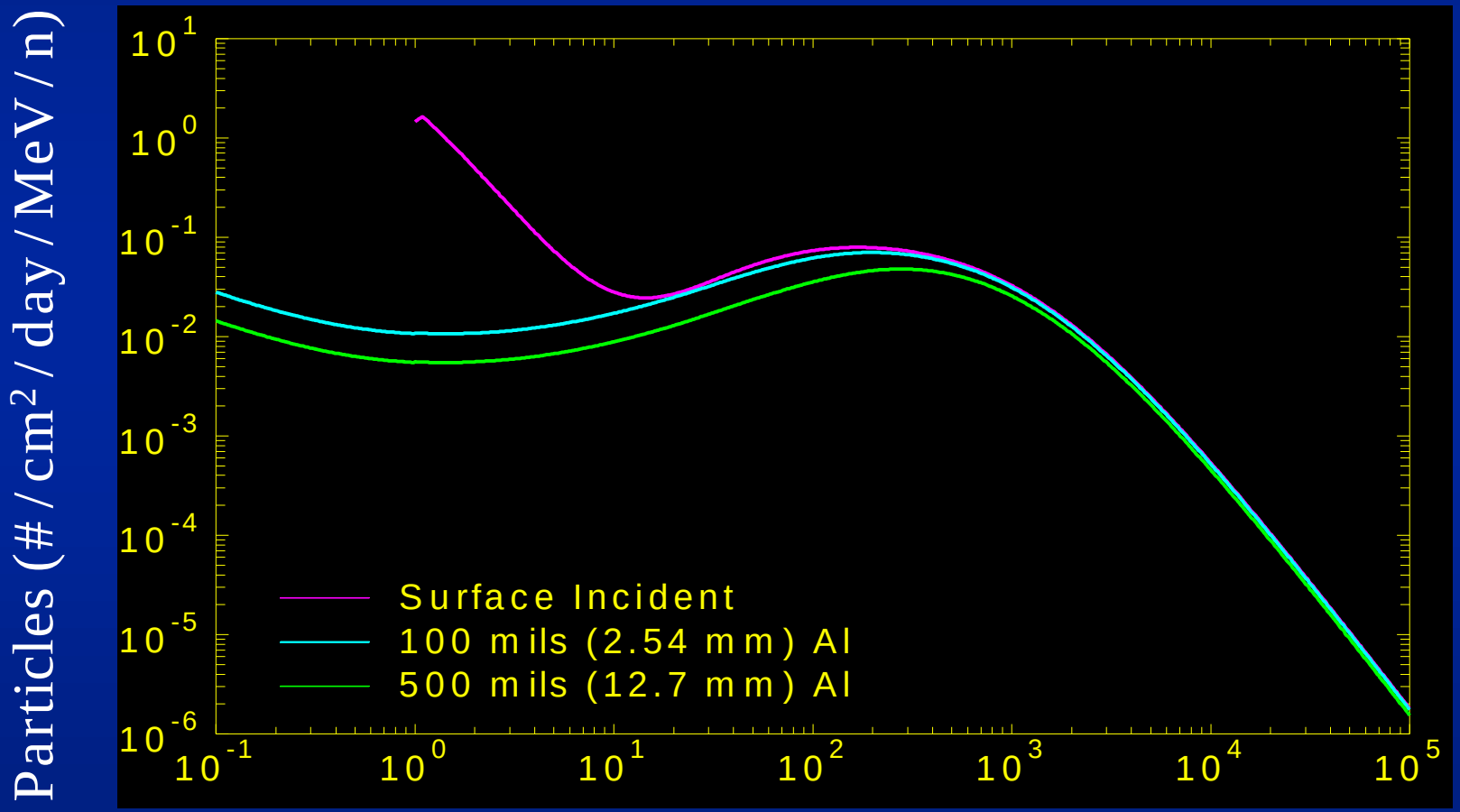
CNO - 24 Hour Averaged Mean Exposure Flux



J. Barth/Code 562

GCRs: Shielded Fluences - Fe

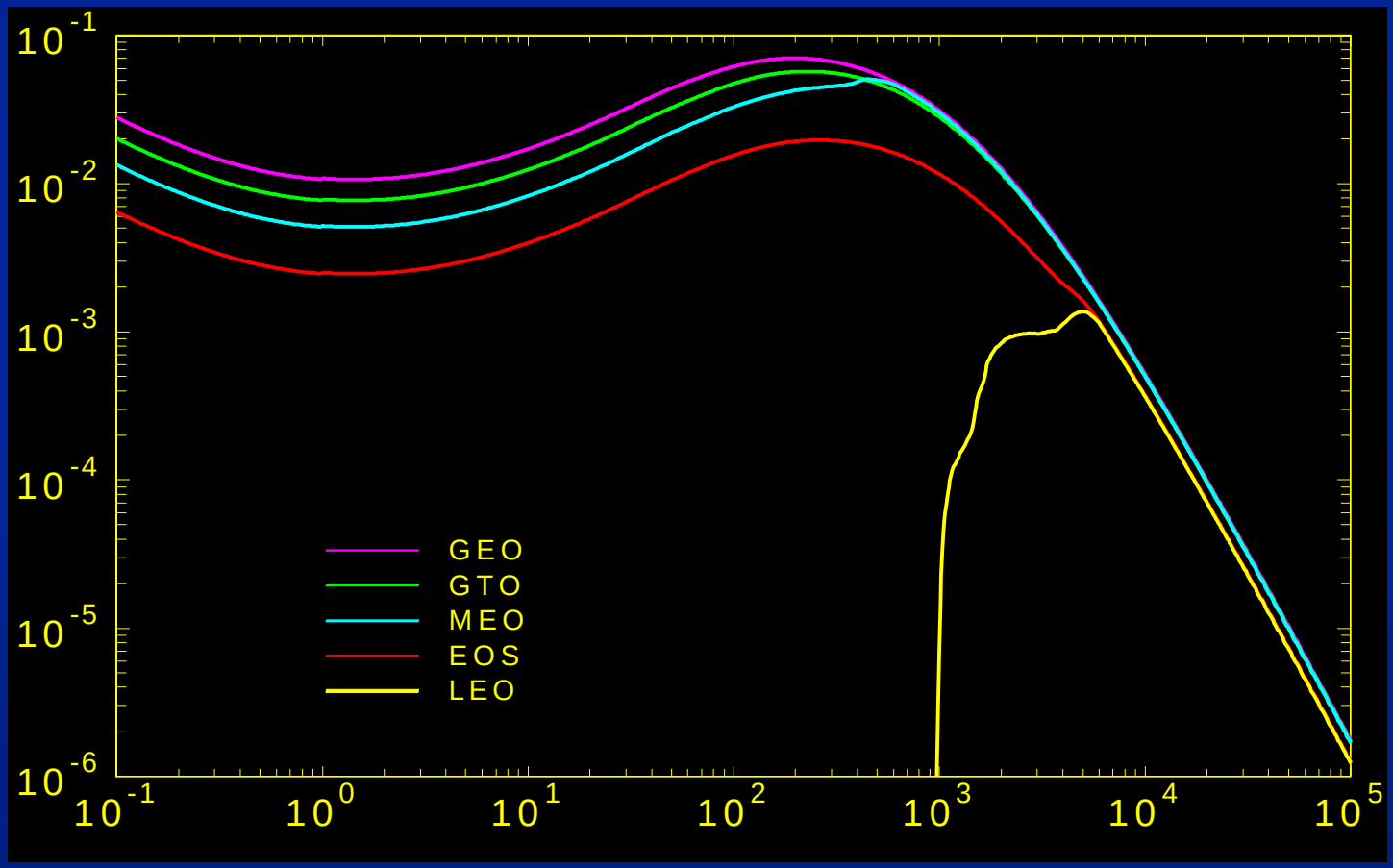
Interplanetary, CREME 96, Solar Minimum



J. Barth/Code 562

GCRs: Shielded Fluences - Fe

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



J. Barth/Code 562

Solar Particle Events

- Increased Levels of Protons & Heavier Ions
- Energies
  - » Protons - 100s of MeV
  - » Heavier Ions - 100s of GeV
- Abundances Dependent on Radial Distance from Sun
- Partially Ionized - Greater Ability to Penetrate Magnetosphere
- Number & Intensity of Events Increases Dramatically During Solar Maximum
- Models
  - » Dose - SOLPRO, JPL, Xapsos / NRL
  - » Single Event Effects - CREME96 (Protons & Heavier Ions)

Solar Particle Events

"The Solar Flare Myth" - Gosling

- Poor Correlation with Solar Flares
- Strong Correlation with Coronal Mass Ejections
  - » No Fundamental Association with Flares
  - » Transient Shock Wave Disturbances in the Solar Wind
  - » Large Geomagnetic Storms
  - » Large Particle Events

Solar Particle Events

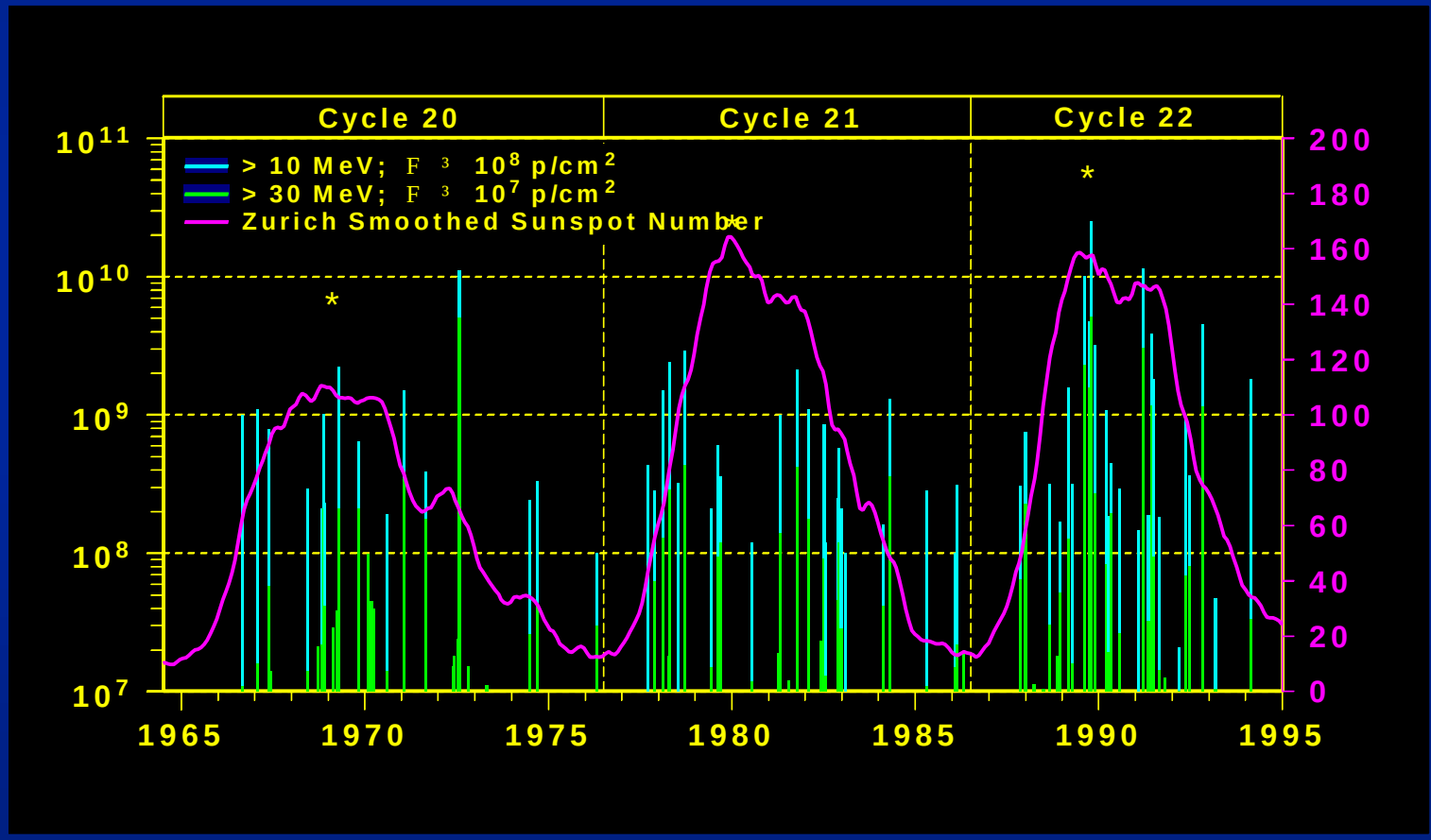
"A New Paradigm" - Reames

2 Types of Events

- Gradual ~ 10 per Year
  - » Coronal Mass Ejection Driven Shocks
  - » Same Elemental Abundances & Ionization States as Coronal & Solar Wind Plasma
- Impulsive ~ 1000 per Year
  - » Flare Accelerated
  - » Abundances Characteristic of Interactions in the Flare Plasma

