Space Environments & Effects

Janet L. Barth

NASA/GSFC (Emeritus)

IEEE Nuclear & Plasma Sciences Society
Distinguished Lectures Program

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To be presented by Janet L. Barth at the Nuclear and Plasma Sciences Society's Distinguished Lecturer Program, Toulouse, France, September 13, 2018.

Acronyms

- ALMA Common Software. (ACS)
- Astronomical Unit (AU)
- Command and Data Handling System (C&DH)
- Charge-Coupled Devices (CCDs)
- Communication (Comm)
- Cosmic Ray Effects on Micro-Electronics (CREME)
- Charge Transfer Ratio (CTR)
- Error Eetection and Correction (EDAC)
- Earth radius (ER)
- Galactic Cosmic Rays (GCR)
- Geostationary orbit or Geosynchronous orbit (GEO)
- Geostationary Operational Environmental Satellite (GOES)
- Goddard Space Flight Center
- Geostationary transfer orbit (GTO)
- Highly elliptical orbit (HEO)
- Hubble Space Telescope (HST)
- Integration and Test (I&T)
- Institute of Electrical and Electronics Engineers (IEEE)
- stable points in interplanetary space
- Low earth orbit (LEO)
- Linear Energy Transfer (LET)
- Microwave Anisotropy Probe (MAP)
- Multiple Bit Upset (MBU)
- Medium earth orbit (MEO)
- National Aeronautics and Space Administration (NASA)
- North American Aerospace Defense Command (NORAD)
- Nuclear & Plasma Sciences Society (NPSS)
- South Atlantic Anomaly (SAA)
- Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX)
- Single Event (SE)
- Single Event Burnout (SEB)
- Single Event Effects (SEEs)
- Single Event Functional Interrupt (SEFI)
- Single Event Gate Rupture (SEGR)
- Single Event Latch-up (SEL)
- Solar Energetic Particles (SEPs)
- Single Event Transient (SET)
- Single Event Upset (SEU)
- Single Event Hard Errors (SHE)
- Solid State Star Tracker (SSST)
- Total Ionizing Dose (TID)
- United States Air Force (USAF)

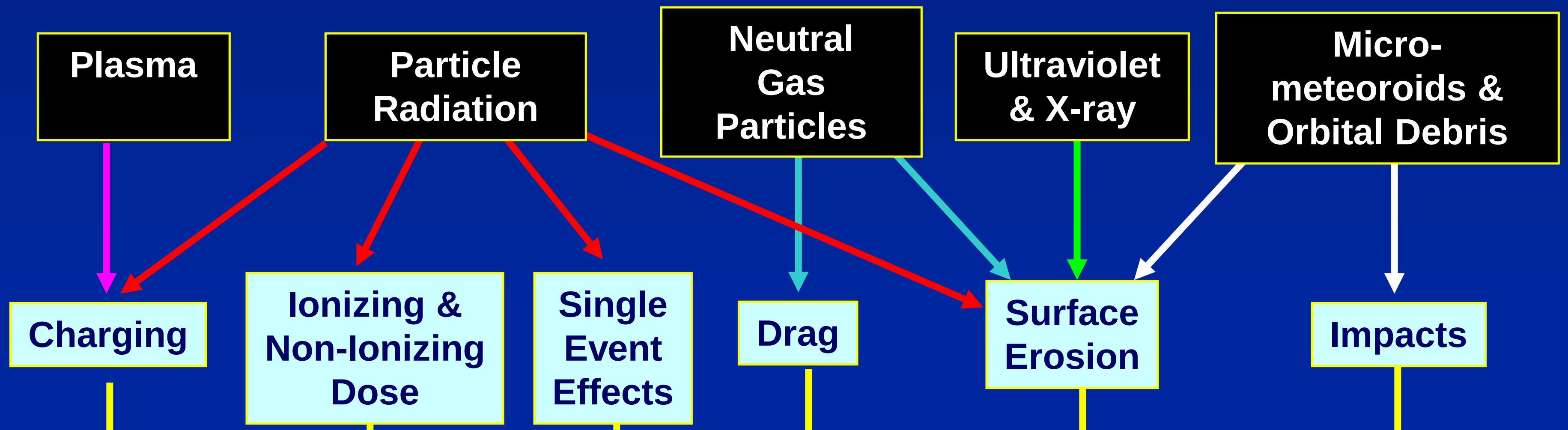
Outline

- Space Environments & Effects
- Definitions & Units
- High Energy Radiation Environment
  - » Solar Protons & Heavier Ions
  - » Cosmic Ray Ions
  - » Trapped Protons & Electrons (Van Allen Belts)
- Radiation Hardness Assurance
- Summary

Space Environments

- Plasma
- Particle Radiation
- Neutral Gas Particles
- Ultraviolet & X-ray
- Micro-meteoroids & Orbital Debris
- Electromagnetic Radiation, Thermal Environment, Geomagnetic Field,Gravitational Field

Space Environments & Effects



Plasma

Particle Radiation

Neutral Gas Particles

Ultraviolet & X-ray

Micro-meteoroids & Orbital Debris

Charging

- Biasing of instrument readings
- Pulsing
- Power drains
- Physical damage

Ionizing & Non-Ionizing Dose

- Degradation of micro-electronics
- Degradation of optical components
- Degradation of solar cells

Single Event Effects

- Data corruption
- Noise on Images
- System shutdowns
- Circuit damage

Drag

- Torques
- Orbital decay

Surface Erosion

- Degradation of thermal, electrical, optical properties
- Degradation of structural integrity

Impacts

- Structural damage
- Decompression

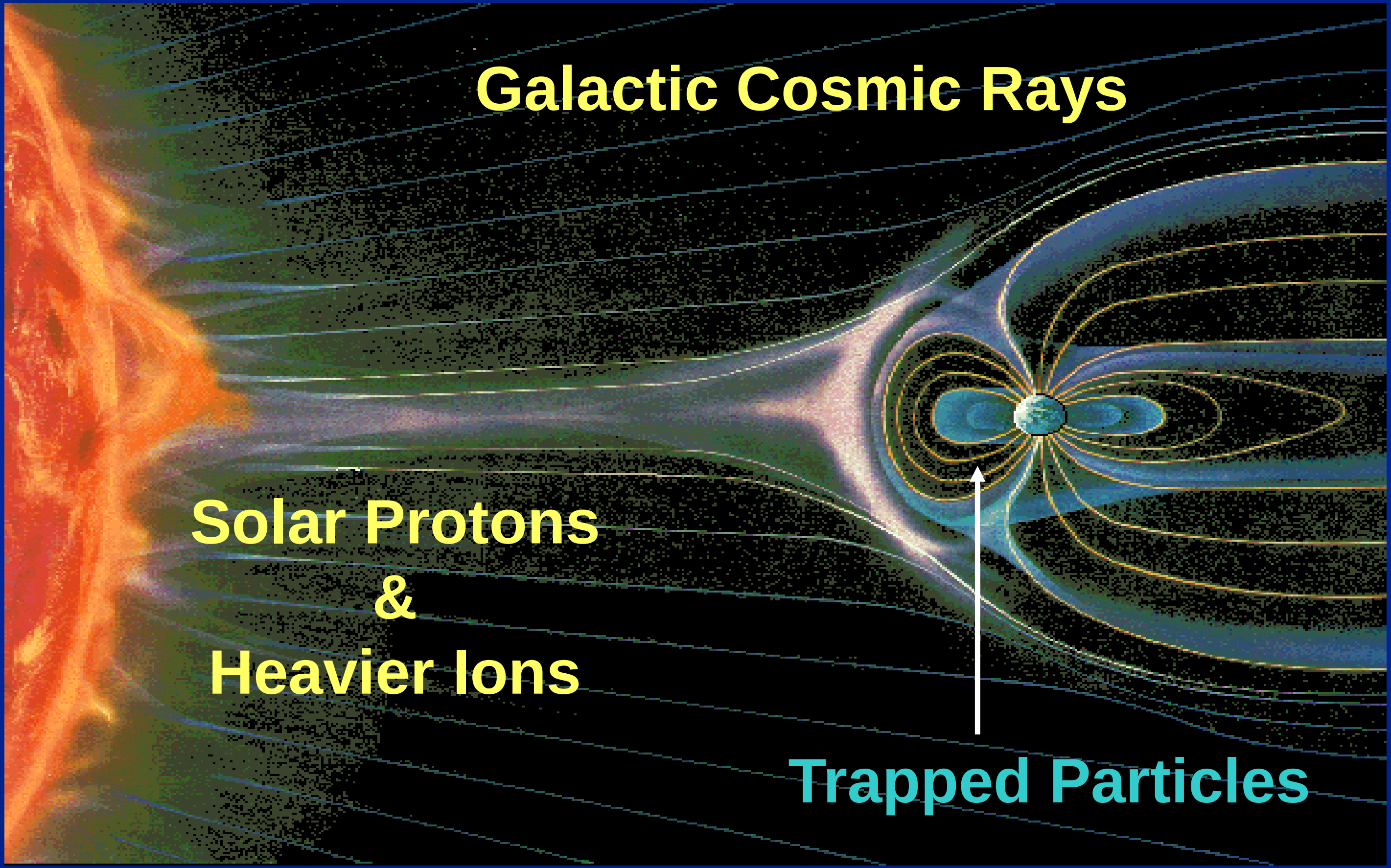
Definitions

- Distance
  - Sun to Earth = 1 Astronomical Unit (AU)
  - Earth radius (ER) = 6378.165 km at equator
- Spacecraft Orbits
  - Inclination – Angle between equatorial plane and orbit plane
  - Altitude – Distance from earth's surface in km
- Orbit Altitude
  - LEO – Low earth orbit < 1000 km
  - MEO – Medium earth orbit 1000 km – 36,000 km
  - GEO – Geostationary orbit = 36,000 km or 6.6 - 7.0 ER
  - GEO – Geosynchronous orbit
  - GTO – Geostationary transfer orbit
  - HEO – Highly elliptical orbit
  - L1, L2, L3, etc. – stable points in interplanetary space

Units

Quantity	Units	Description
Particle Energy, E	eV, MeV, GeV	Electron volt - the amount of work done on an electron when it moves through a potential difference of one volt
Particle Flux Density, ϕ	# cm^{-2} s^{-1}	Transfer of particles per unit time across a unit area form either side
Particle Fluence, Φ	# cm^{-2}	Time rate of particle fluence
Ionizing Dose, D	Rads, seiverts	The amount of radiation that deposits 0.01 joule of energy in 1 kg of material
Linear Energy Transfer, LET	Fluence/material density MeV cm^2 mg^{-1}	dE/dX – mean energy lost by a charged particle in electronic collisions per unit length of its trajectory

High Energy Radiation



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

Characteristics of the Radiation Environment

- **High energies**
  - » **Electrons – 10s of MeV**
  - » **Protons – 100s of MeV**
  - » **Heavier Ions – 1000s of MeV**
- **Solar variability drives population levels**
  - » **Long term solar cycle**
  - » **Solar rotation**
  - » **Solar storms, magnetospheric storms**
- **Magnetosphere filters galactic and solar particles**
  - » **Polar, low-earth orbits are exposed to interplanetary levels during passes over the poles**
- **Trapped population has complex spatial distribution**

Surface Charging

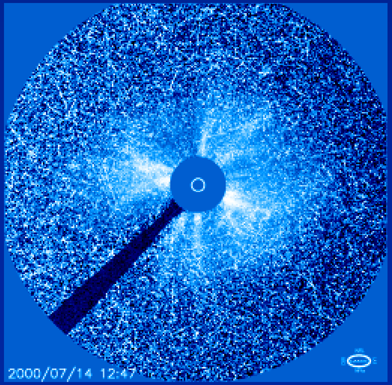
- Induced charge on surface
  - Low energy plasma & photoelectric currents
  - “Hot” plasma (LEO vs. GEO)
- Orbits with high risk
  - LEO – maybe
  - MEO - ? probably
  - GEO - generally a greater concern
  - GTO
- Risk factors
  - Geomagnetic substorms resulting in injection of keV electrons
  - Passage from eclipse to sunlight – positive charge surface due to photoelectron emission
  - Large spacecraft
  - High voltage power system

Deep Dielectric Charging

- Process
  - » High energy electrons penetrate into dielectric materials (circuit boards and cables).
  - » Charge builds up and gives rise to intense electric fields.
  - » When charge exceeds the breakdown potential, discharge occurs.
- Missions affected
  - » Any spacecraft spending long periods in Van Allen belt electron regions
  - » MEO, GEO, GTO, Phasing loops
  - » Jovian
- Risk factors
  - » Accumulation of $> 10^{10}$ E > 1 MeV electrons within 10 hours
  - » Accumulation of $> 3\text{x}10^{8}$ E > 2 MeV electrons/day for 3 consecutive days
  - » Accumulation of $> 10^{9}$ E > 2 MeV electrons in a single day

Displacement Damage Dose (DDD)

- Cumulative long term non-ionizing damage
- Effect:
  - » Production of defects which result in charge transfer ratio (CTR) degradation
  - » Optocouplers, solar cells, CCDs, linear bipolar devices
- Shielding has some effect
  - » Solar cell cover glasses and mounting panels
  - » Only for some orbits



Total Ionizing Dose (TID)

- Cumulative long term ionizing damage
- Strongly dependent on mission duration, orbit, and shielding
- Effects
  - » Threshold Shifts
  - » Leakage Current
  - » Timing Skew
  - » Functional Failures
- Can reduce with shielding
  - » Low energy protons
  - » Electrons

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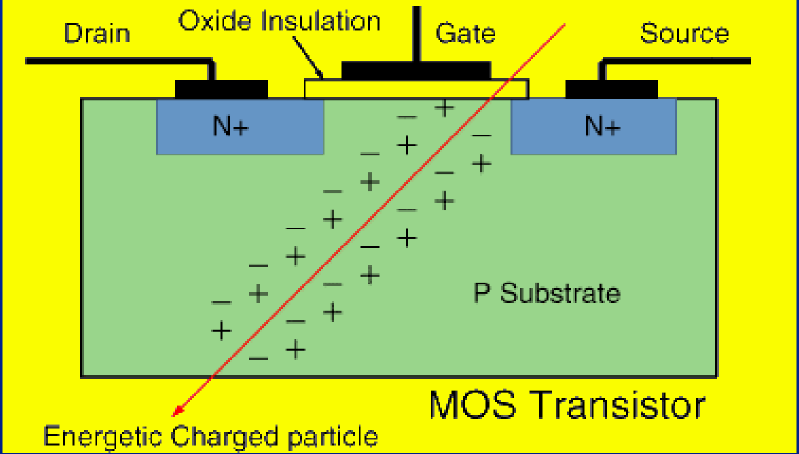
Single Event Effects (SEEs)

- Event caused by a single charged particle
- Effects:
  - Non-destructive: SEU, SET, MBU, SEFI, SHE
  - Destructive: SEL, SEGR, SEB
- Severity is dependent on:
  - type of effect
  - system criticality
- Shielding has little effect