Sunspot Cycle with Solar Proton Events

Proton Event Fluences



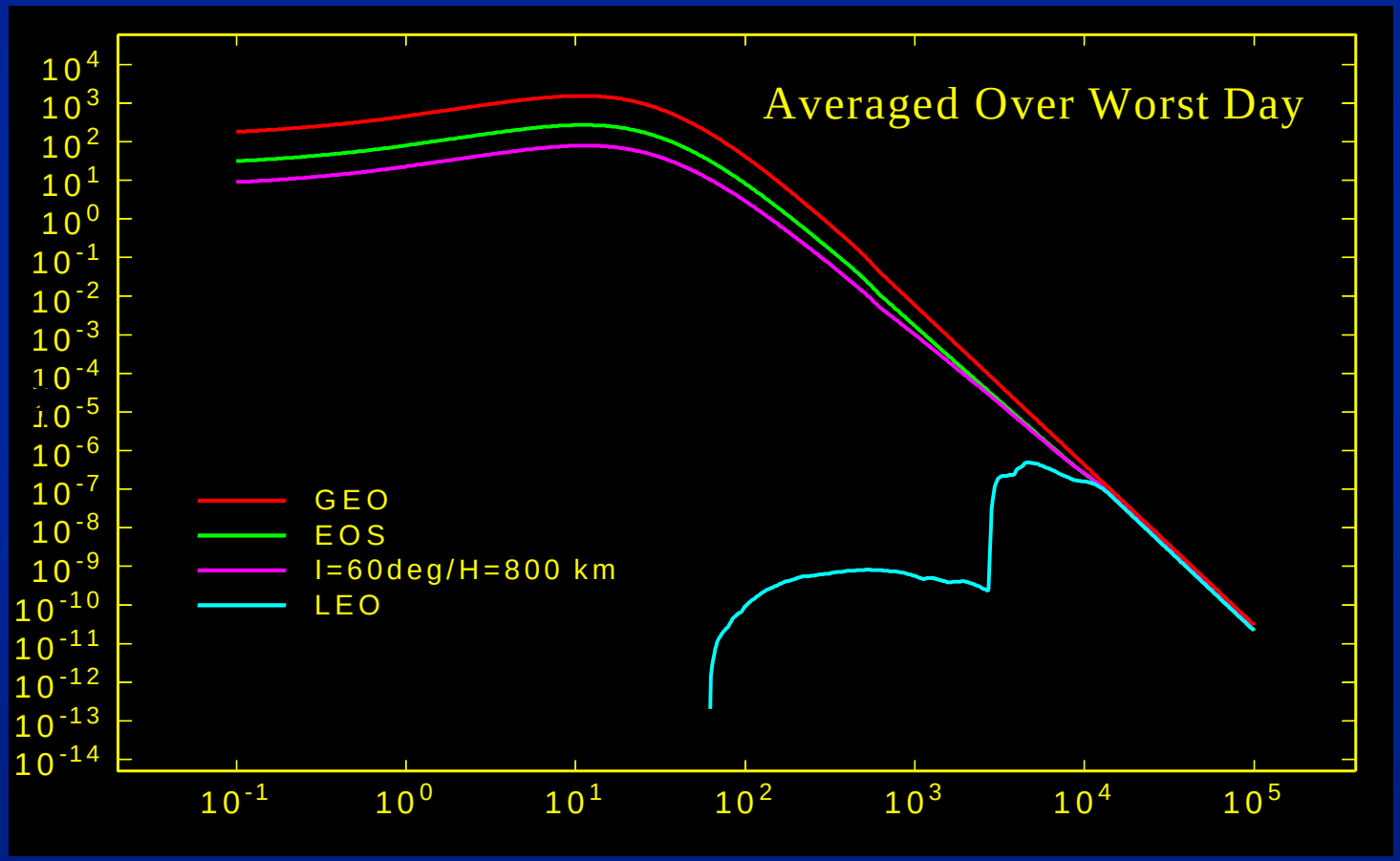
J. Barth/Code 562

Modeling Approach

- Statistical Engineering Model
  - » Intensity as a Function of Mission Duration & Confidence Level
  - » Does Not Predict When Events Occur
- Use Maximum Entropy Principle - Incomplete Data Set
  - » Determines Frequency Distribution of Large Solar Proton Events
  - » Frequency Distribution Consistent with Other Complex Physical Phenomena such as Earthquakes
- Use Extreme Value Theory
  - » Determines Upper Limit for Occurrence of Huge Events
  - » New Upper Limit Consistent with Data Sets Dating Back to Ancient Times - Lunar Rock Record

Solar Protons: Orbits

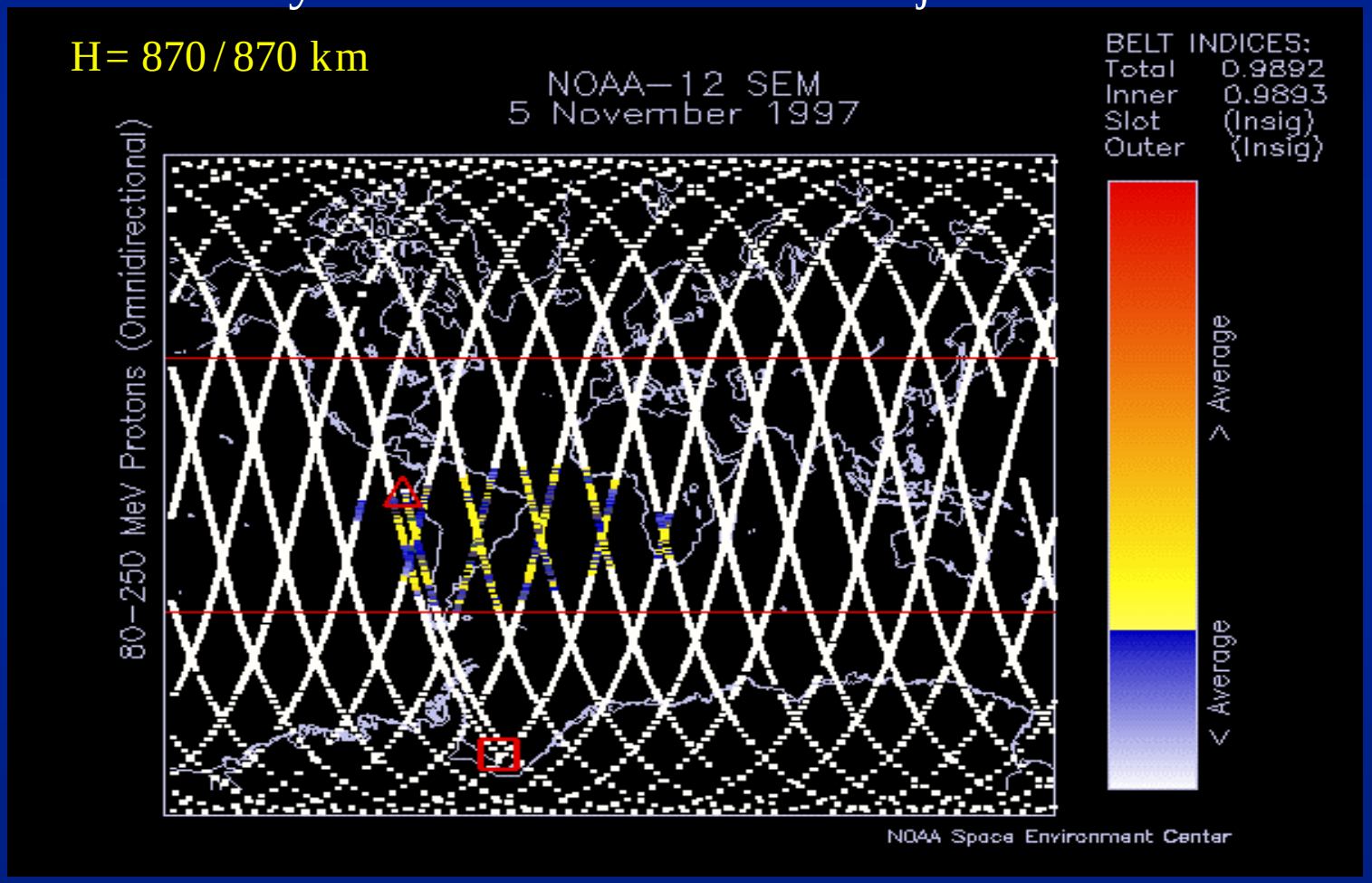
Proton Levels Predicted by CREME 96



J. Barth/Code 562

TIROS Measurement of Protons

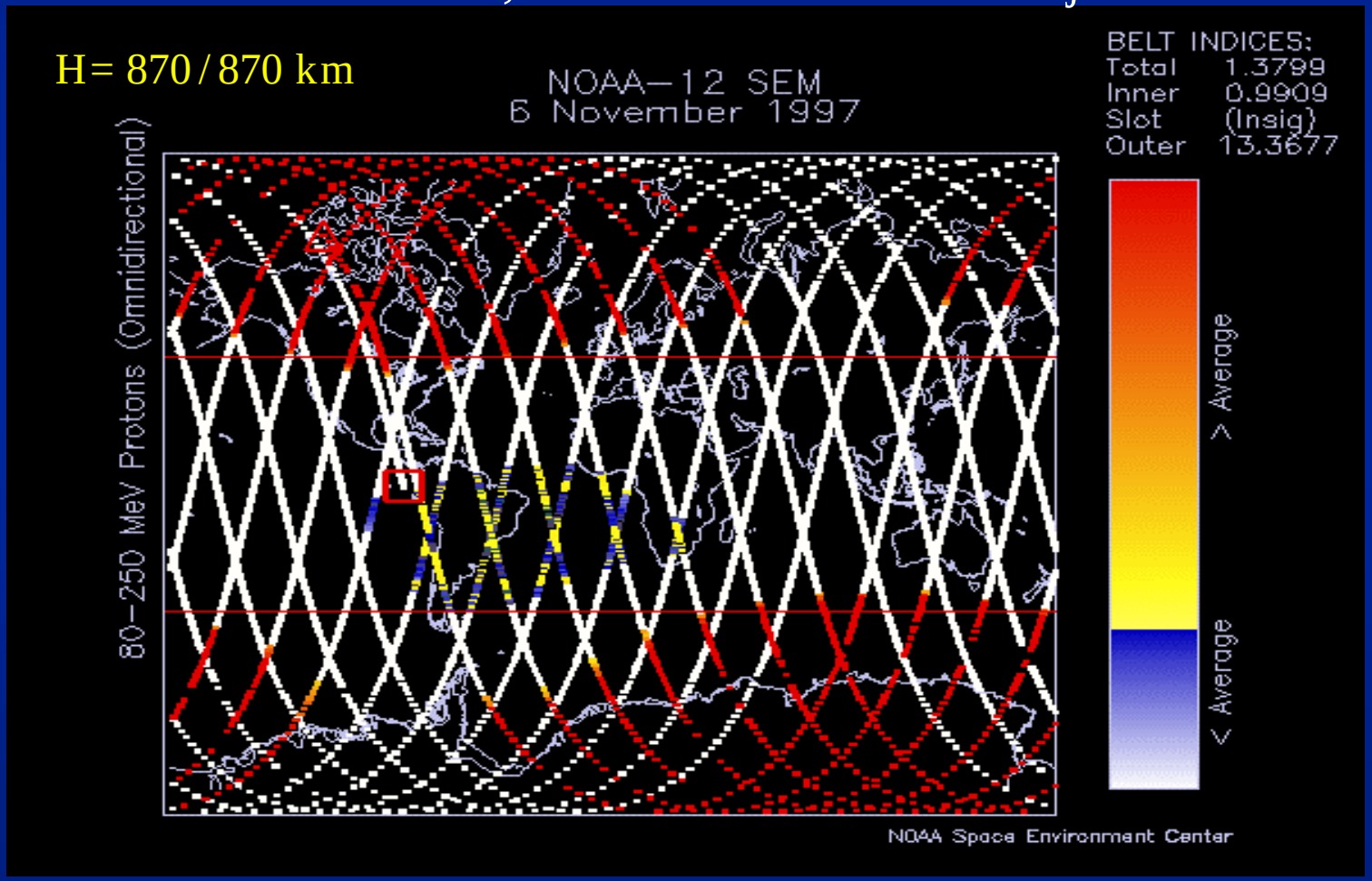
Day Before Coronal Mass Ejection



J. Barth/Code 562

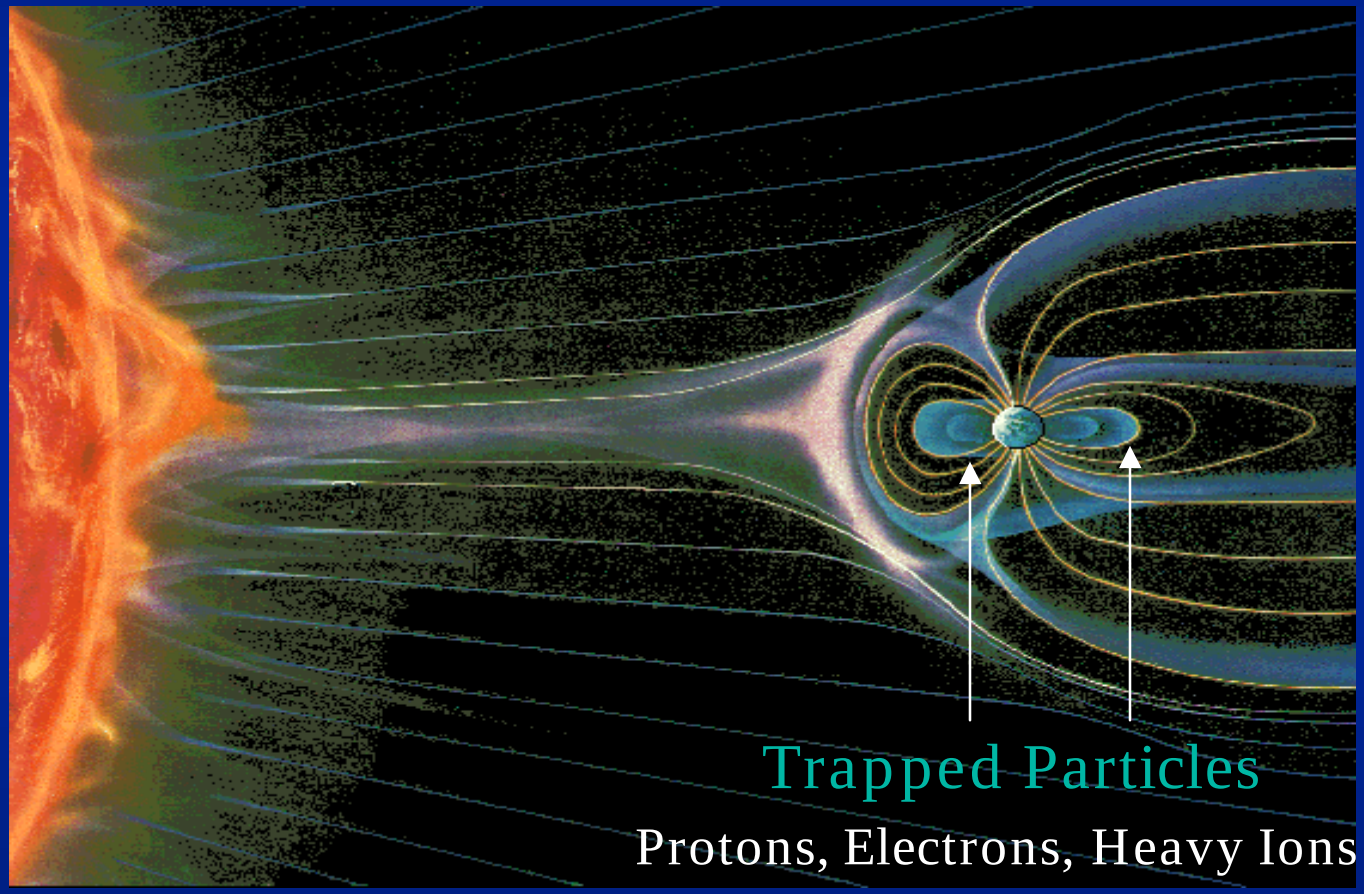
TIROS Measurement of Protons

November 6, 1997 Coronal Mass Ejection



J. Barth/Code 562

Trapped Radiation



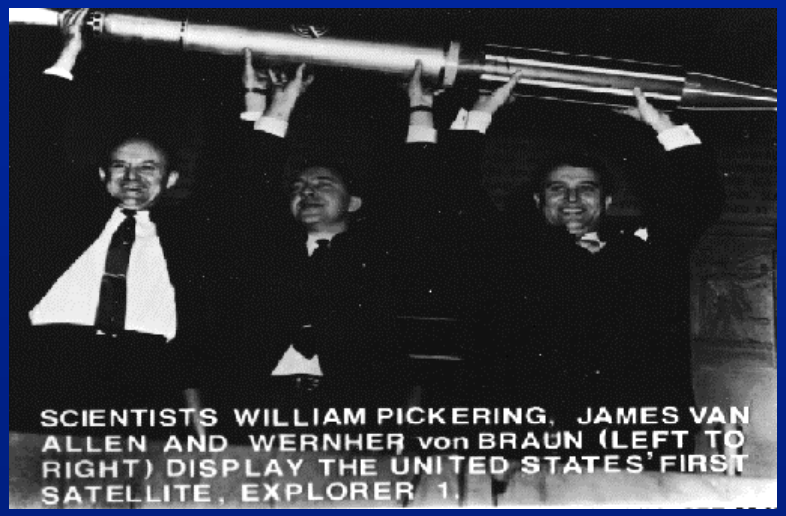
Nikkei Science, Inc. of Japan, by K. Endo

Charged Particle Motion

- Birkeland - 1895
  - » Vacuum chamber experiments to study aurora
  - » With Poincare showed that charged particles spiraled around field lines and are repelled by strong fields
- Stöermer -
  - » Continued work of Birkeland on aurora
  - » Calculations led to theory that there was a belt-like area around the earth in which particles were reflected back and forth between the poles
- Singer (U. o f Md) - 1957
  - » Proposed that ring current could be carried by lower energy particles injected by into trapped orbits by magnetic storms
- Christofilos
  - » Study of particle motion in magnetic fields - Project Argus

Discovery of the Radiation Belts

- James Van Allen
  - » First Observation of Auroral Electrons with a Rocket
  - » Cosmic Ray Detector
- Highlight of US Participation in IGY

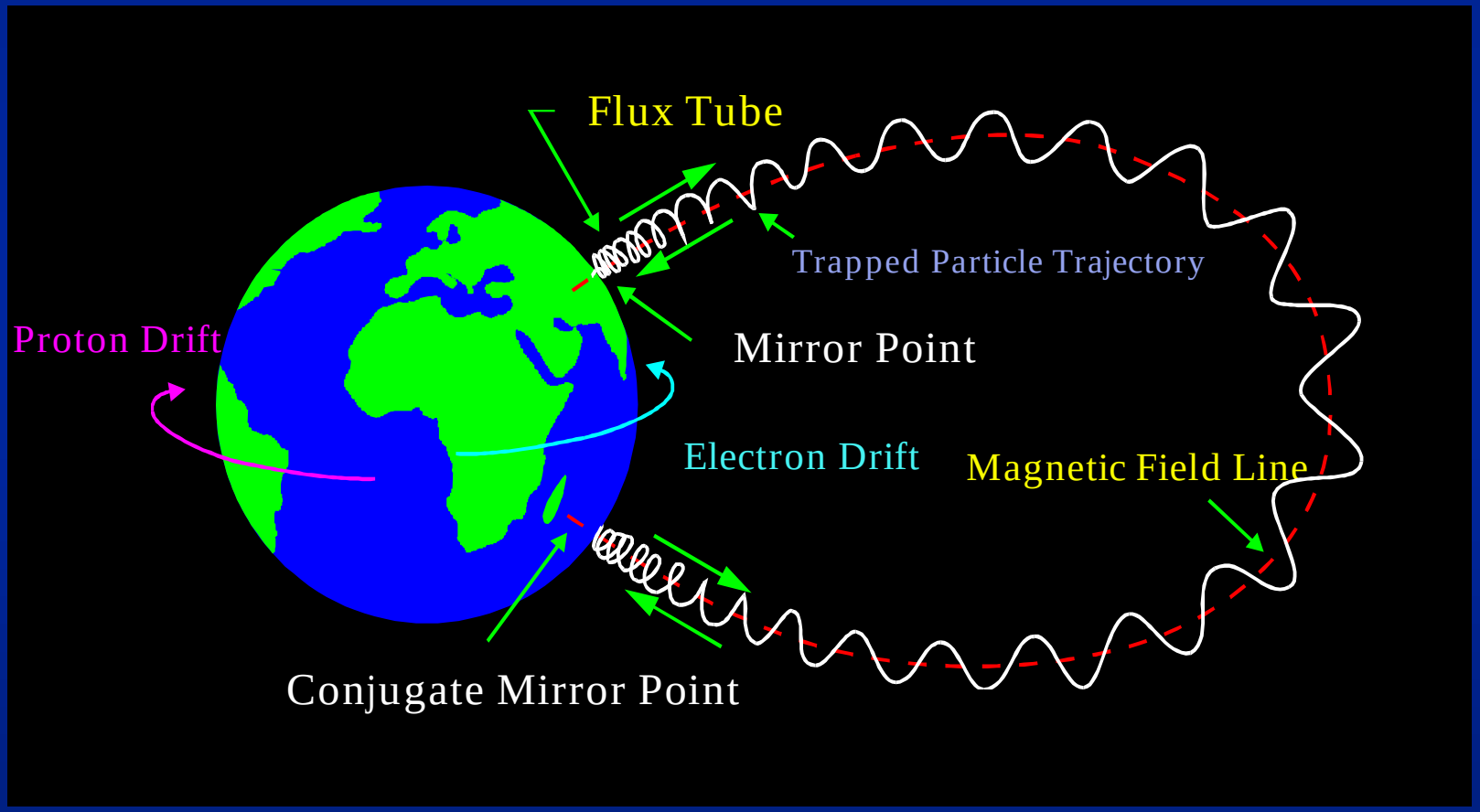


Trapped - Van Allen Belts

- Omnidirectional
- Components
  - » Protons: E ~ .04 - 500 MeV
  - » Electrons: E ~ .04 - 7(?) MeV
  - » Heavier Ions: Low E - Non-problem for Electronics
- Location of Peak Levels Depends on Energy
- Average Counts Vary Slowly with the Solar Cycle
- Location of Populations Shifts with Time
- Counts Can Increase by Orders of Magnitude During Magnetic Storms
  - » March 1991 Storm - Increases Were Long Term