Interaction of a Cosmic Ray and Silicon



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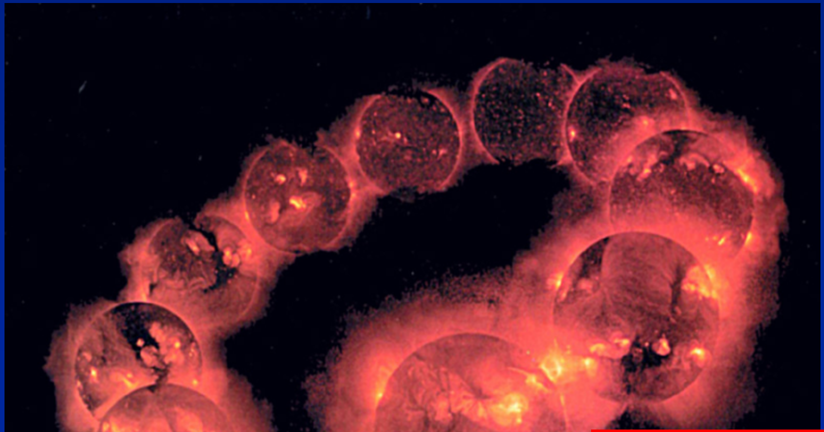
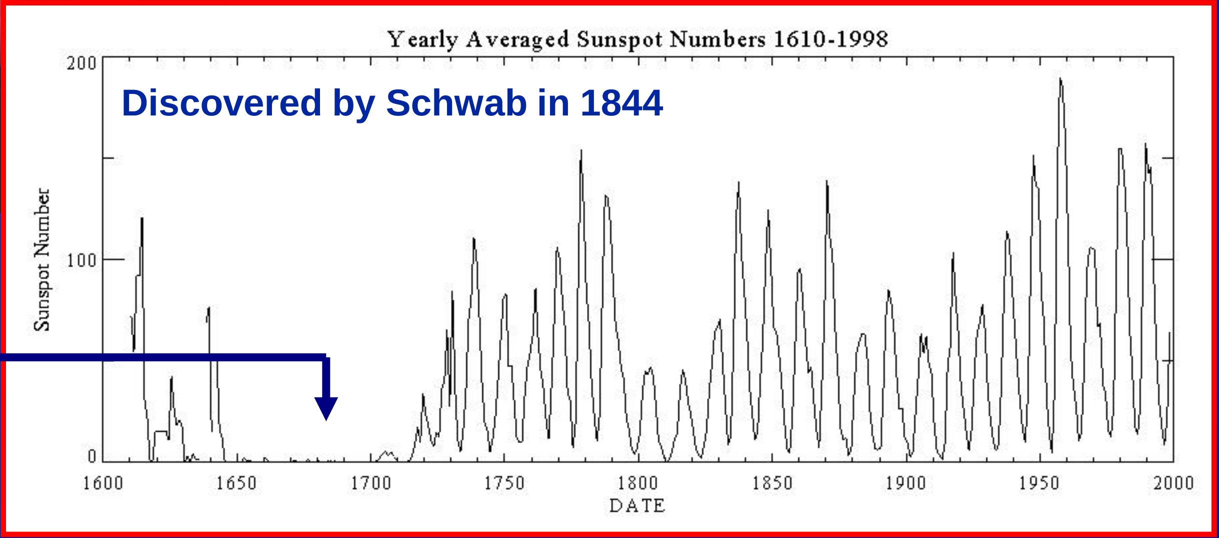
Solar Activity Cycle



- **Caused by reversal of solar magnetic field**
- **Many indicators of the cycle**
  - **Sunspot count**
  - **$F_{10.7}$ radio flux**
  - **Atmospheric density**



Discovered by Schwab in 1844

Little Ice Age in 1645 to 1715

Length varies from 9 - 13 years
Recent solar cycles – 10 years

Interplanetary Particles – Galactic Cosmic Ray Heavy Ions (GCRs)


Victor Hess, 1913

- 1913 - Victor Hess' Balloon experiments
- 1960's - Light flashes in astronauts' eyes
- 1975 - Binder *et al.* documented logic upsets on spacecraft
- Properties
  - » All elements in Periodic Table
  - » Energies in TeVs
  - » Found everywhere in interplanetary space
  - » Omnidirectional
  - » Filtered by the magnetosphere
  - » Mostly fully ionized
- Effects
  - » Astronaut dose
  - » Single event effects

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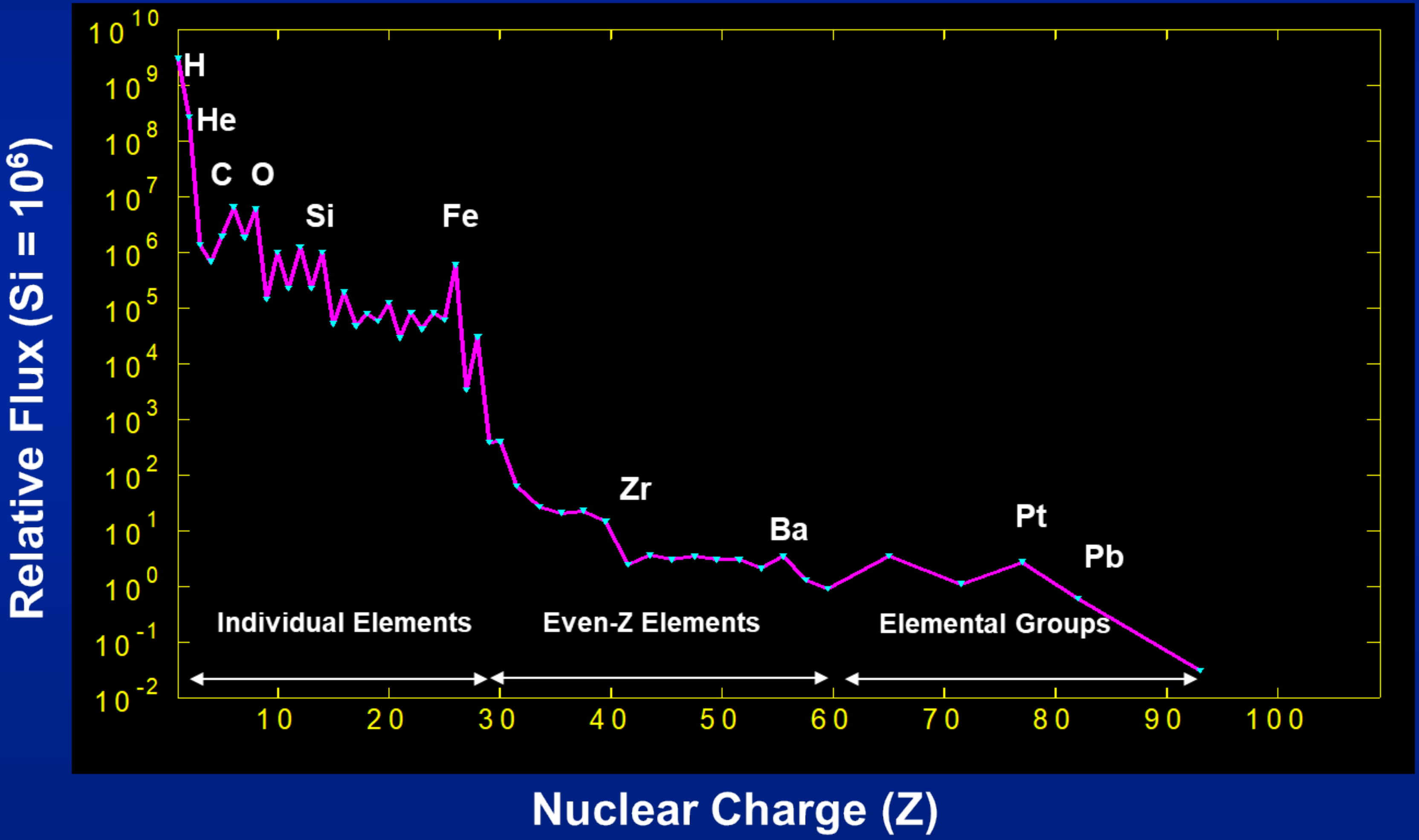
GCRs: Nuclear Composition

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



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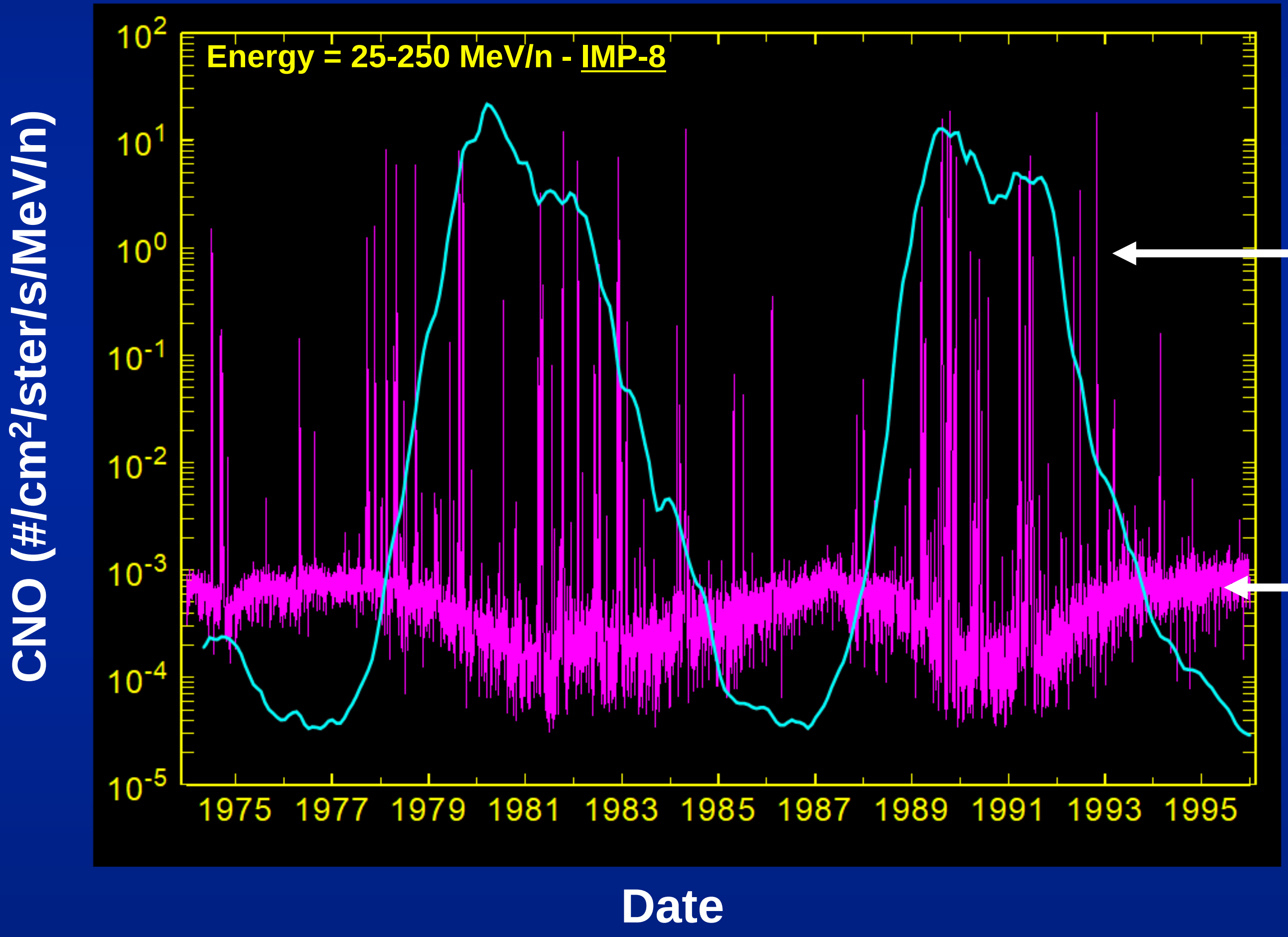
Solar Cycle Effects: Heavy Ions