Trapped Particle Motions

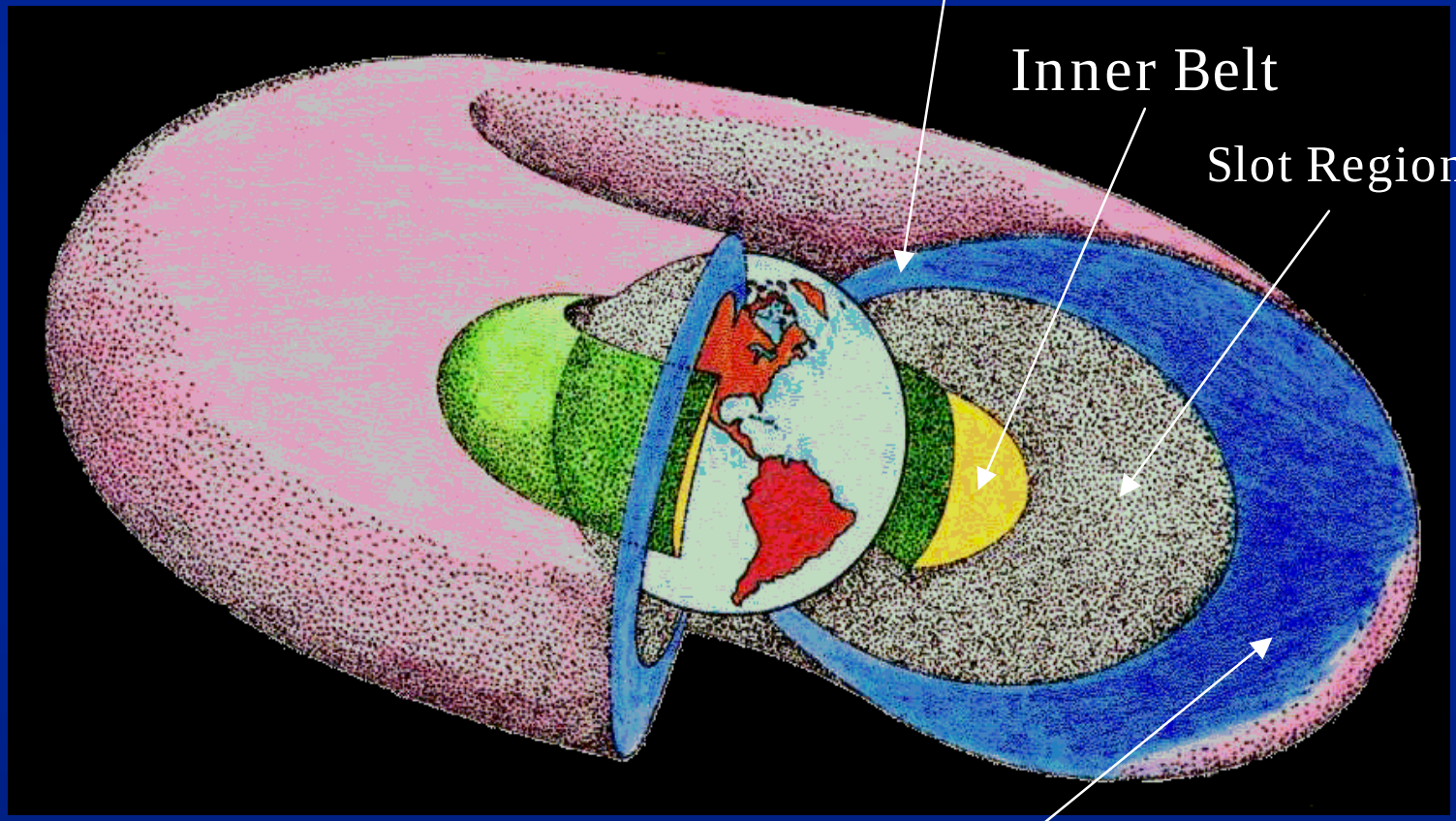
Spiral, Bounce, Drift



after Hess

J. Barth/Code 562

Van Allen Belts

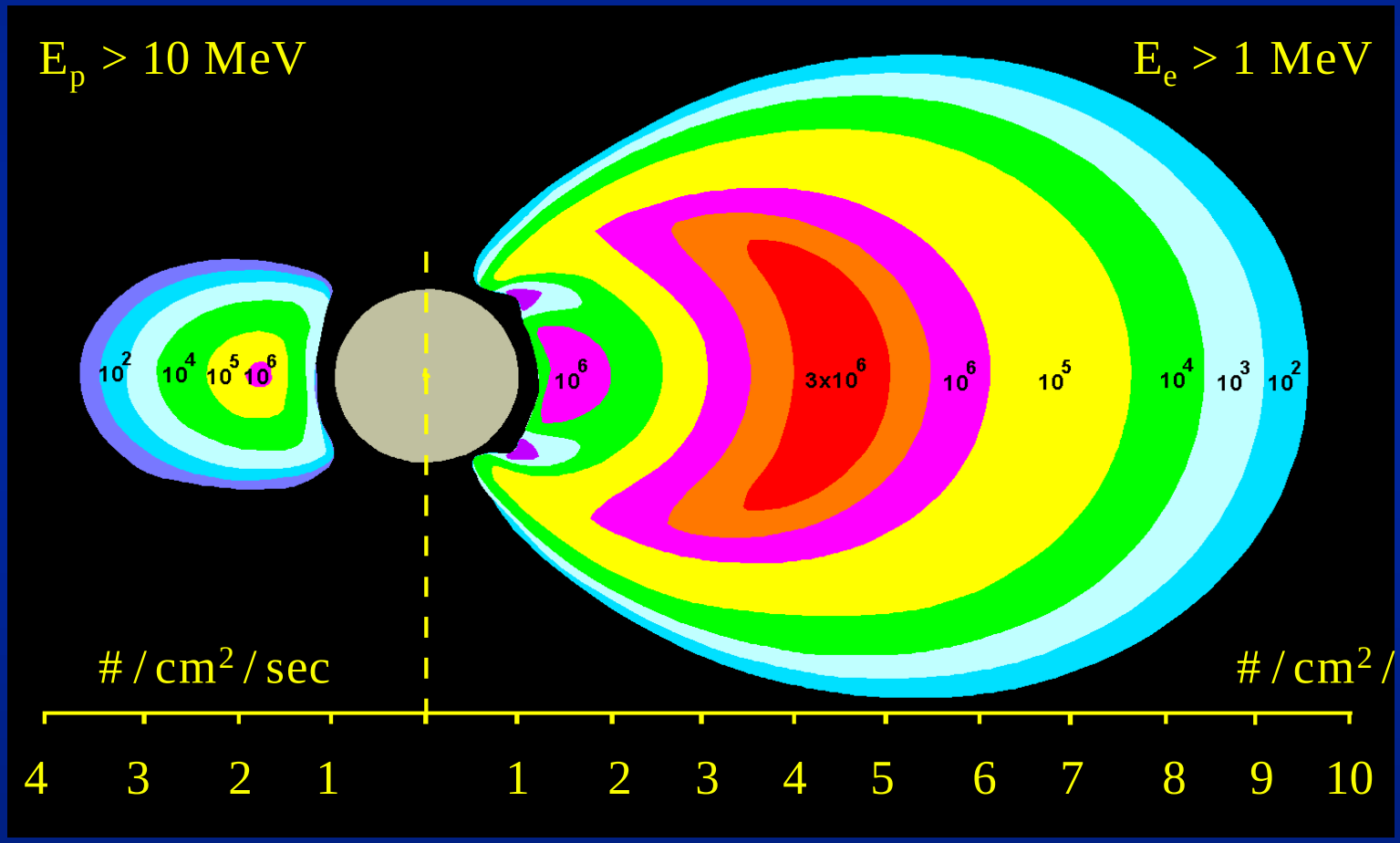


BIRA/IASB

J. Barth/Code 562

Proton & Electron Intensities

AP-8 Model AE-8 Model

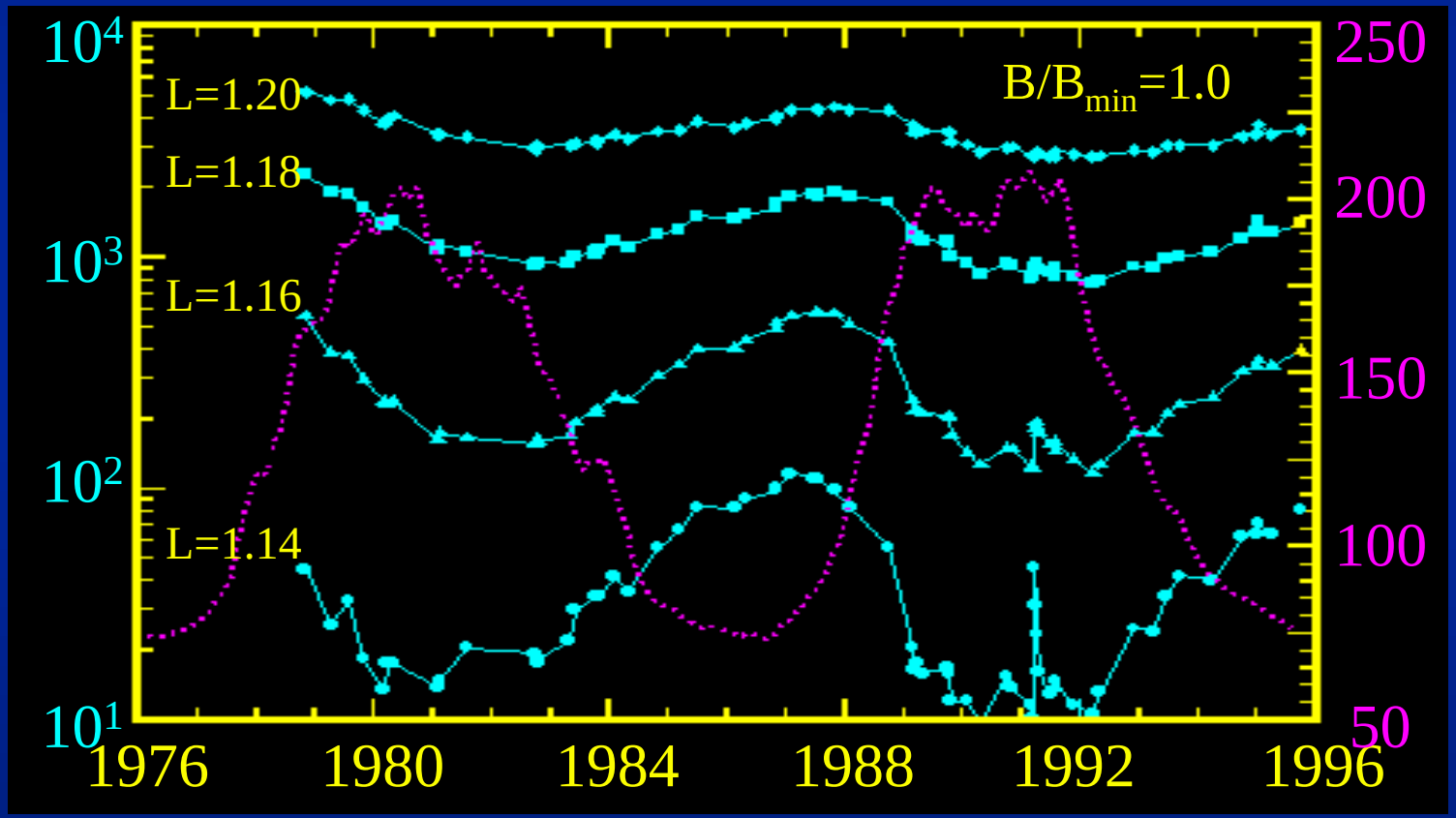


J. Barth/Code 562

NASA / GSFC

TIROS/NOAA Trapped Protons

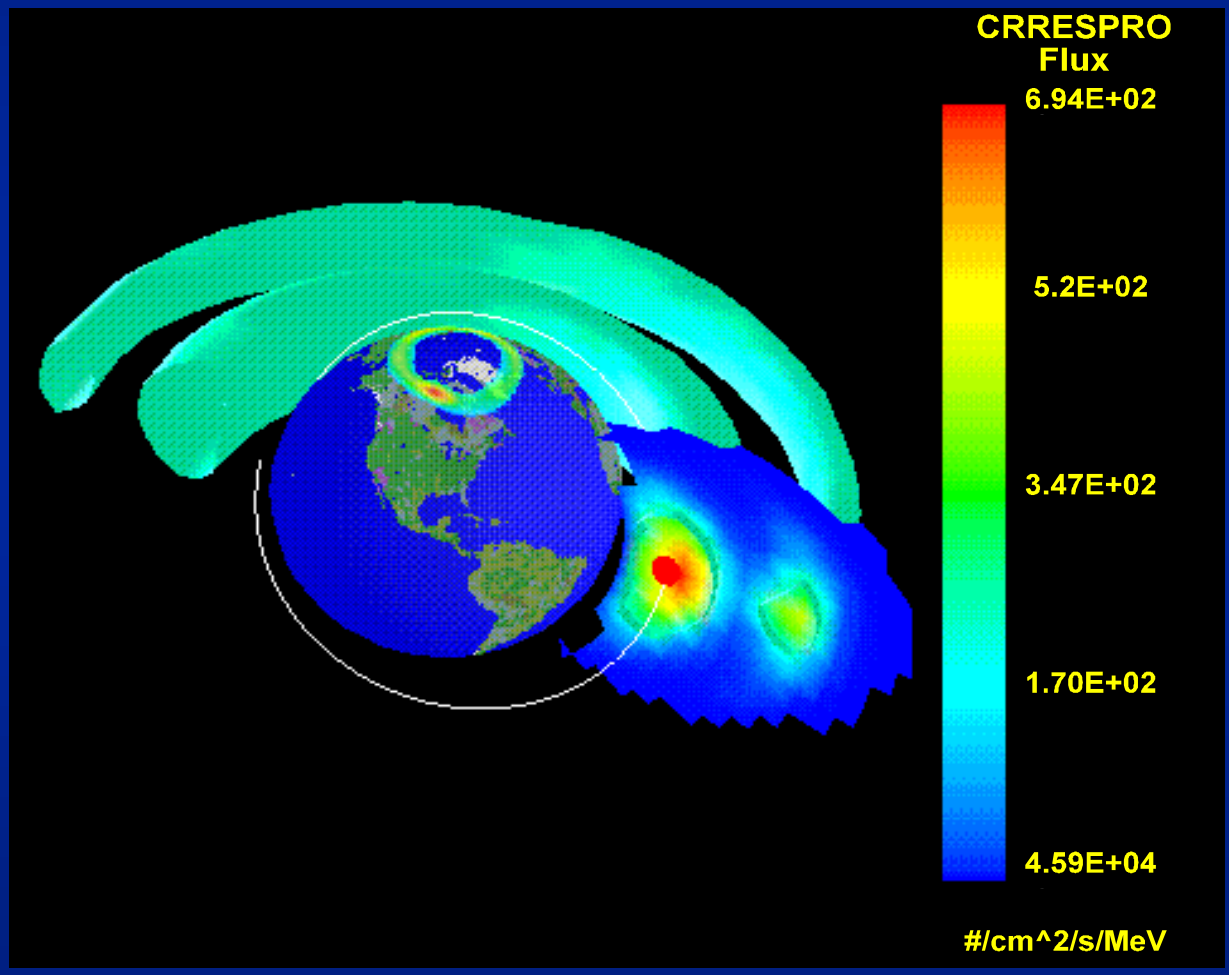
Solar Cycle Variation: 80-215 MeV Protons



Huston et al.