CNO - 24 Hour Averaged Mean Exposure Flux



Storms

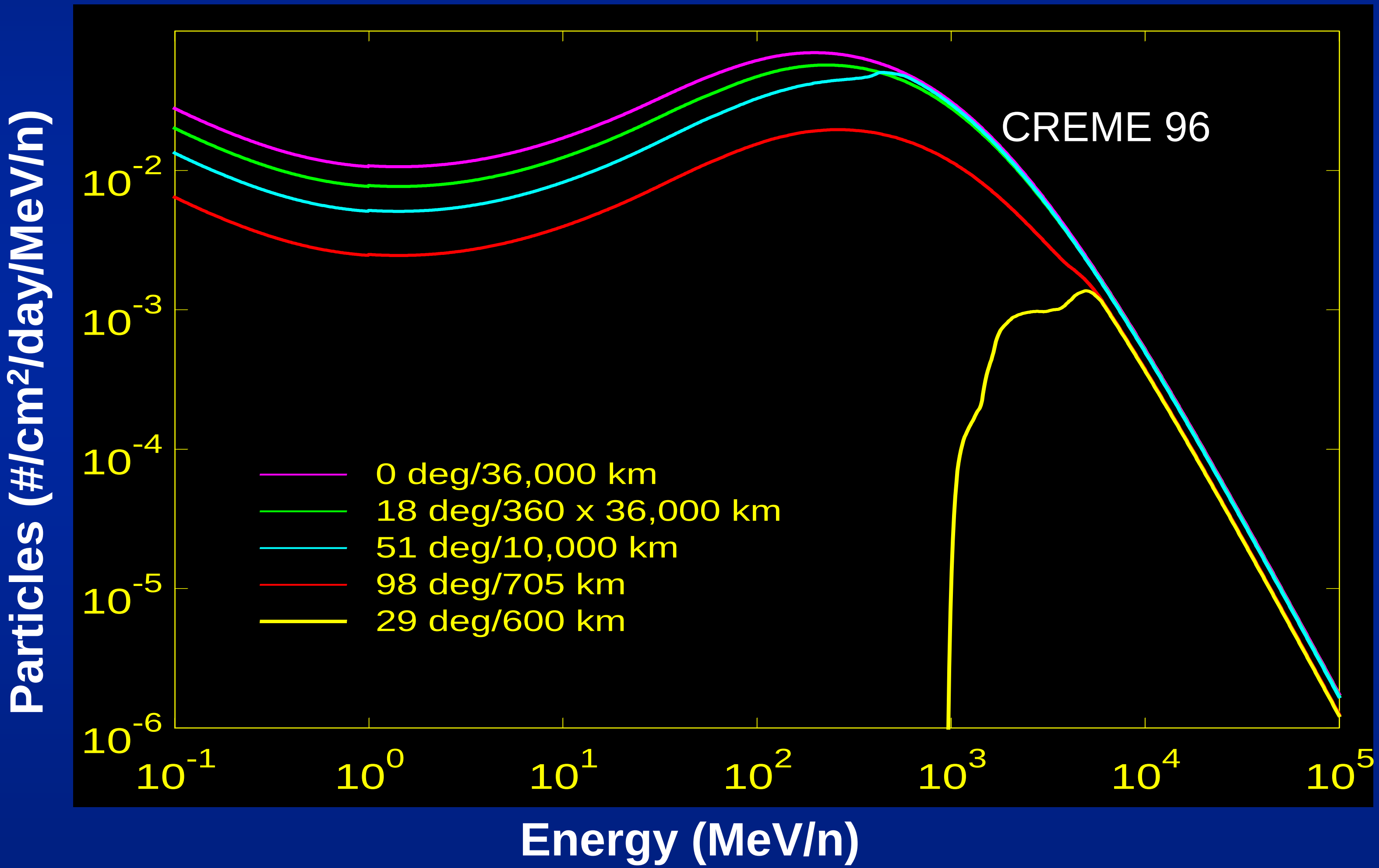
Solar Heavy Ions

Background

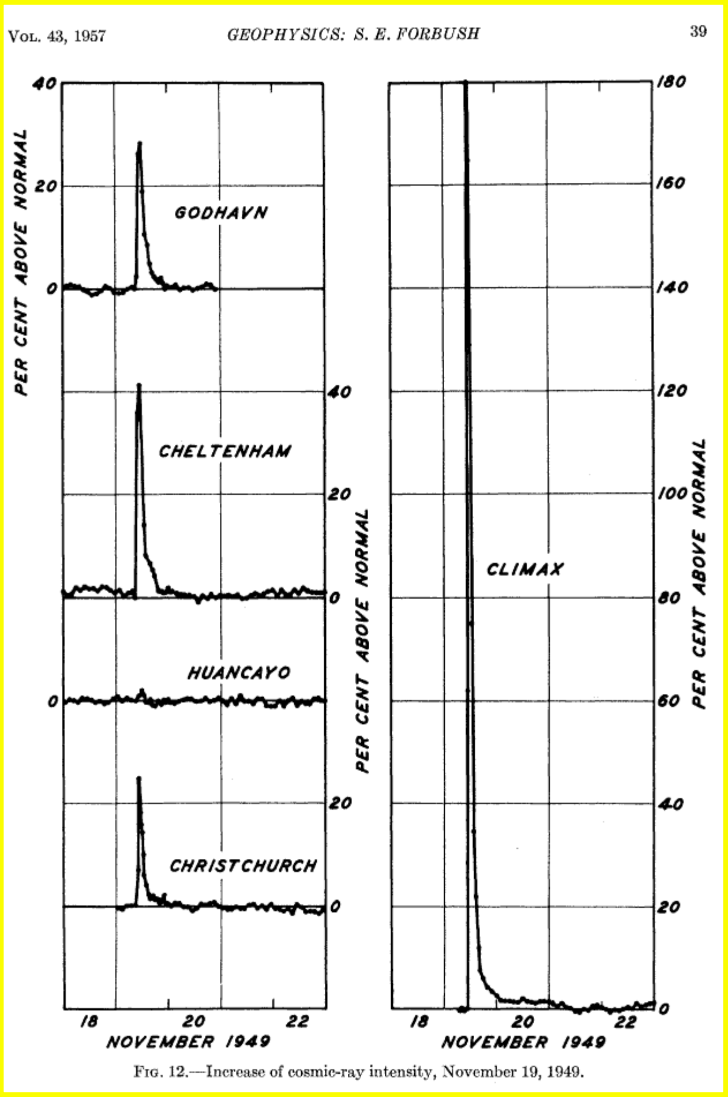
Galactic Cosmic Rays

GCRs: Shielded Fluences - Fe

Solar Minimum, 100 mils (2.54 mm) Al



Interplanetary Particles – Solar Energetic Particles (SEPs)



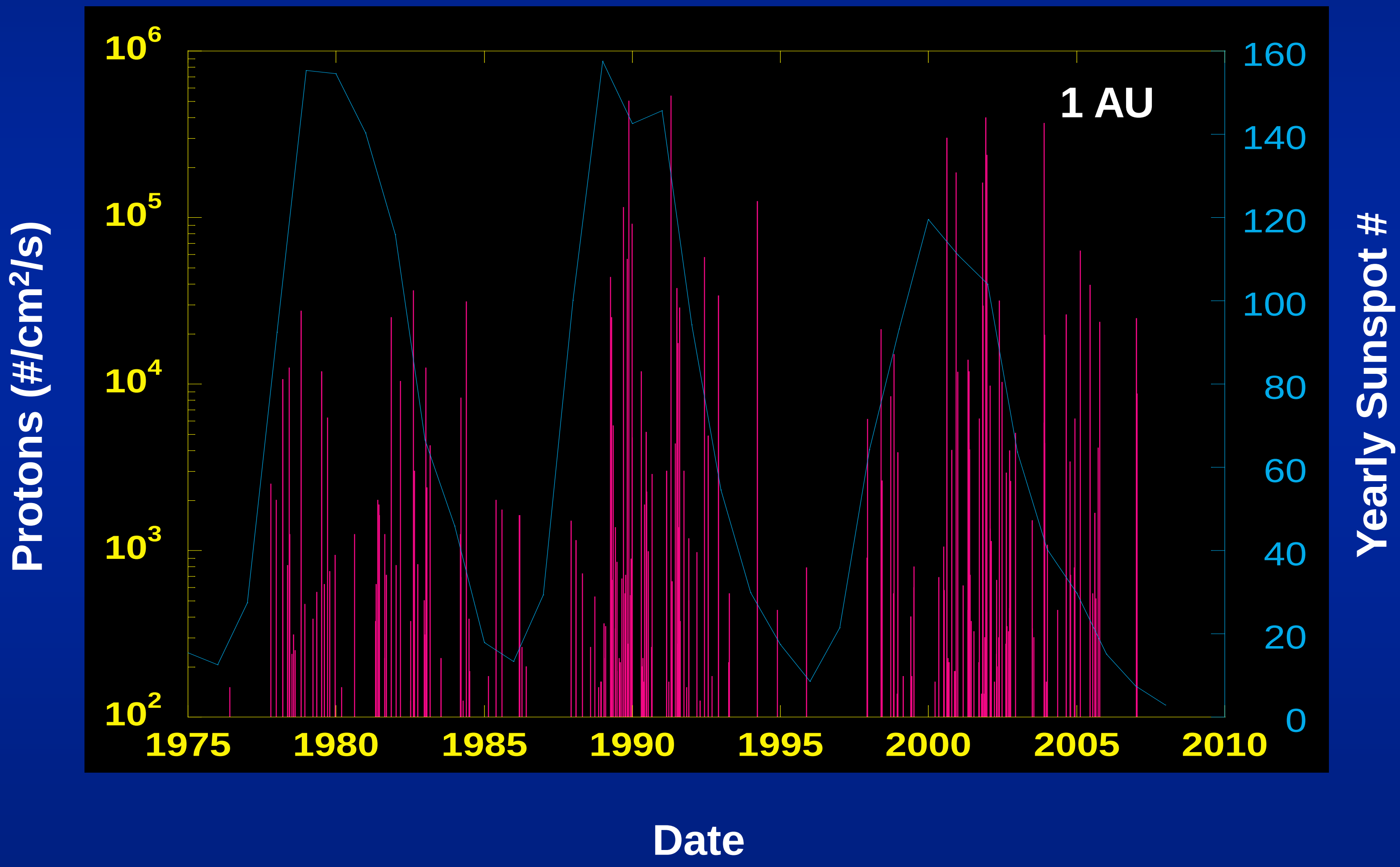
Vol. 43, 1957 GEOPHYSICS: S. E. FORBUSH 39

Fig. 12.—Increase of cosmic-ray intensity, November 19, 1949.

- **1946 - Scott Forbush**
- **Increased levels of protons & heavy ions due to SEP events**
- **Properties**
  - » **Protons - 100s of MeV**
  - » **Heavy ions - 100s of MeV**
  - » **Abundances dependent on radial distance from Sun**
  - » **Partially ionized**
  - » **Number & intensity of events increase dramatically during "solar active" periods**
- **Effects**
  - » **Degradation**
  - » **Single event effects (protons & heavy ions)**

Solar Cycle Effects: Solar Protons

Protons from Solar Energetic Particle Events E > 10 MeV



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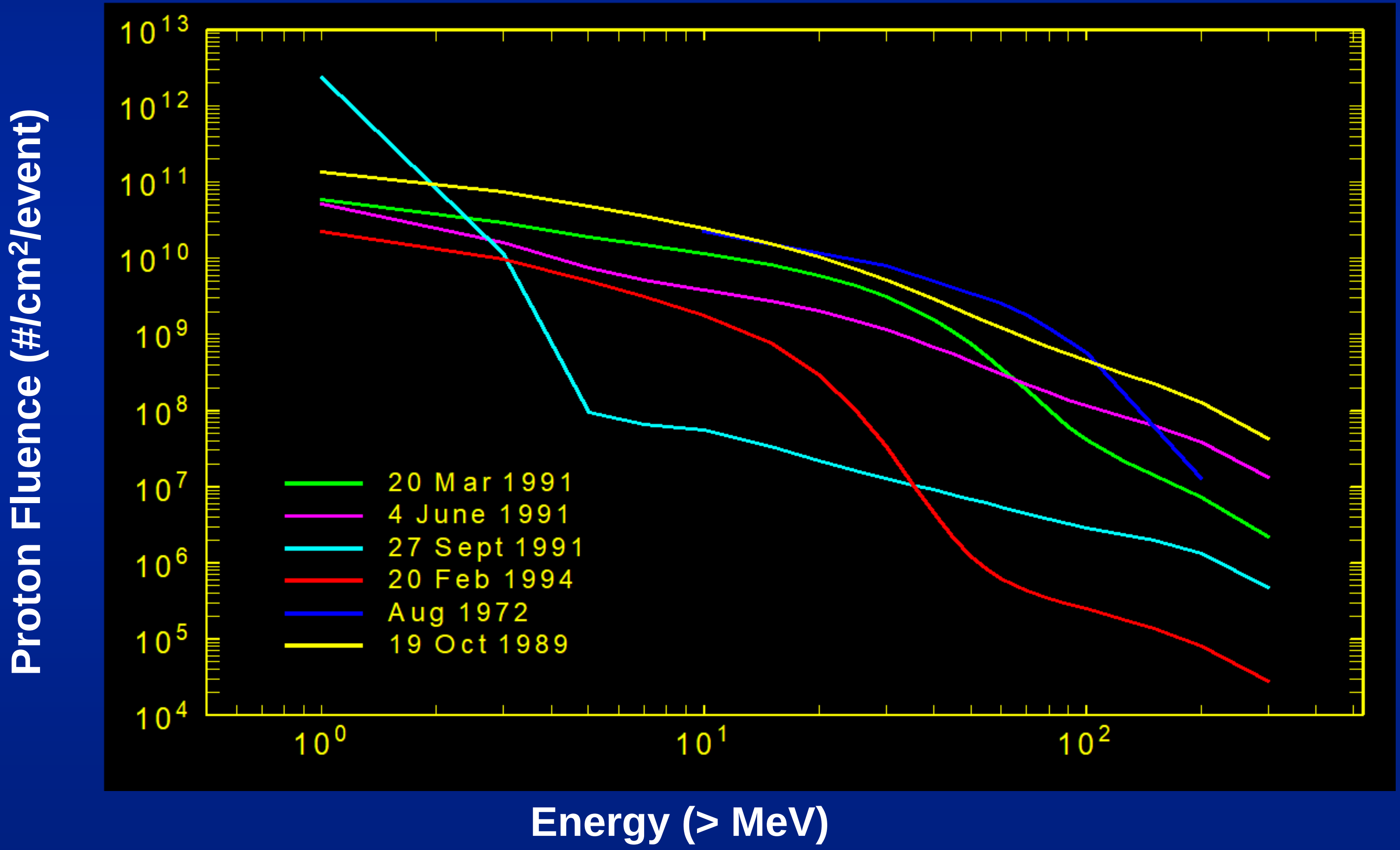
SEPs: Proton Event Spectra

Total Integral Proton Fluence Measured by GOES



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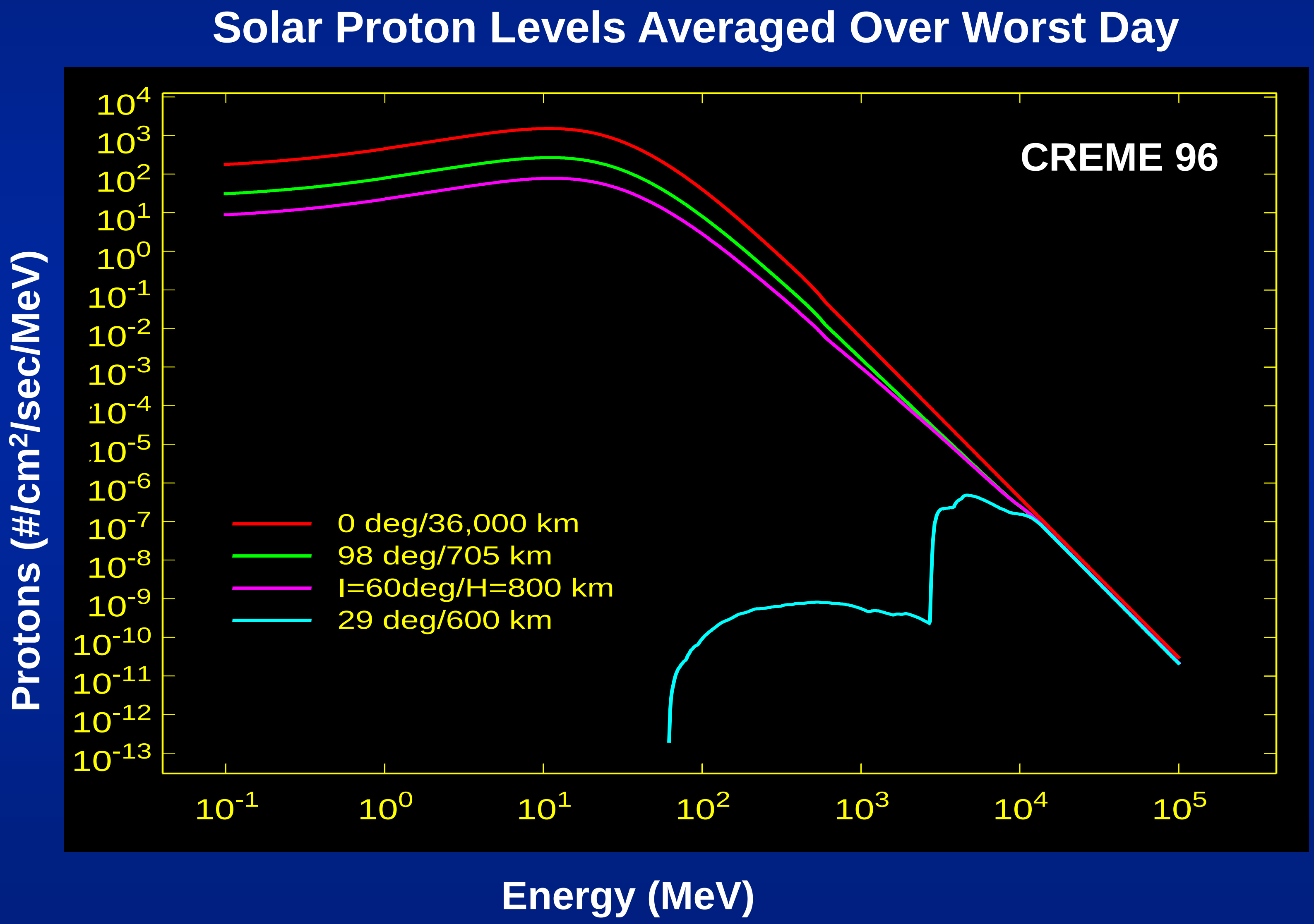
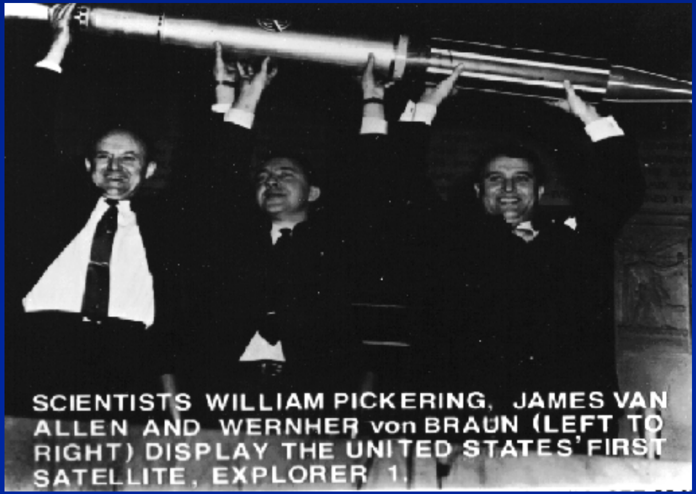
SEPs: Shielded Fluences



Trapped Particles



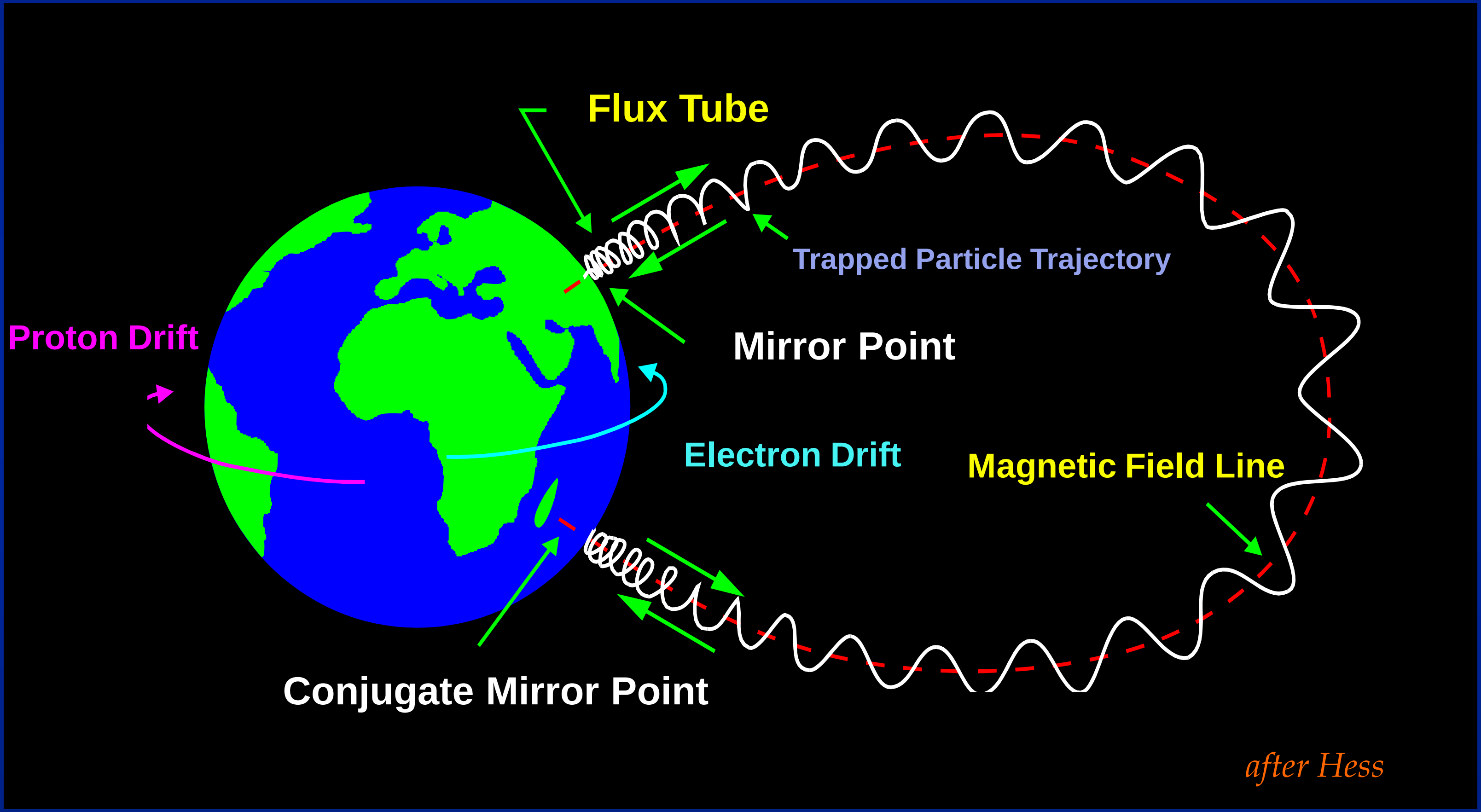
SCIENTISTS WILLIAM PICKERING, JAMES VAN ALLEN AND WERNHER von BRAUN (LEFT TO RIGHT) DISPLAY THE UNITED STATES' FIRST SATELLITE, EXPLORER 1.

- Cosmic ray detector on Explorer I, 31 Jan 1958
  - » “Zero” levels on instrument
- Highlight of US participation in IGY

- 1895 - Birkeland theorizes particle trapping
- 1904 – Stöermer calculations support theory of particle trapping around the Earth
- 1958 – James Van Allen
- Properties
  - » Omnidirectional
  - » Protons: E ~ 1 keV - 500 MeV
  - » Electrons: E ~ 1 keV - 10 MeV
  - » Heavy Ions: Low E (non-problem for electronics)
  - » Complex distribution based on energy & solar conditions
- Effects
  - » Degradation – protons and electrons
  - » Single event effects – protons
  - » Surface charging, Deep dielectric charging - electrons

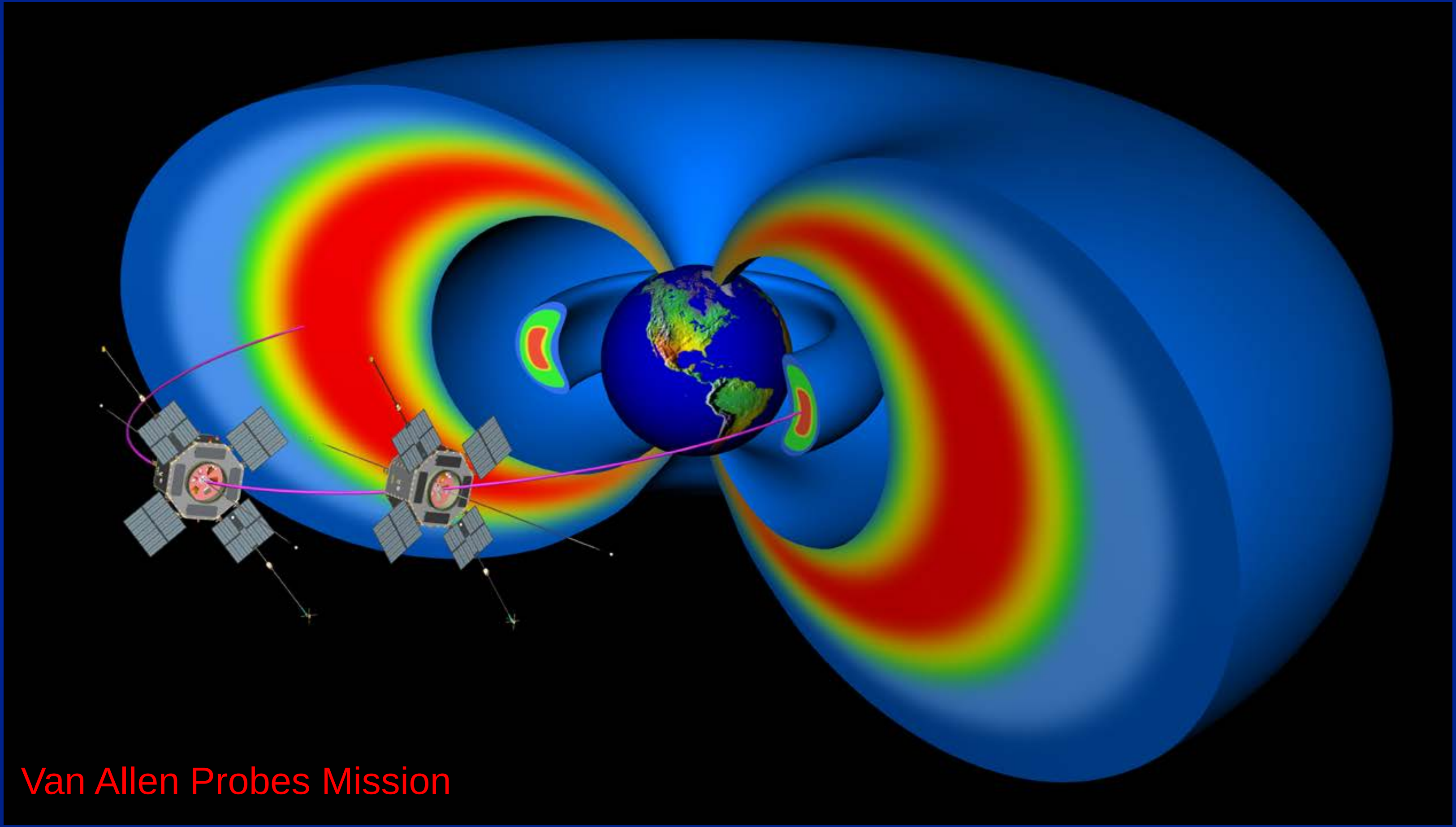
Trapped Particle Motions

Spiral, Bounce, Drift



after Hess

Trapped Radiation Belts

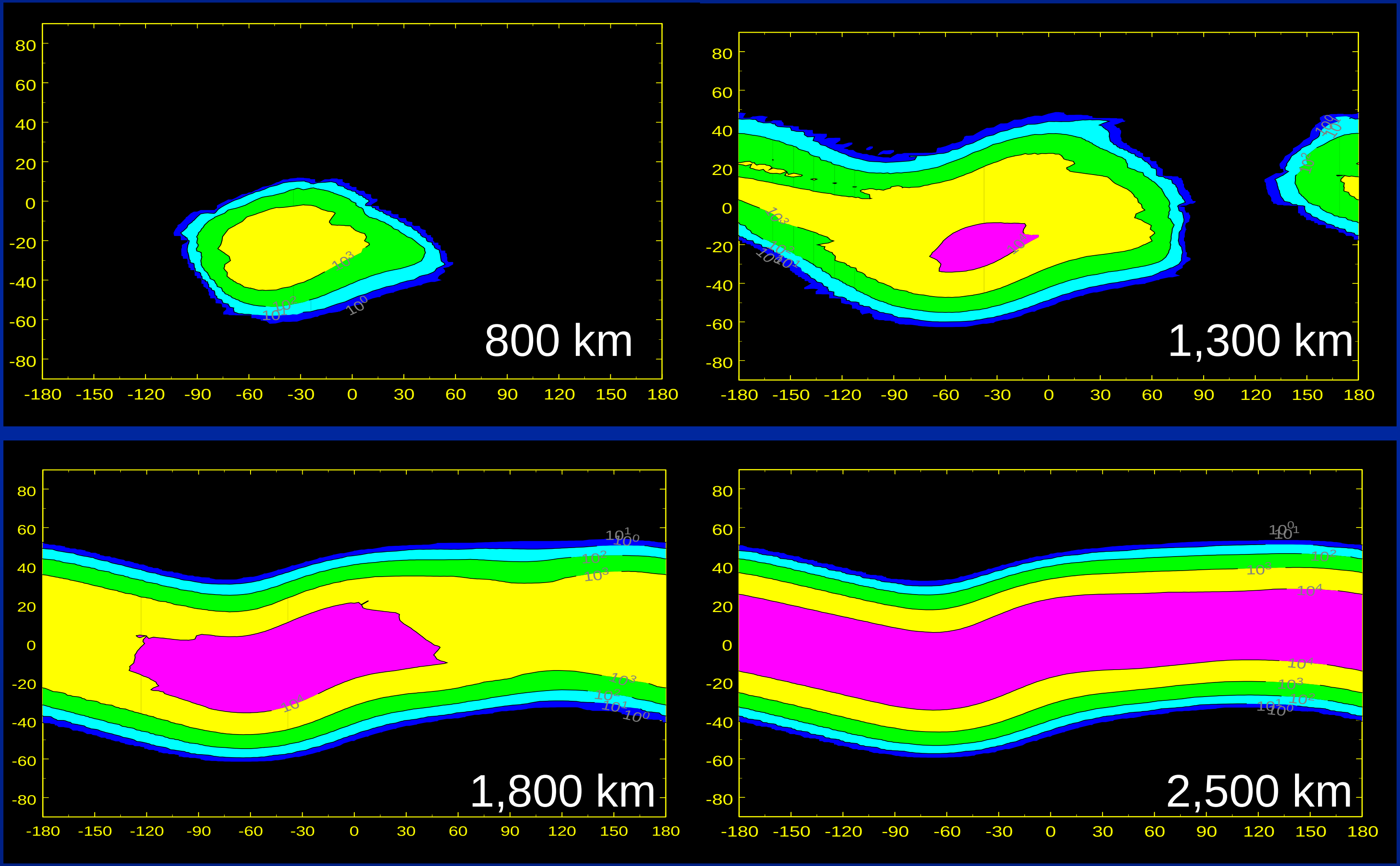


Van Allen Probes Mission

NASA/LWS Program, Johns Hopkins University Applied Physics Laboratory

Trapped Protons

South Atlantic Anomaly (SAA) & Belt Region



E > 30 MeV (#/cm^2/s) - Solar Minimum

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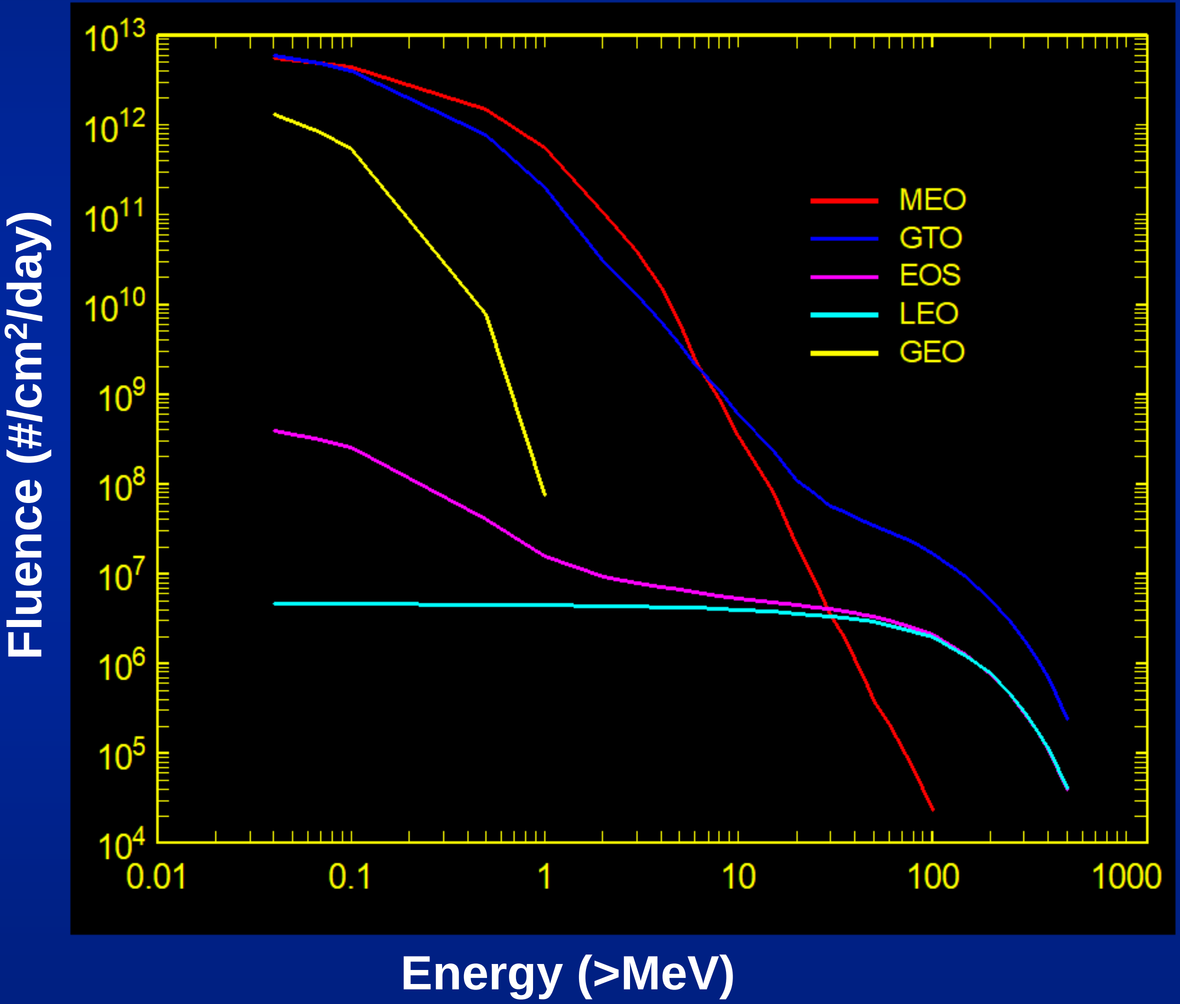
Trapped Proton Spectra