J. Barth/Code 562

CRRES - Measured Proton Belt

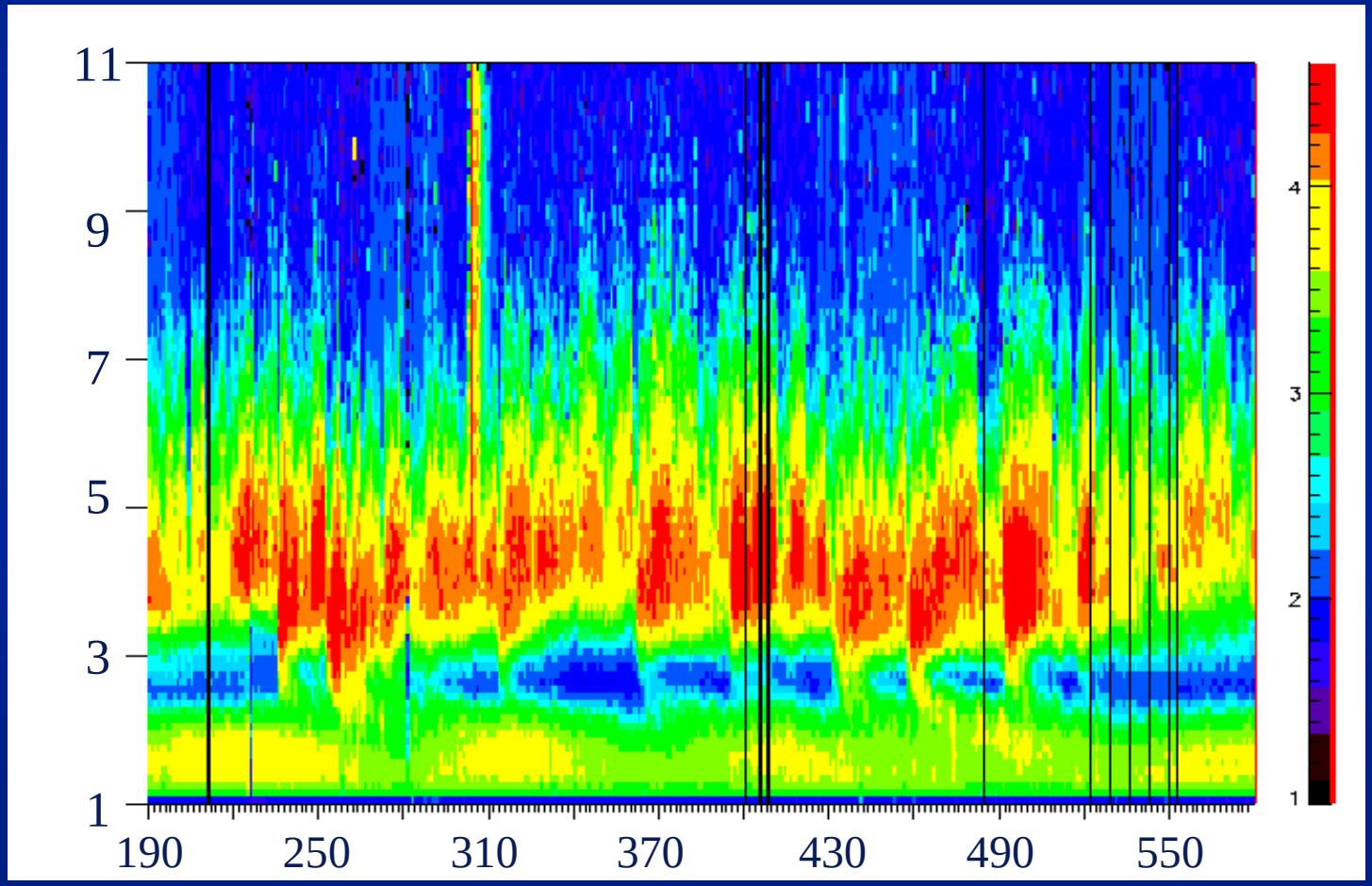


J. Barth/Code 562

AF Phillips Laboratory, SPD/GD

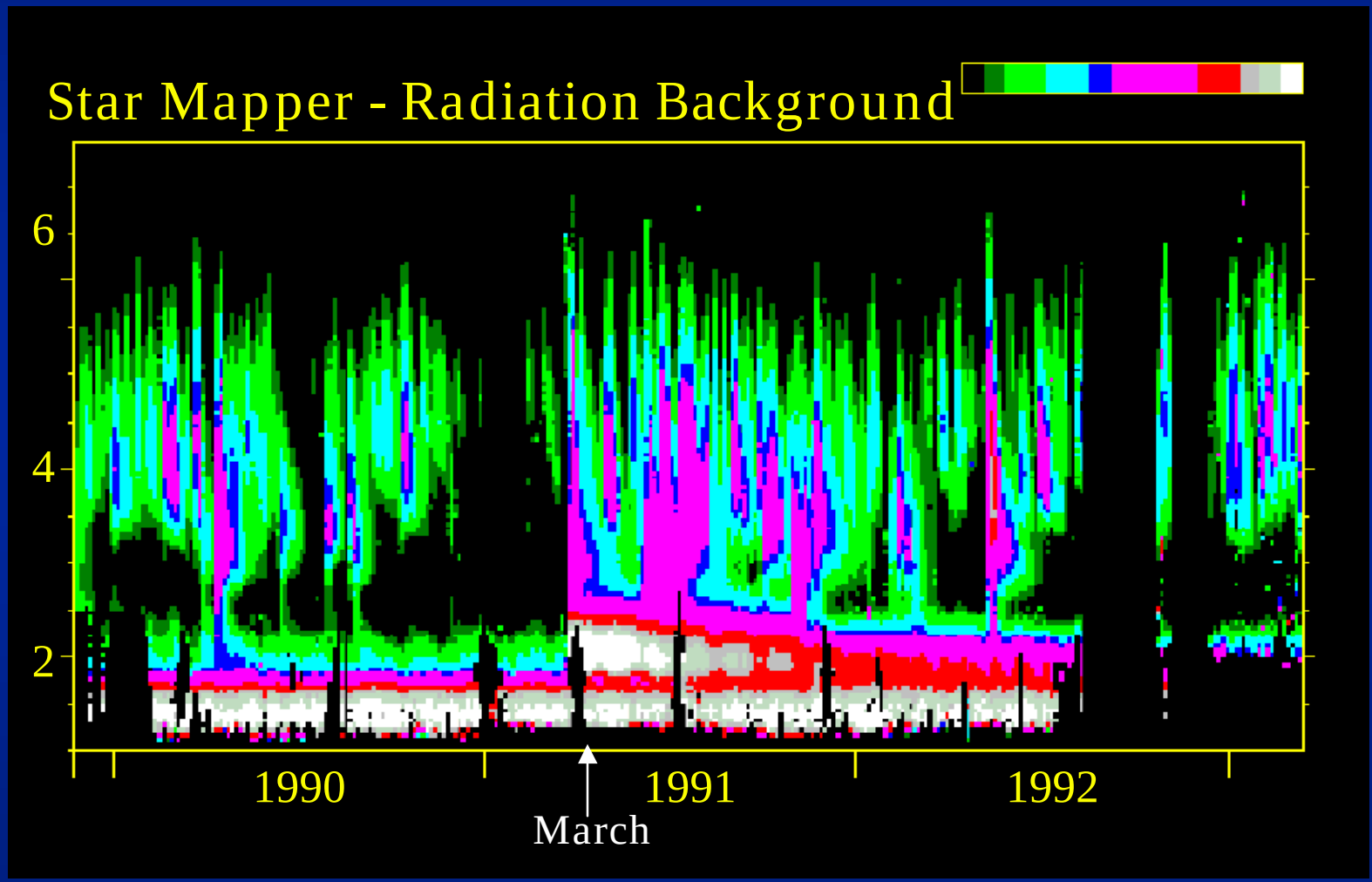
Activity in the Slot Region - SAMPEX

SAMPEX / P1ADC: Electrons E > 0.4 MeV



J. Barth/Code 562

Magnetic Storms - Hipparcos

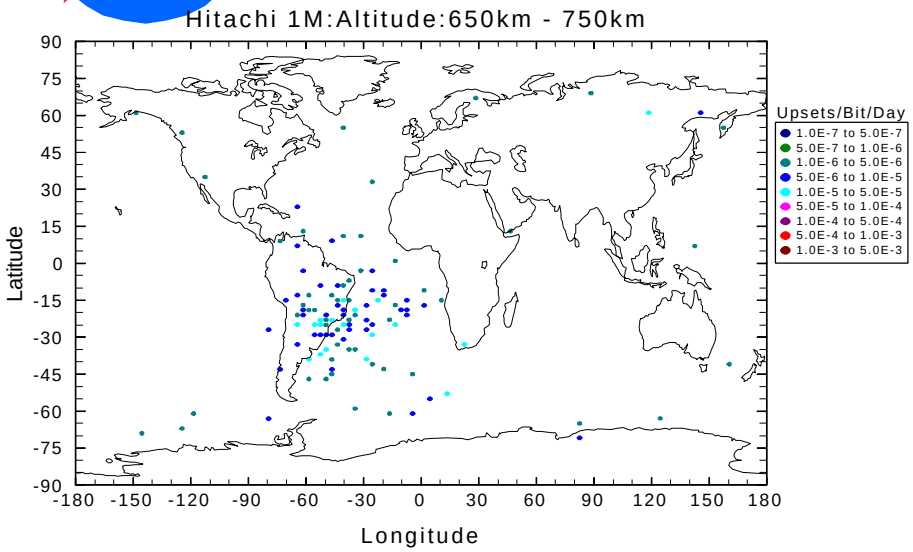


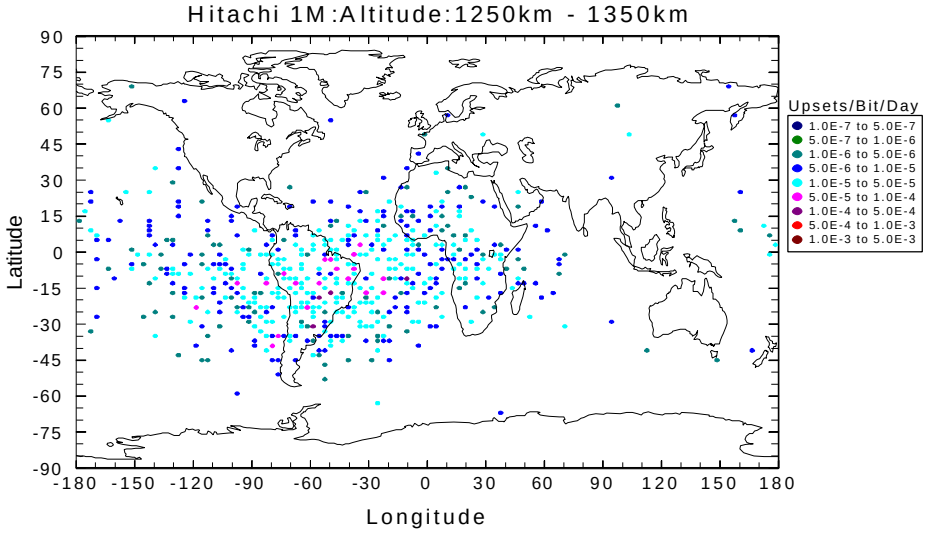
4-Day, 9-Orbit Averages

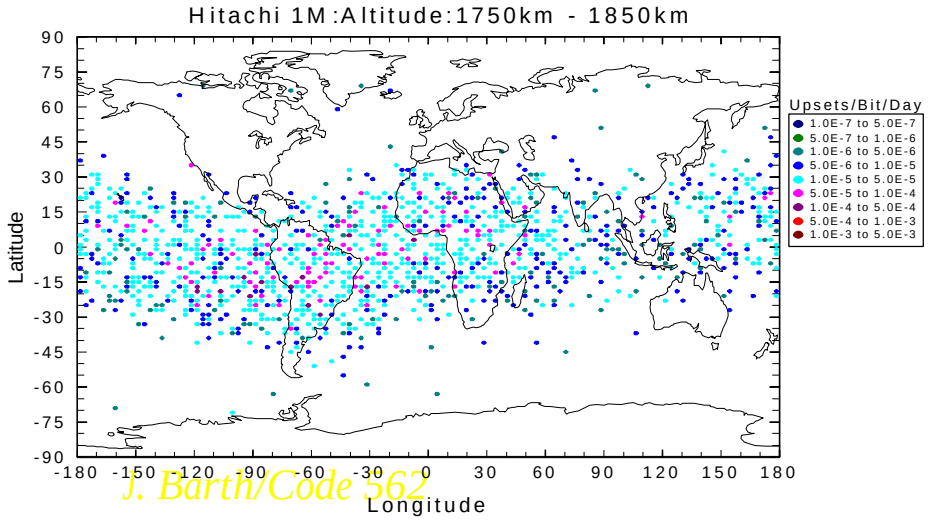
Daly, et al.

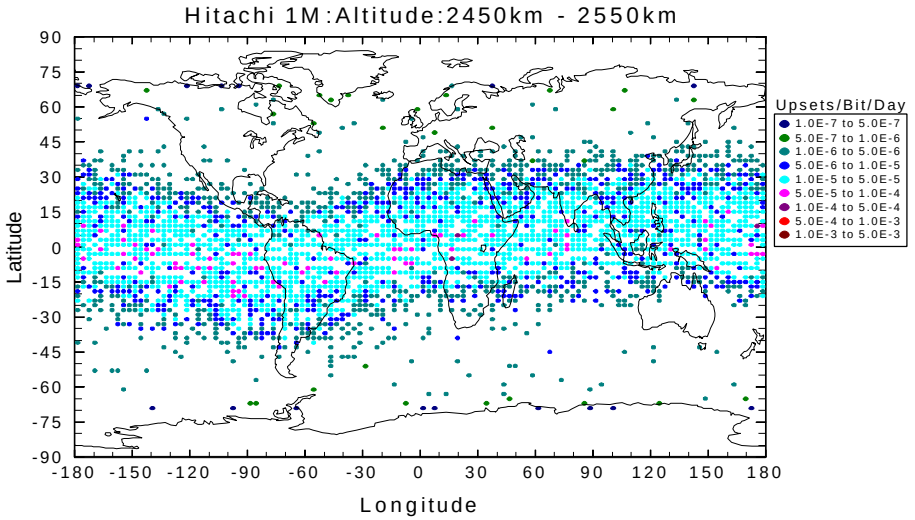
J. Barth/Code 562

SRAM Upset Rates on CRUX/APEX



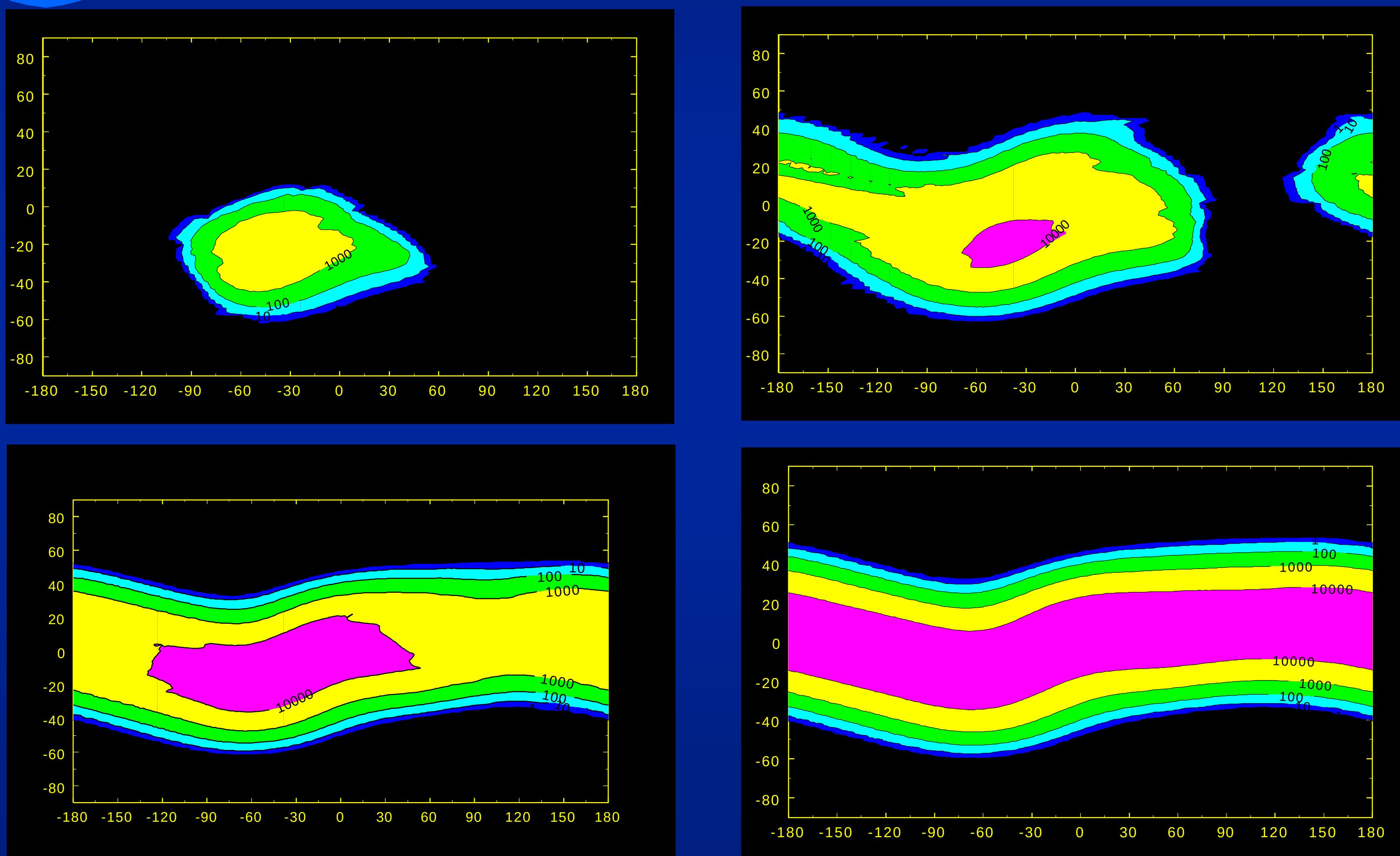






J. Barth/Code 562

Trapped Protons for E > 30 MeV ($\#/cm^2/s$) - Solar Minimum



J. Barth/Code 562

Particle Cascades in Atmosphere

- Collisions between cosmic rays & atmospheric O & N
- Important product is neutrons
  - » Single Event Upsets
    - Shuttle
    - Aircraft
    - Ground
  - » Passenger & crew exposure in aircraft

Neutrons

- Source - Secondary Products of Particle Cascades
  - » Spacecraft Materials
  - » Galactic Comic Ray Collisions with Atmospheric O & N
- Single Event Upset Hazard
  - » Ground Level in Large Memory Banks
  - » Avionics
  - » Low Earth Orbits - Shuttle
- First Recognized as Problem in 1980s

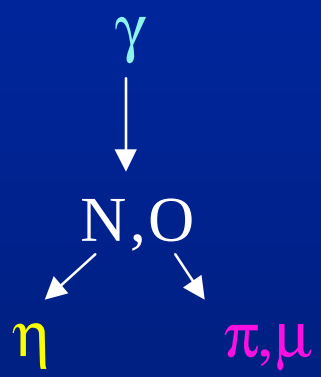
Neutron Environment

Normand et al.