- Energy range
  - » .04 - 500 MeV
- Range in Al:
  - » 30 MeV ~ .17 inch
- Effects:
  - » Total dose
  - » Single event effects
  - » Solar cell damage

Integral Proton Fluences



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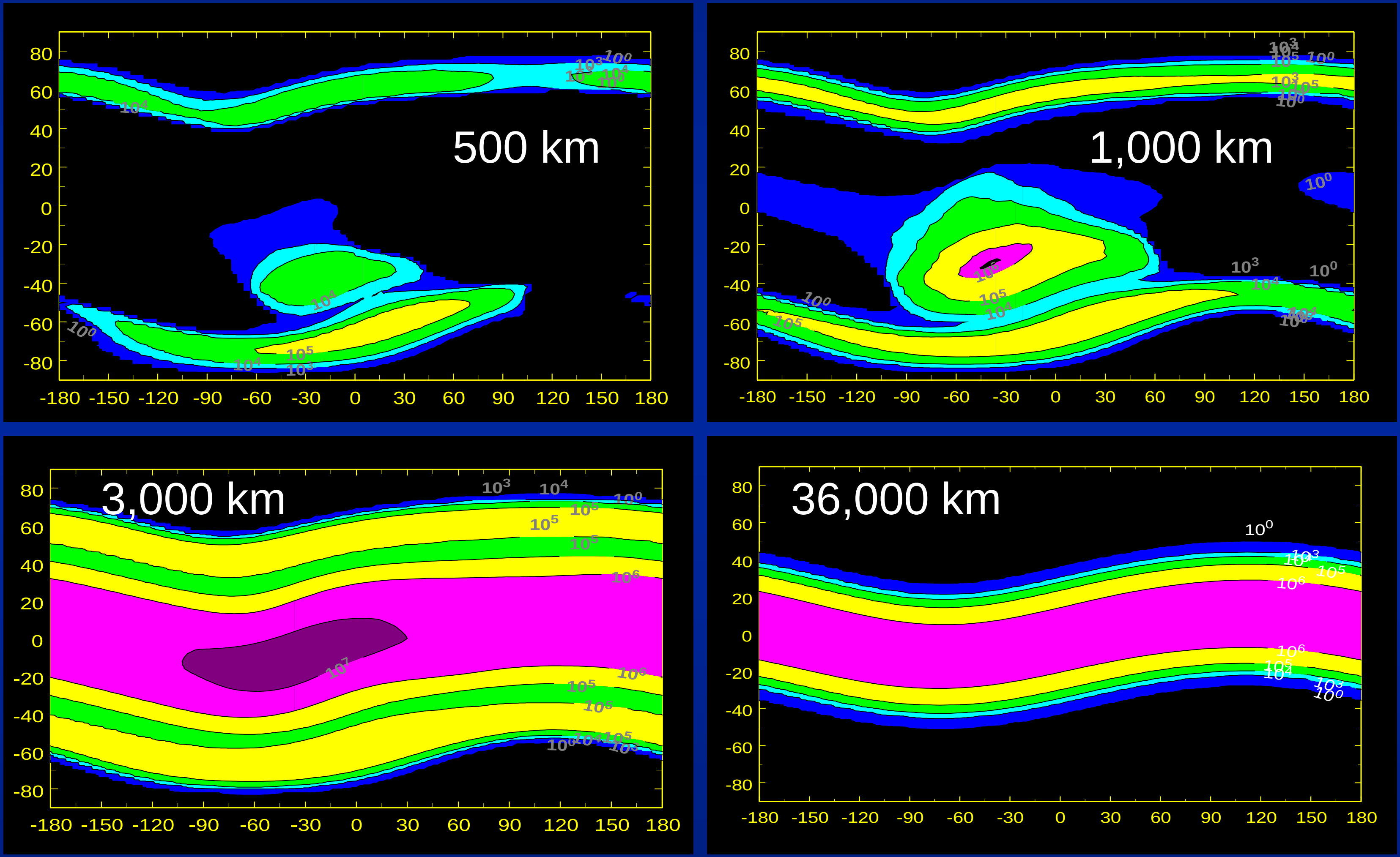
Trapped Electrons

SAA & Outer Zone Electrons



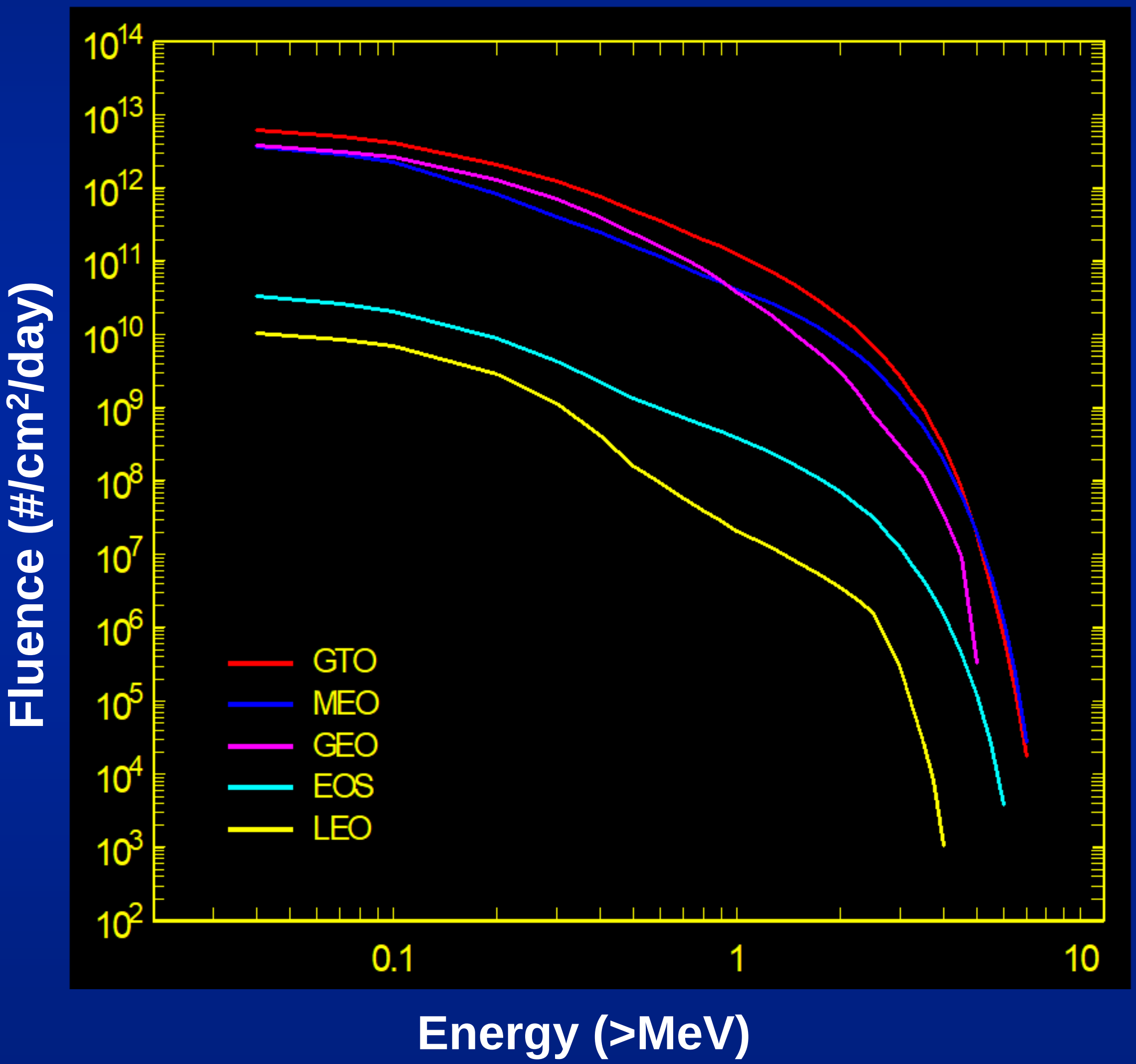
E > 0.5 MeV (#/cm^2/s) - Solar Minimum

Trapped Electron Spectra

- Energy range
  - » .04 - 7 MeV
- Range in Al:

- Effects:
  - » Total dose
  - » Surface charging
  - » Deep dielectric charging
  - » Solar cell damage

Integral Electron Fluences



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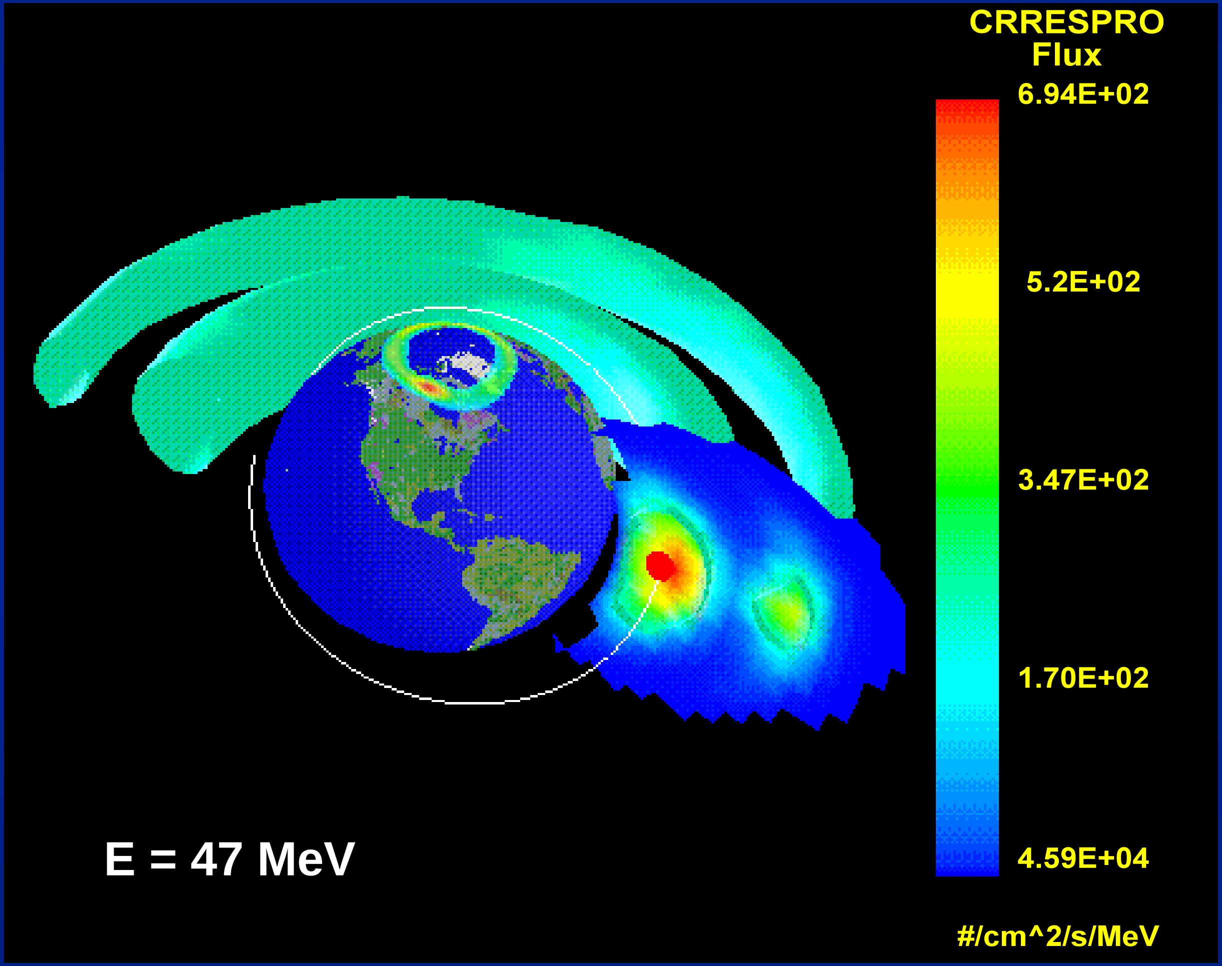
Effect of Solar Storms on Trapped Protons – CRRES Measurements

March 1991



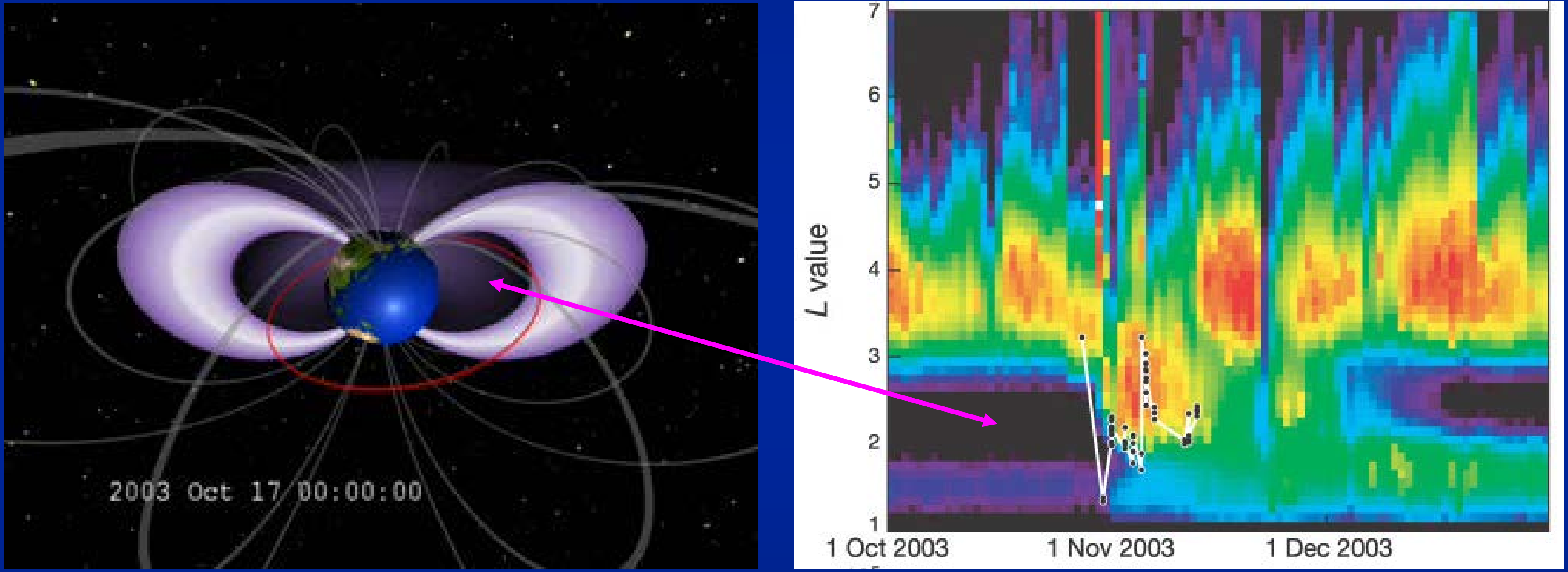
Don Brautigam, AF Phillips Laboratory, SPD/GD, used by permission

Effect of Solar Storms on Trapped Electrons – SAMPEX Measurements

2–6 MeV Electrons

Threshold = 100 e^-

Threshold = 1 e^-



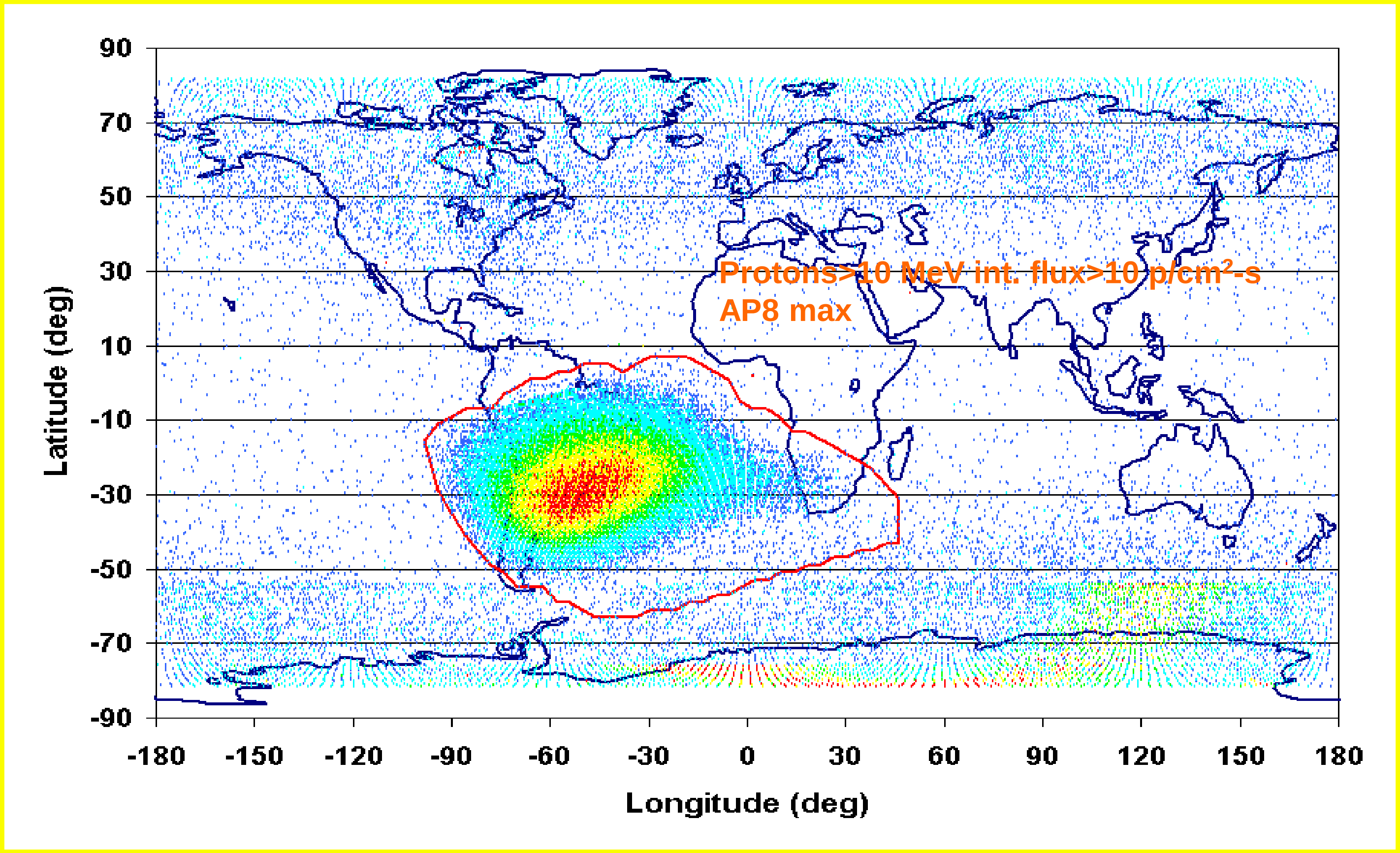
NASA/Goddard Space Flight Center/Scientific Visualization Studio

D. N. Baker et al.

- **Electron belt changes during Oct 2003 solar storm events**
- **Daily-averaged particle flux data from the SAMPEX satellite.**

Single Event Upsets on Seastar Solid State Recorder

Orbit: 705 km, 98deg, Duration: 4 years



● 1SEU ● 1<SEU<10 ● 10≤SEU<20 ● 20≤SEU<40 ● ≥ 40 SEU

Harvey Saffron, Orbital Sciences, work performed for NASA GSFC

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Radiation Environment Levels

Examples

Low: < 10 krads

Moderate single event effects environment
Low displacement damage environment

Low altitude/
low inclination
(HST, Shuttle, XTE)
If Short mission duration

Moderate: 10-100 krads

Intense single event environment
Moderate displacement damage environment

Low altitude/
high inclination
(EOS, GLAS)
L1, L2, GEO
Medium mission duration

High: >100 krads

Intense single event effects environment
Intense displacement damage environment

Europa, GTO, MEO,
<< 1 AU
or Long mission duration

after LaBel

Radiation Hardness Assurance

- **Space radiation penetrates spacecraft shielding and interacts with components to produce a broad range of effects.**
- **A rigorous methodology is needed to ensure that the radiation environment does not compromise the functionality and performance of the electronics.**

Single Event Effects on Missions

- **Equator-S – SE Latchup on processor & redundant processor**
- **HST – SE Transients on an optocoupler**
- **Terra – Single particle events on the solid state star tracker (SSST)**
- **Flight Data Recorders – SE upsets**
  - HST
  - SAMPEX
  - Seastar
- **MAP – SE Transient on a voltage comparator**

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Janet's Top 5 Quotes About Harness Assurance

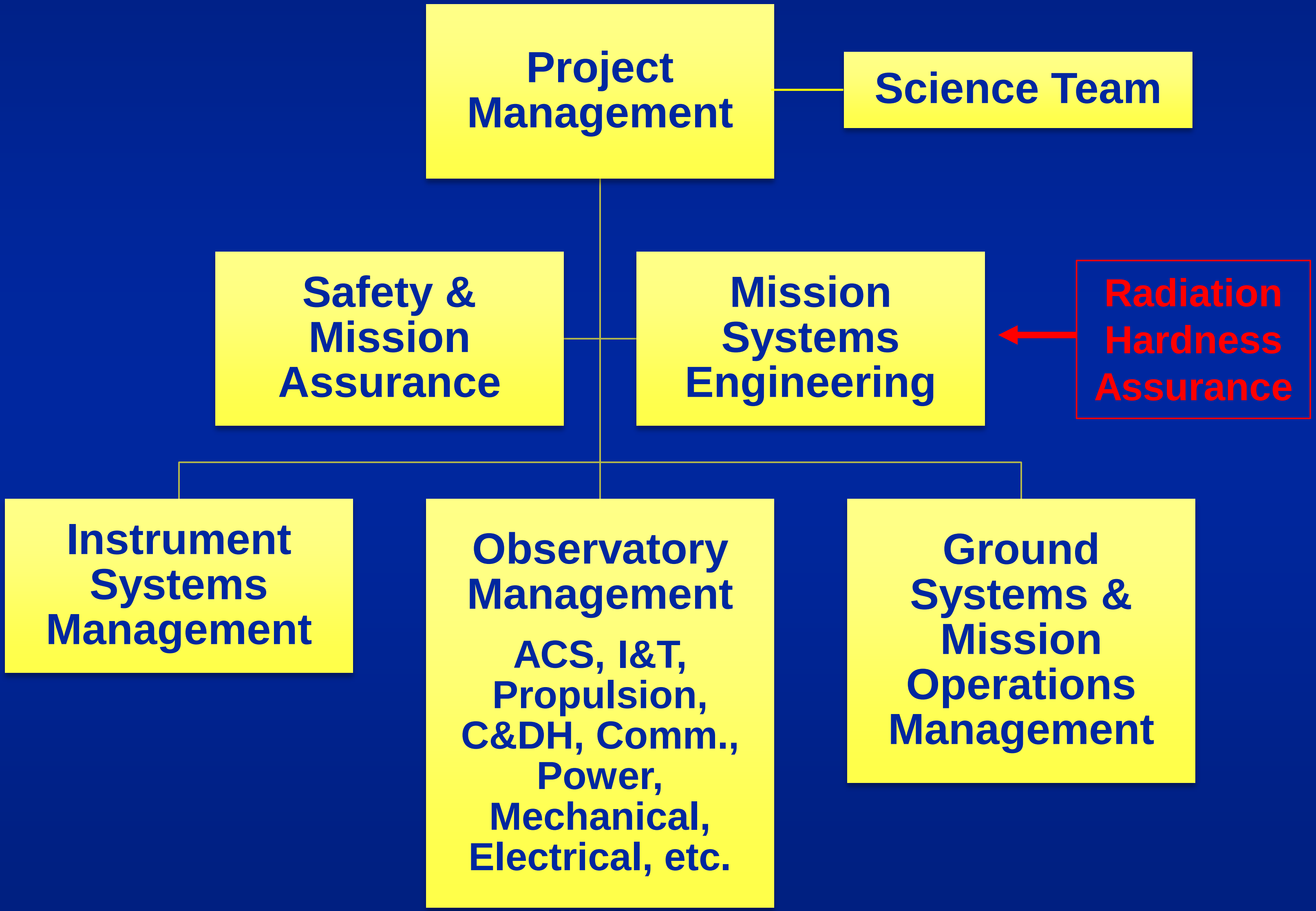
5. **"I hired radiation specialists from ACME, and I need you to fix their calculations for my program review tomorrow."**
4. **"I called to get the radiation environment for my mission. I need the number now so I'll wait while you look it up in your table."**
3. **"Extra overhead like radiation engineering is not part of our program philosophy." (followed with 2 weeks of 3-page emails with questions about radiation)**
2. **"Well, my radiation plan was to add some spot shielding after the board is built."**
1. **"Hello, you don't know me but I'm launching next week and I need you to sign these waivers."**

NASA GSFC Missions

Hardness Assurance Methodology

- **Definition**
  - » **Activities undertaken to ensure that the electronic piece parts placed in the space system perform to their design specifications after exposure to the space radiation environment**
- **Goal**
  - » **A system tolerant to the radiation environment within the level of risk that is acceptable for the mission**

Typical Project Organization



Project Management

Science Team

Safety & Mission Assurance

Mission Systems Engineering

Radiation Hardness Assurance

Instrument Systems Management

Observatory Management

ACS, I&T, Propulsion, C&DH, Comm., Power, Mechanical, Electrical, etc.

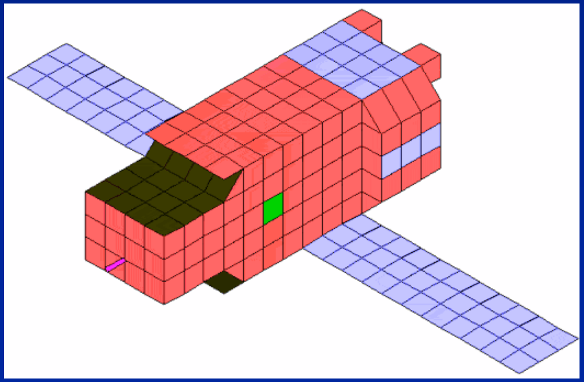
Ground Systems & Mission Operations Management

Hardness Assurance Methodology

- Step 1 - Describe the mission radiation environment and define the radiation levels within the spacecraft
- Step 2 - Assess the radiation sensitivity of the parts based on radiation databases and relevant radiation tests
- Step 3 – Perform Worst Case Analysis (WCA) of the impact of the radiation effect taking into account the system and circuit design
- Step 4 – Categorize parts for acceptability
- Step 5 – If needed, develop Risk Management Plan

Spacecraft Charging – System Hardening

- Two distinct problems
  - » Surface charging
  - » Deep-dielectric charging
- Risk Avoidance
  - » Assume there will be a problem
  - » Evaluate with NASCAP 2K
  - » Follow accepted design practices
    - – Grounding
    - – Shielding
    - – Material selection
    - – Circuit design



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TID - System Hardening

- Risk avoidance
  - » Component selection
  - » Shielding strategies
    - – May need more accurate knowledge of component shielding
- Risk management
  - » Plan for graceful degradation
  - » Requires accurate knowledge of how device will respond in the space environment
    - – System criticality
    - – Application
    - – Characterization of device response
      - ❖ Parametric degradation
      - ❖ Enhanced low dose rate

DDD - System Hardening

- Risk Avoidance
  - Not possible for all technologies
  - Protons are difficult to stop with shielding
  - Hardening techniques are not effective
  - Hardness changes with processing
- Risk Management
  - Reduce effect with shielding
  - Plan for degradation
  - Knowledge of radiation environment at detector
  - May require on-ground simulation
  - Models are not validated – need test flights
  - Mitigation through software

SEEs – System Hardening

- Risk avoidance
  - Rad-hard does not always imply SEE hard.
  - Shielding is not an effective mitigator.
  - System should be hard to latchup.
    - Is not always possible to find replacement part
  - Performance requirements push designers to use sensitive technologies.
- *Risk management*
  - Typical for non-destructive events - EDAC
  - Destructive - rate prediction for assessment of level of risk
  - Both require accurate knowledge of how device will respond in the space environment
    - Type of effect & system criticality
    - Definition of peak & average environments
    - Characterization of device response to particle hits

Summary

- **The radiation environment has complex spatial distribution and solar variability**
  - **Environment definition for Project “A” will not work for Project “B”**
- **Start early in in the program – avoid retrofitting & redesign**
  - **Mission concept – identify show stoppers**
  - **Mission planning – trade studies**
  - **Mission design – detailed analyses, quantify residual risk**
  - **Launch & operations – manage residual risk**
- **Radiation hardness assurance Is a system issue – not a component issue**
- **Shielding is not a “cure-all”.**

References

C. Poivey, “Radiation Hardness Assurance for Space Systems,” Notes from the 2002 IEEE Nuclear and Space Radiation Effects Short Course, Phoenix, AZ.

J.L. Barth ; K.A. LaBel ; C. Poivey, “Radiation assurance for the space environment,” 2004 International Conference on Integrated Circuit Design and Technology (IEEE Cat. No.04EX866).

J.L. Barth, “Modeling Space Radiation Environments,” Notes from the 1997 IEEE Nuclear and Space Radiation Effects Short Course, Snowmass, CO.

Thank you!