γ Primary Cosmic Rays

η Neutrons

π,μ Secondary Cosmic Rays



1,000,000 feet
330 km
Shuttle

150,000 feet
50,000 m
Top of Atmosphere

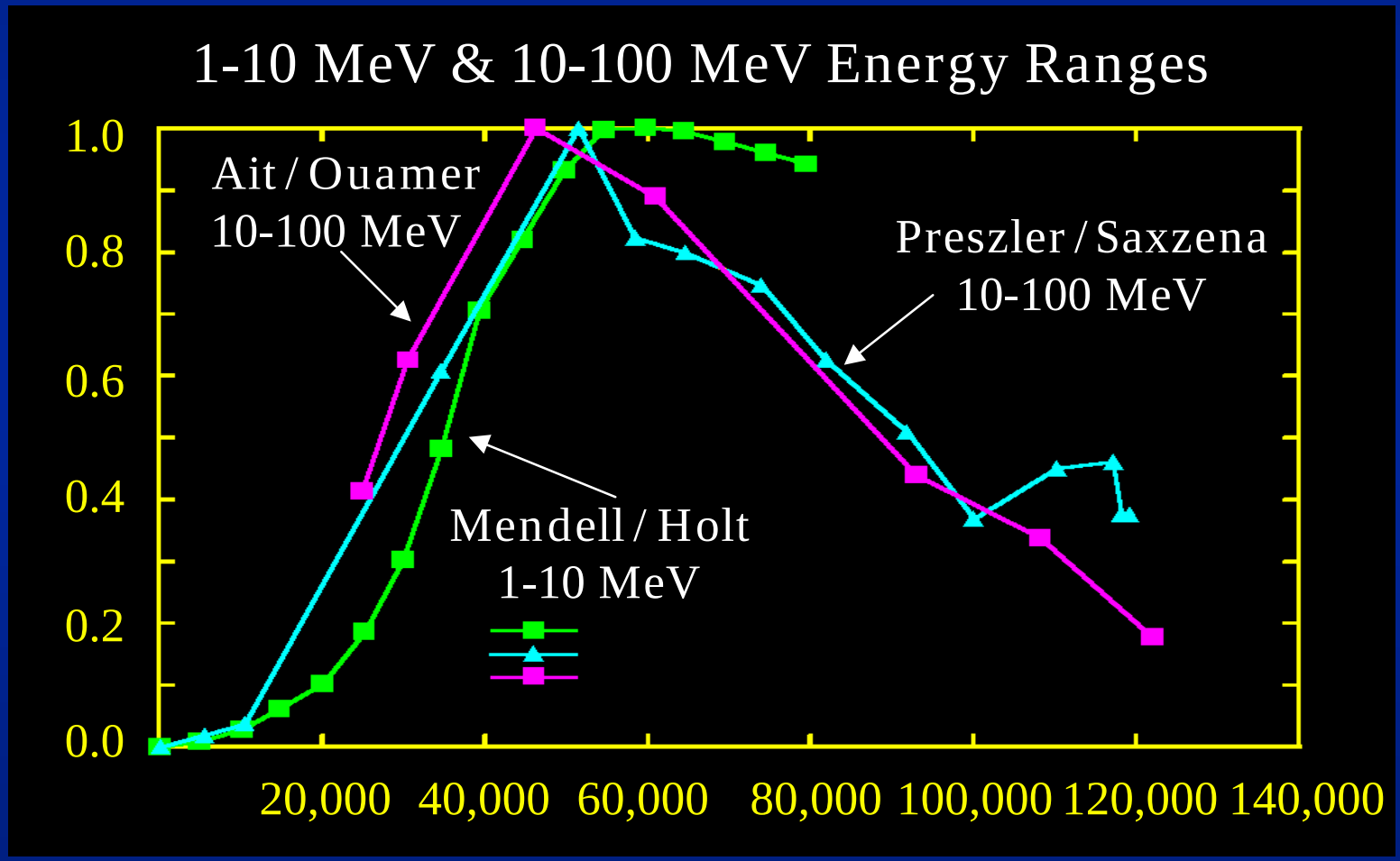
60,000 feet
20,000 m
Peak Neutron Flux

~ 35,000 feet
10,000 m
Aircraft

Ground ~ 1/500 of Peak Flux

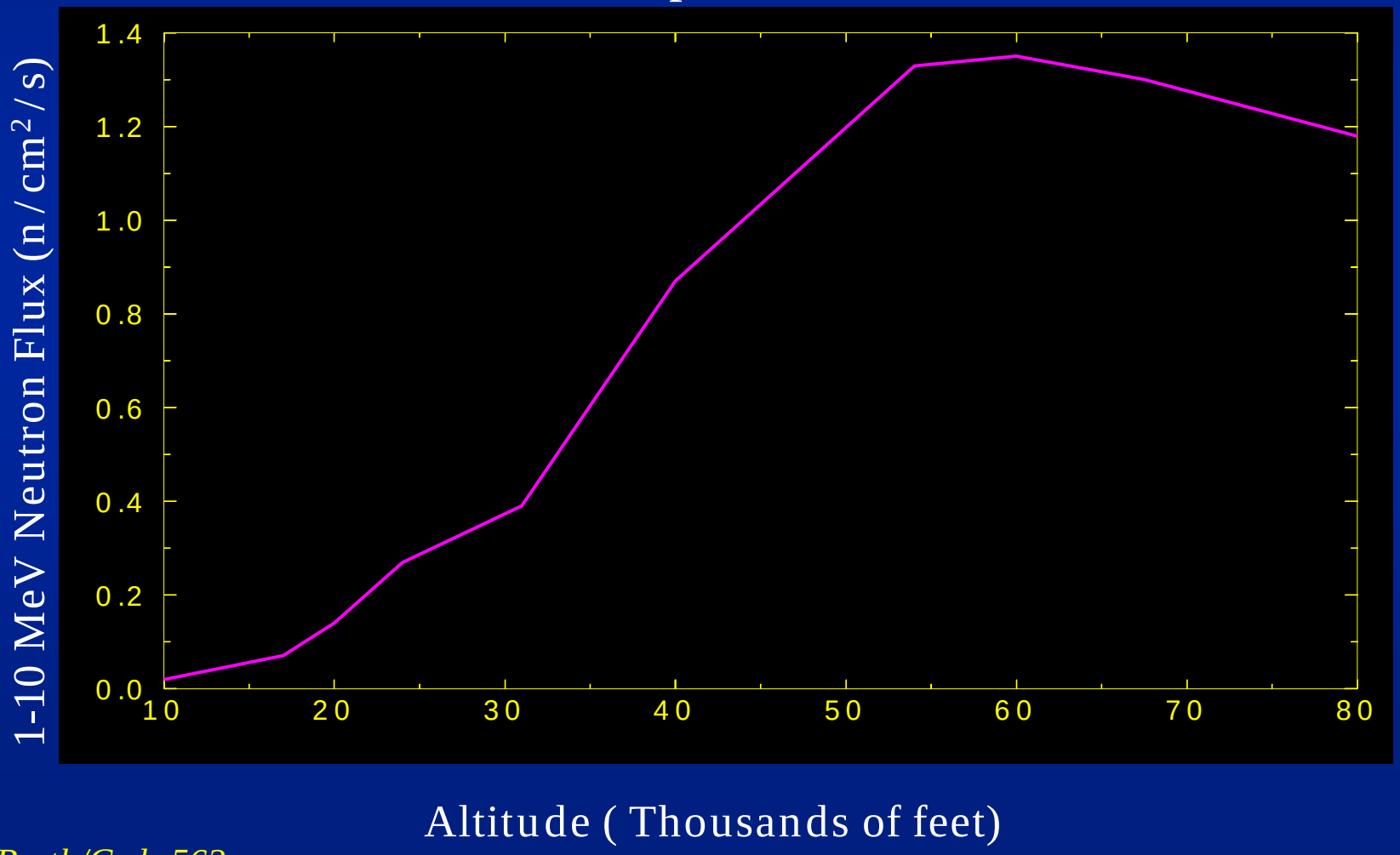
J. Barth/Code 562

Neutron Flux Measurements



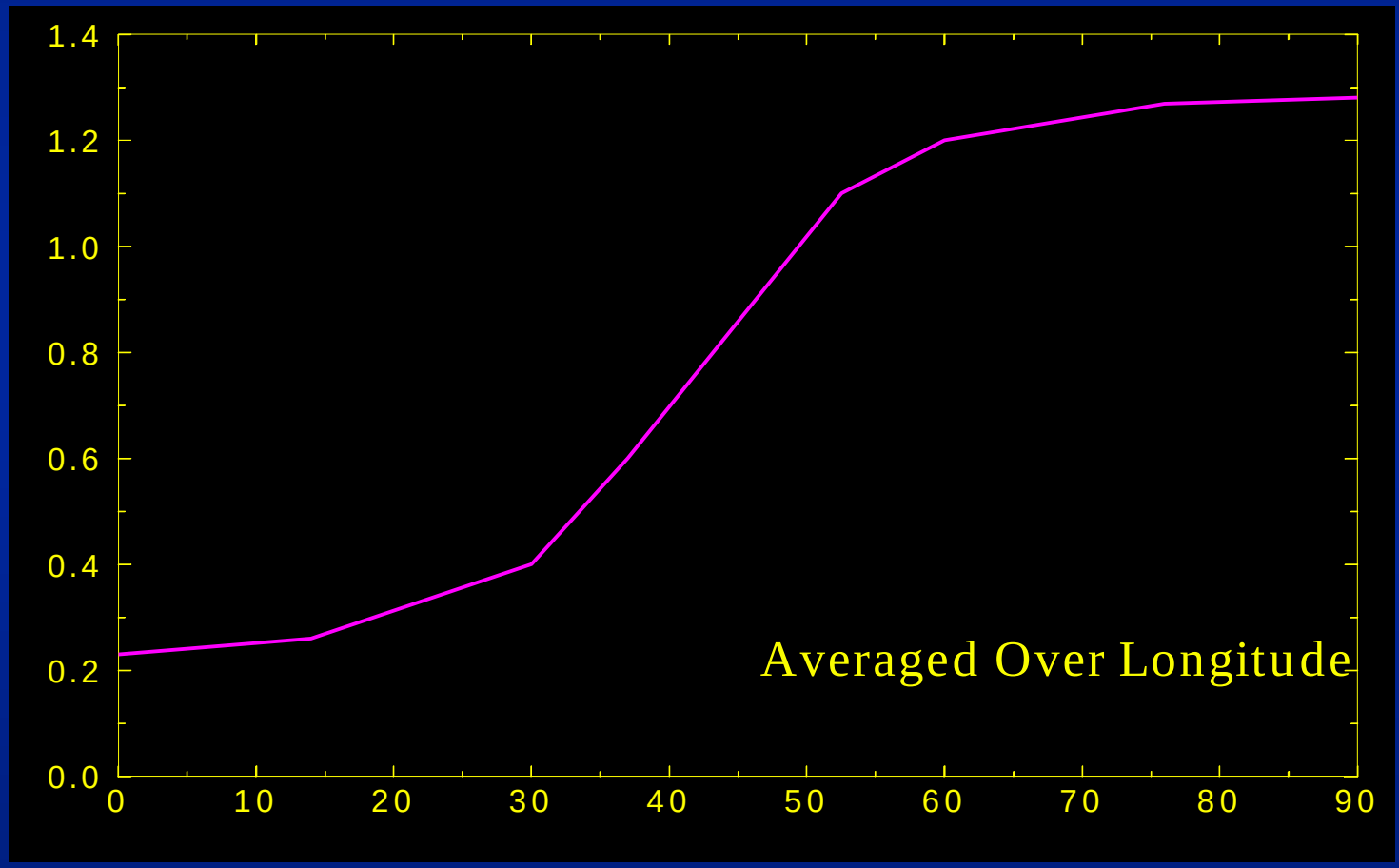
J. Barth/Code 562

Neutron Models: Flux vs. Altitude



J. Barth/Code 562

Neutron Model: Flux vs. Latitude



J. Barth/Code 562

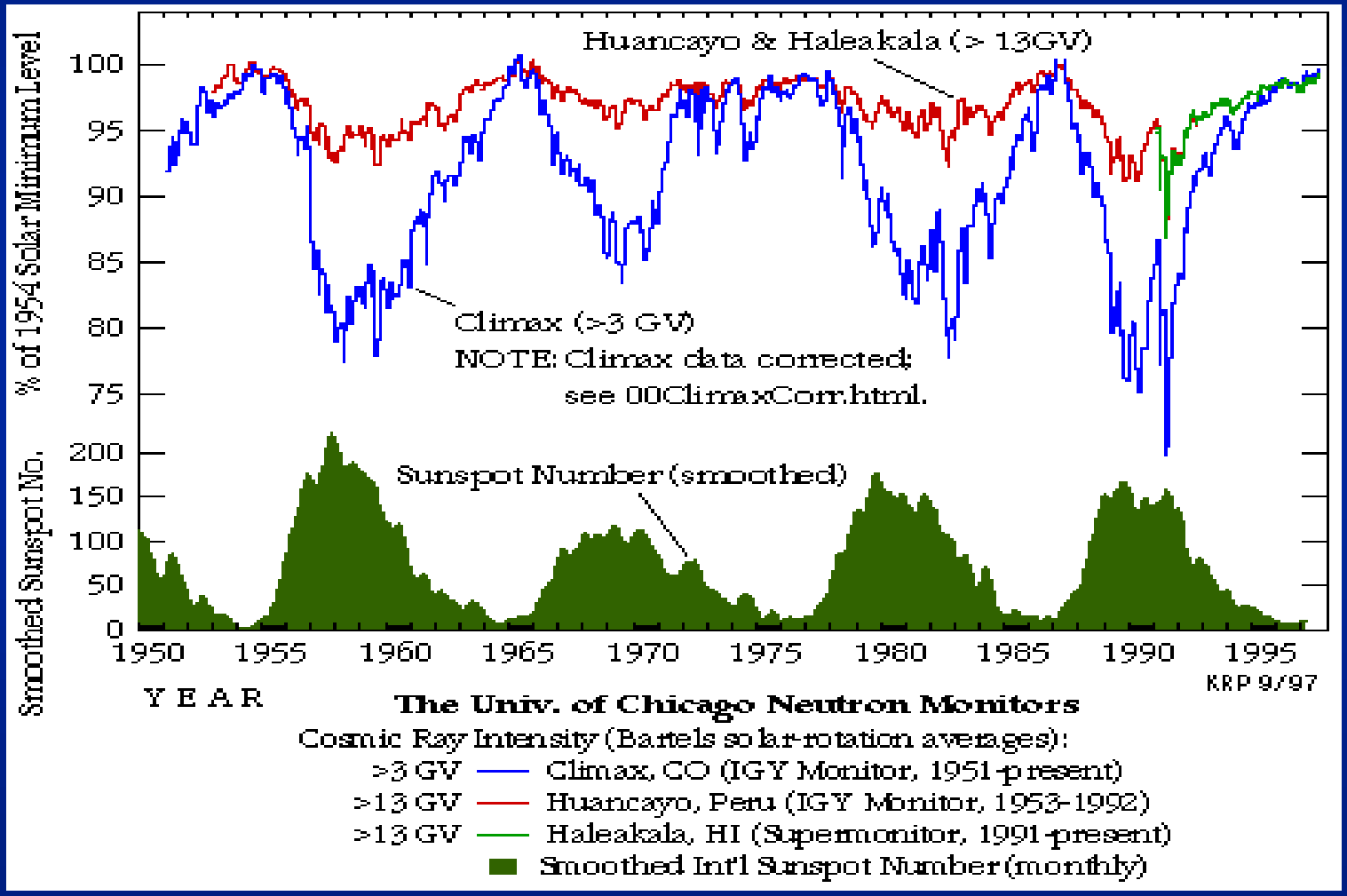
Terrestrial Radiation Sources

- Man-made
- Natural Emissions from Earth Materials
  - » Package Contamination
- Cosmic Rays - Particle Showers

Terrestrial Cosmic Rays

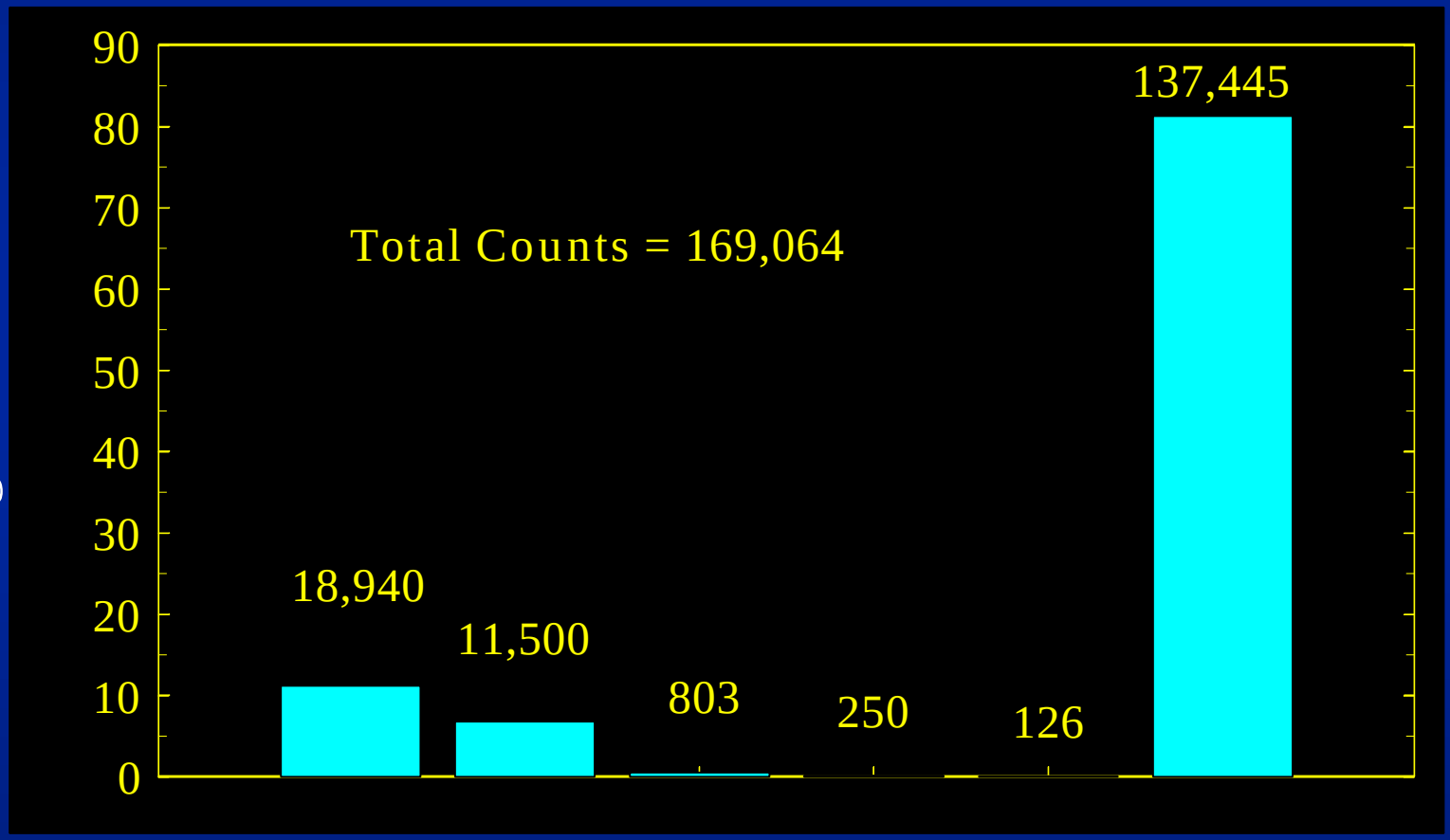
- Particles That Hit the Earth from Outer Space
- Need > 1 GeV to Penetrate to Sea Level
- Fewer Than 1% Are Primary
- Mostly 3rd to 7th Generation Cascade Particles