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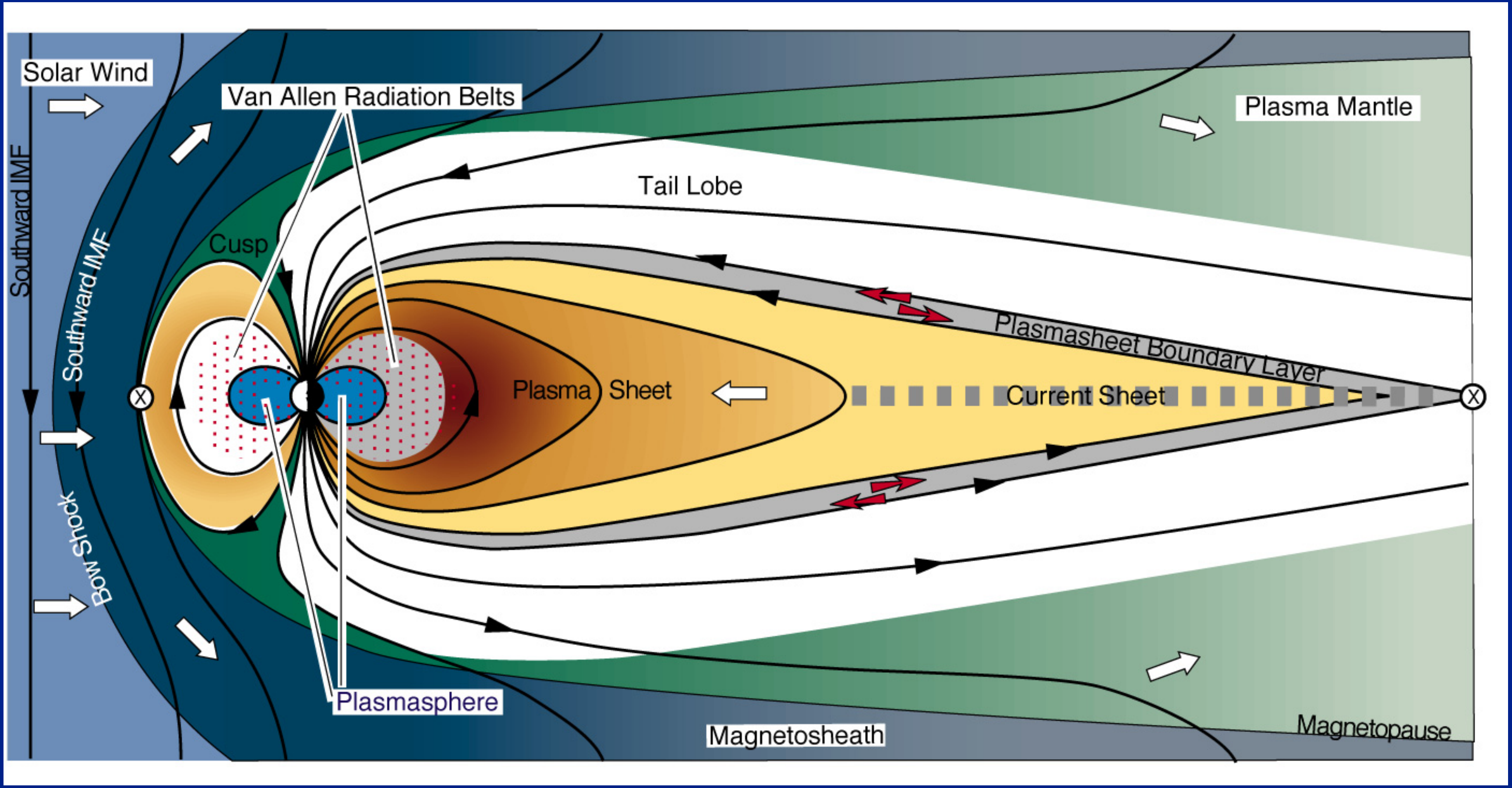
Women in Engineering Events
Young Professionals Events

Backups

Earth's Magnetosphere



adapted from T. W. Hill by P.H. Reiff

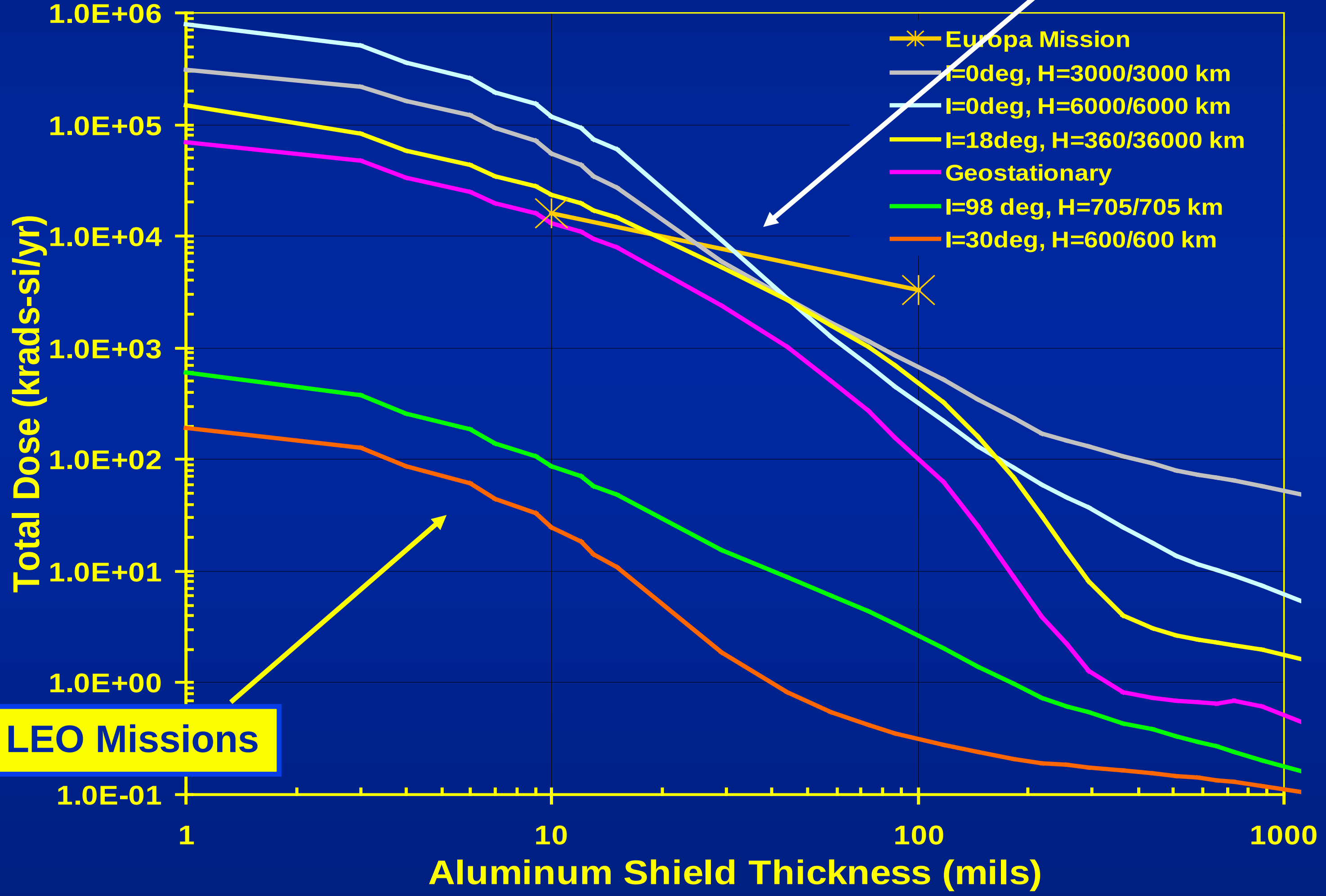
Trapping Mechanisms

- Sources
  - Outer zone - Solar wind & ionospheric electrons & ions
  - Inner zone - Cosmic ray albedo neutron decay (CRAND)
  - Trapped heavy ions - Interplanetary particles
  - Others
    - *In situ* acceleration
    - Artificial, e.g. Starfish explosion
- Losses
  - Collisions
    - Earth's atmosphere
    - H in the exosphere
    - Particles in the plasmasphere
- Stable over long periods of time
  - Inner belts – Years
  - Outer belts - Minutes

TID - Compare Missions

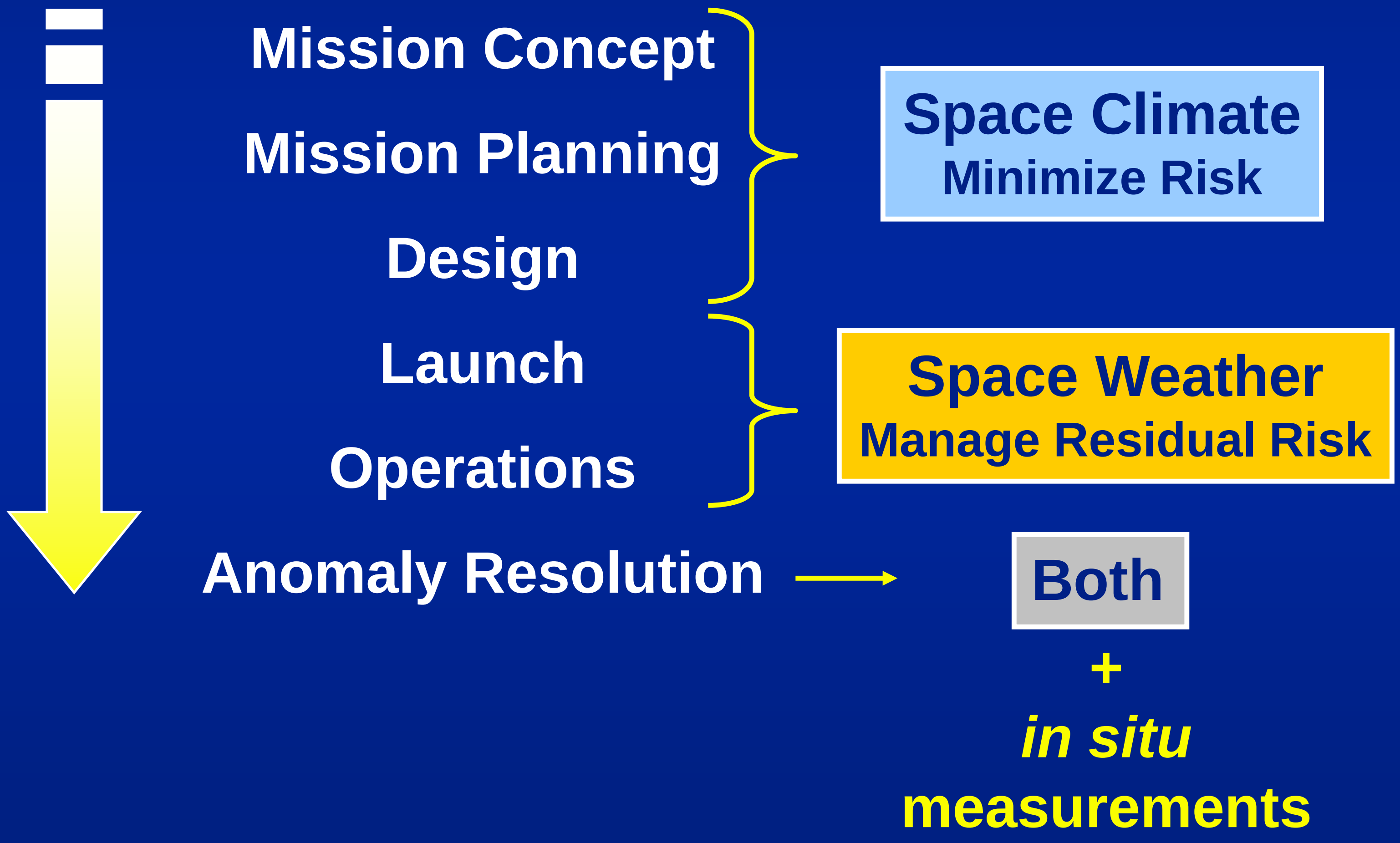
MEO, GEO, GTO Missions

Solid Aluminum Spheres for 1 Year



LEO Missions

Space Environment Model Use in Spacecraft Life Cycle



Mission Concept

Mission Planning

Design

Launch

Operations

Anomaly Resolution

Space Climate
Minimize Risk

Space Weather
Manage Residual Risk

Both

+

***in situ* measurements**

Pre-Launch Phases: Climatology

- **Mission Concept**
  - » **Observation requirements & observation vantage points**
  - » **Development and validation of primary technologies**
- **Mission Planning**
  - » **Mission success criteria, e.g., data acquisition time line**
  - » **Architecture trade studies, e.g., downlink budget, recorder size**
  - » **Risk acceptance criteria**
- **Design**
  - » **Component screening, redundancy, shielding requirements, grounding, error detection and correction methods**

Launch & Post-Launch: Space Weather

- **Launch & Operations**
  - **Asset protection**
    - **Shut down systems**
    - **Avoid risky operations, such as, maneuvers, system reconfiguration, data download, or re-entry**
- **Anomaly Resolution**
  - **Lessons learned need to be applied to <u>all</u> phases**

To be presented by Janet L. Barth at the Nuclear and Plasma Sciences Society's Distinguished Lecturer Program, Toulouse, France, September 13, 2018.