- Search for Cause of Interference on Laboratory Instruments in Early 1900s
  - » Led to Discovery of Cosmic Rays by Hess
- Induce SEUs: Neutrons + Protons + Pions

Terrestrial Cosmic Rays



IGY Neutron Monitor Response

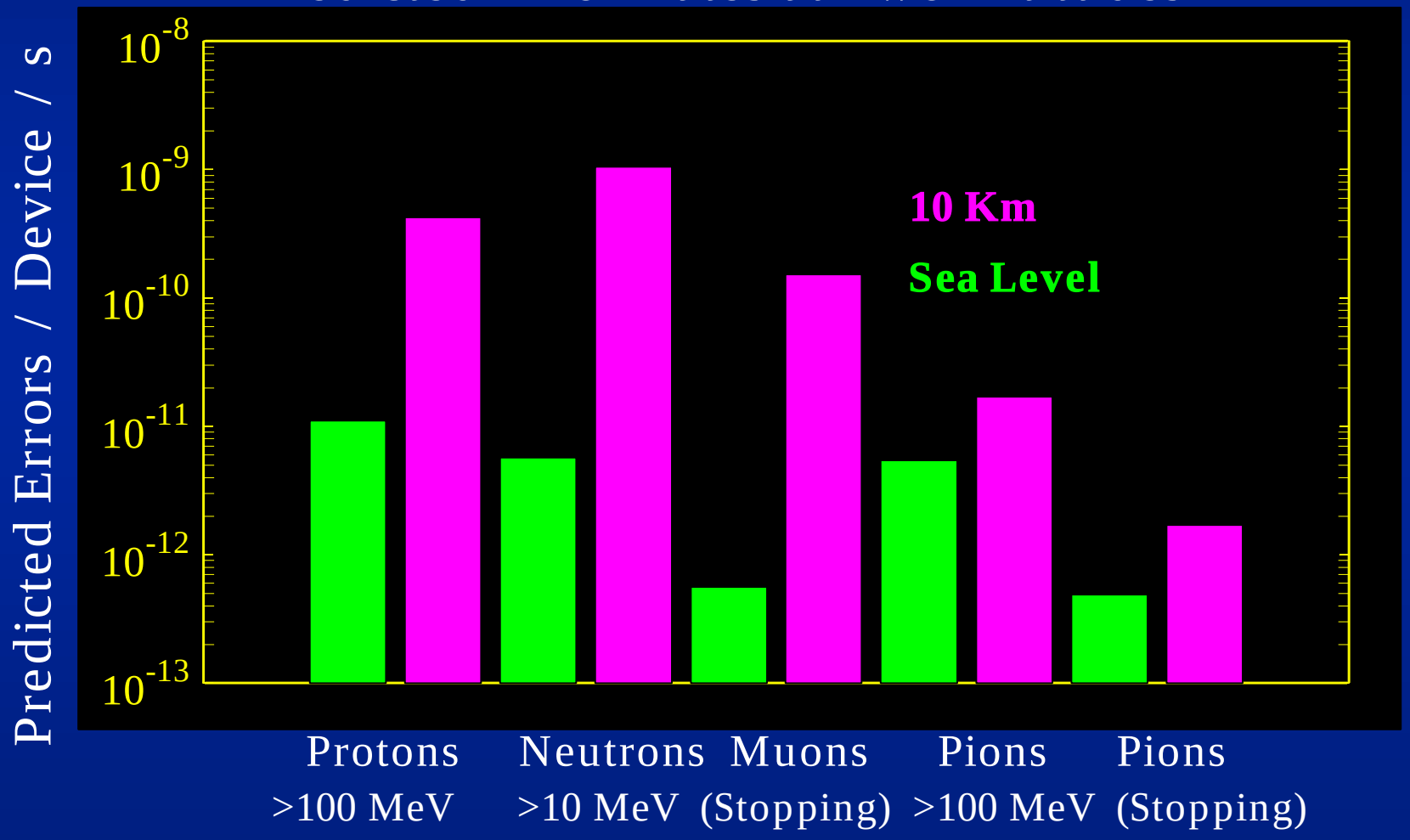
Cosmic Ray Contributions at Sea Level



J. Barth/Code 562

E.B. Hughes & P.L. Marsden, 1966

AM9114 4K NMOS Error Rates



J. Barth/Code 562

J.F. Dicello, et al.., 1989

Radiation Issues -
Three Prime Technical Drivers

- COTS & Emerging Technologies
  - » More sensitive to radiation
  - » Some devices have new effects
- COTS - greater uncertainty about radiation hardness
  - » Limited control
  - » Frequent process changes
- Devices exposed to more radiation on-orbit
  - » Use of composite materials in spacecraft structures
  - » Shrinkage in spacecraft size & weight

Result:

We are using more radiation sensitive components with less protection