The Solar Cycle

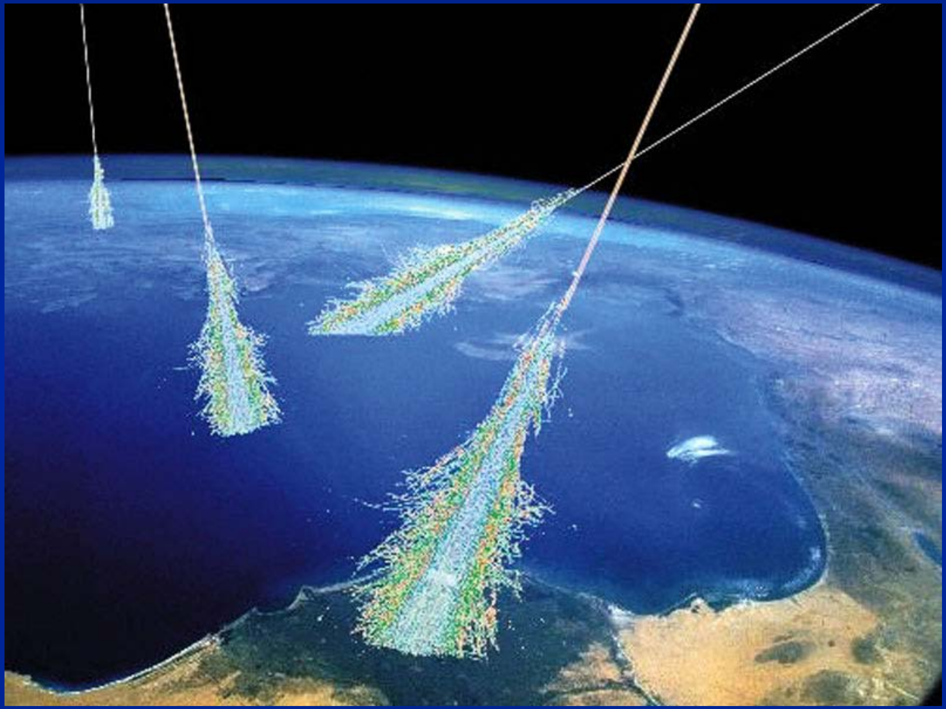
- **Solar Maximum**
  - Intensity and frequency of solar energetic particle (SEPs) events increase
  - Magnetic storms associated with solar event activity increase

- **Declining Phase**
  - Coronal holes expand (non-polar) resulting in high velocity solar wind streams → Recurrent magnetic storms (& electron storms in belts)

- **Ascending Phase**
  - Sunspots appear
  - Solar wind flow is increasingly perturbed by coronal mass ejections
  - Atmospheric heating increases

- **Solar Minimum**
  - Solar wind flow not disturbed due to minimal SEP event occurrence
  - Atmospheric heating decreases

Planetary Atmospheres



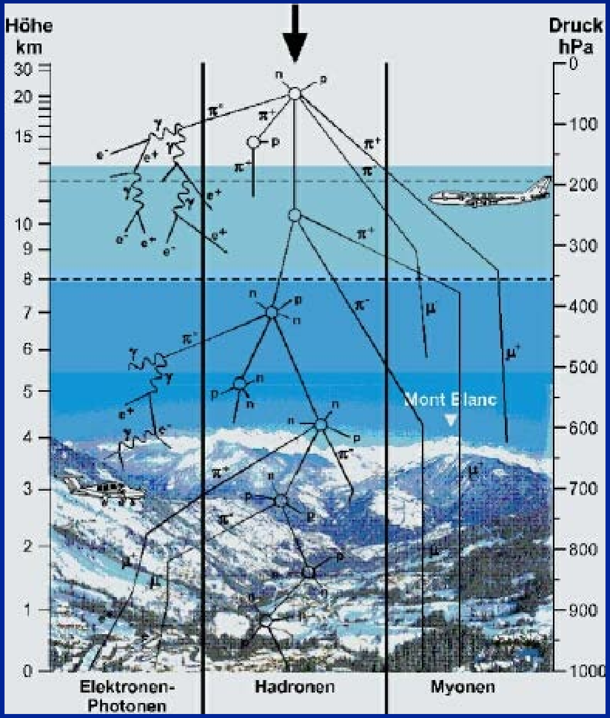
Galactic Cosmic Rays Entering Atmosphere

Simon Swordy (U. Chicago), NASA

◆ **GCRs enter atmosphere & collide with matter**

- **Secondary particles are produced - Important product is neutrons**
- **Earth**
  - » **Magnetic field causes a latitude dependence**
  - » **GCRs enter atmosphere & collide with O & N**
- **Mars**
  - » **No magnetic field – Primary cosmic rays are important component**
  - » **Thin atmosphere - Products from interactions with Mars atmosphere and surface materials are also important**

Atmospheric Radiation

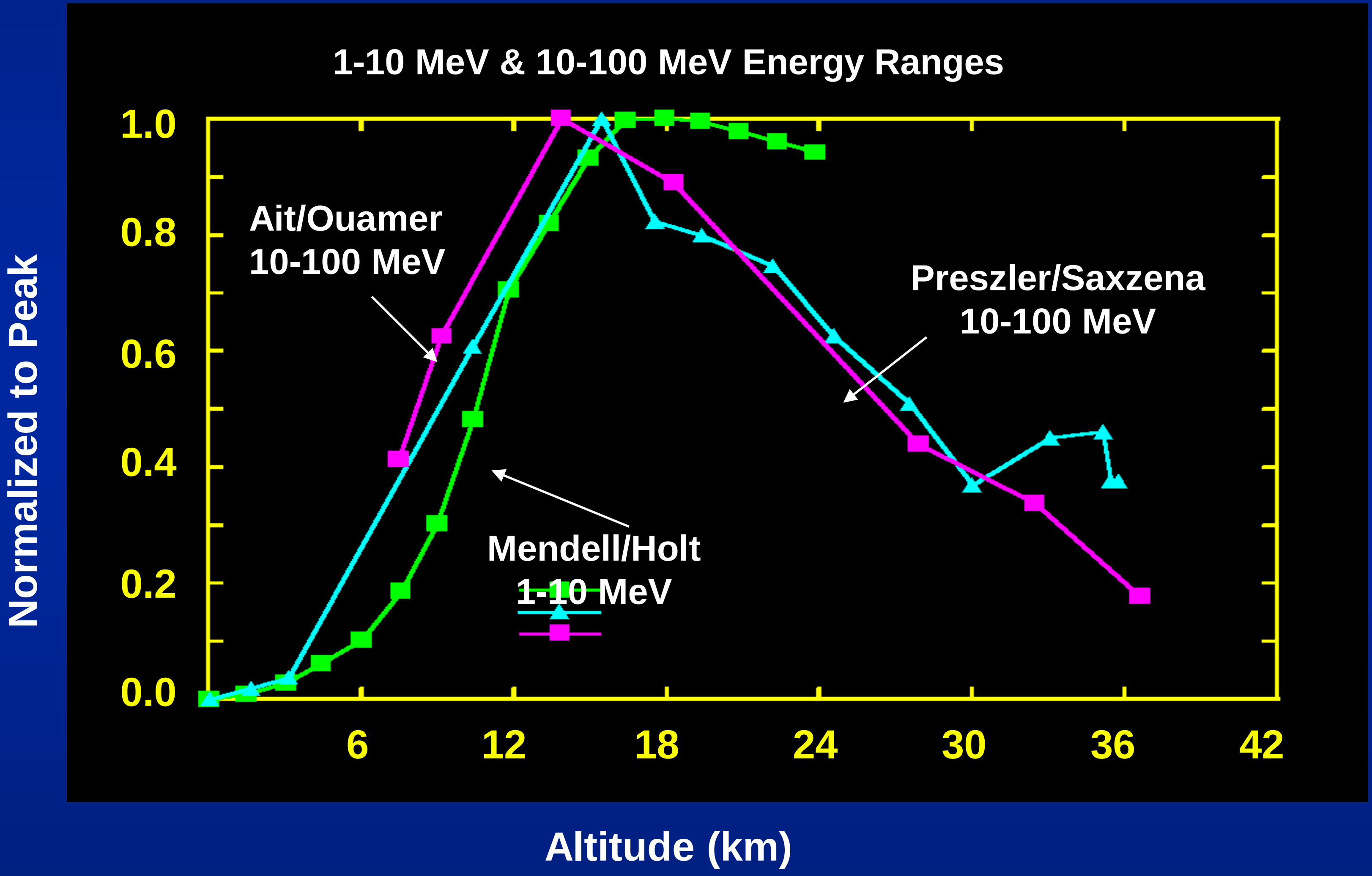


U. J. Schrewe

- ◆ **Serge Korff**
  - » **Balloon observations, high elevations, rockets, high-flying aircraft**
  - » **Published study included effects of altitude and latitude dependence**

- ◆ **1951 – Serge Korff**
- **Collisions between cosmic rays & atmospheric O & N**
  - » **Product - High energy neutrons**
- **1990’s – Neutron induced effects in aircraft avionics & ground systems**
- **Effects**
  - » **Single Event Upsets (Low Earth orbits, aircraft, ground)**
  - » **Passenger & crew exposure in aircraft**

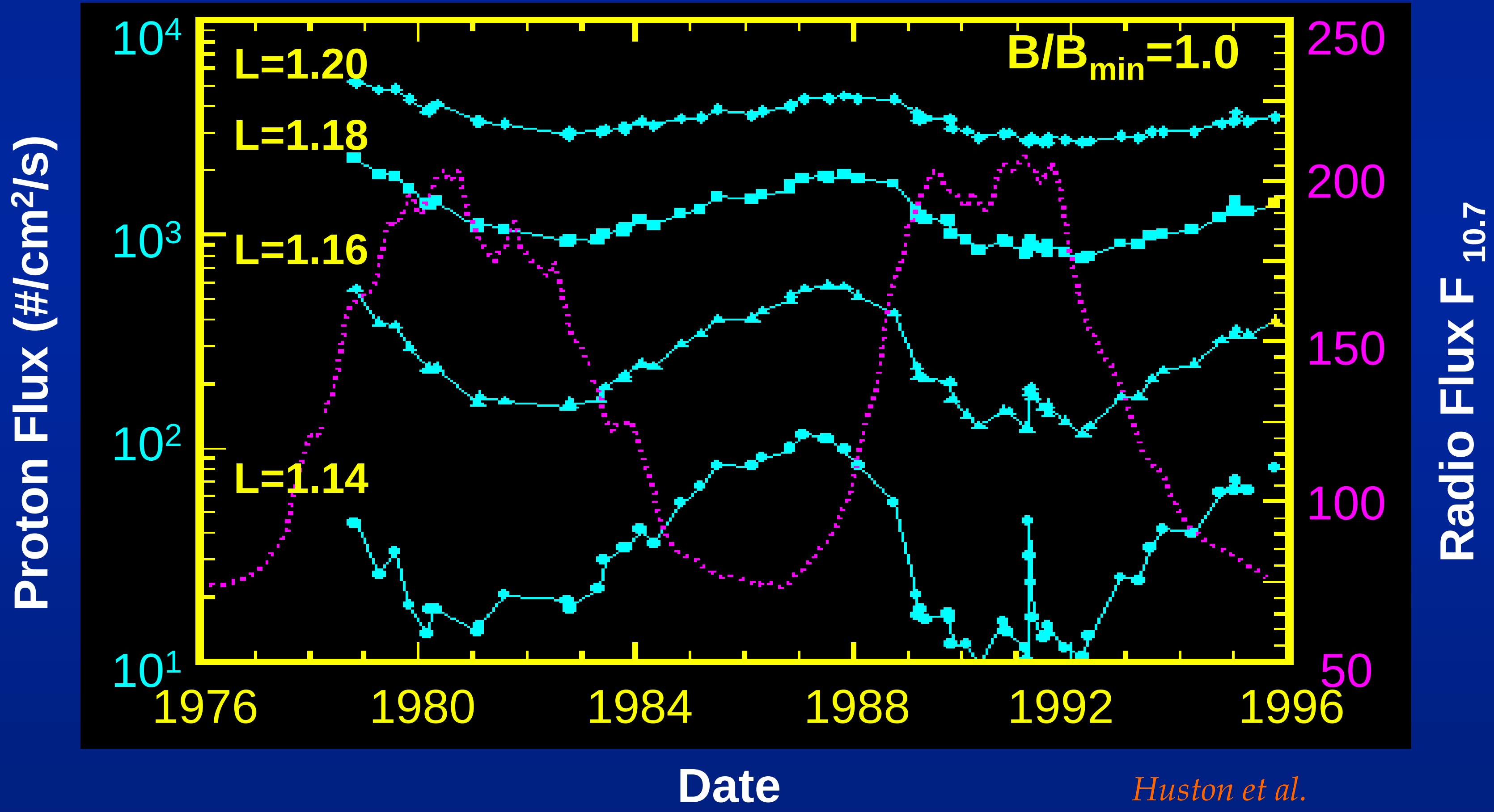
Neutron Flux Measurements



Solar Cycle Effects: Trapped Protons

Solar Cycle Variation: 80-215 MeV Protons

TPM-1 Model



Huston et al.

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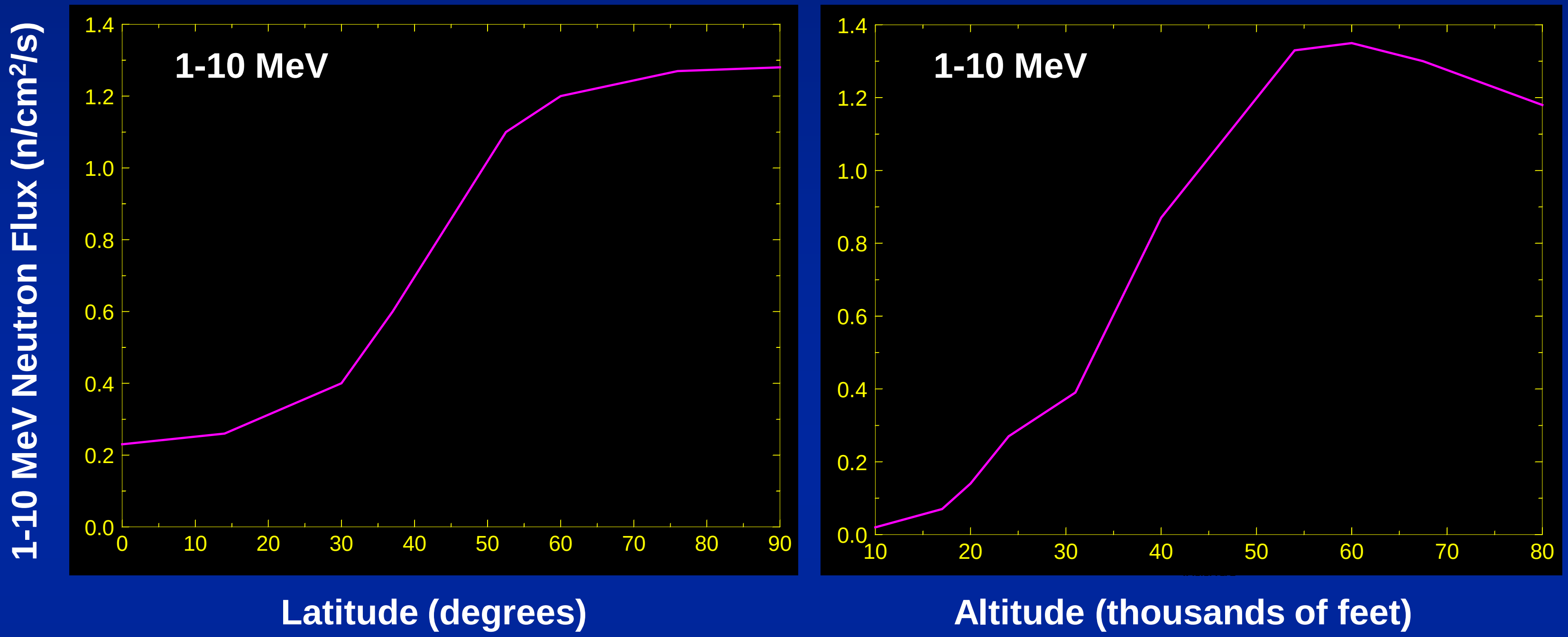
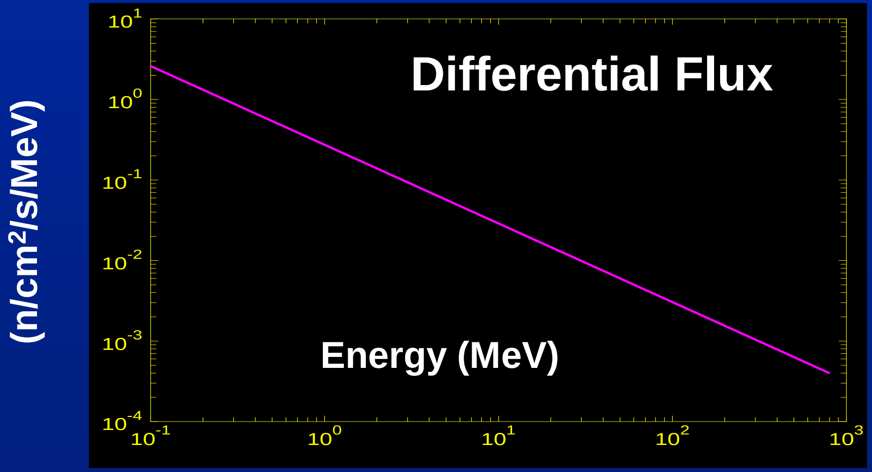
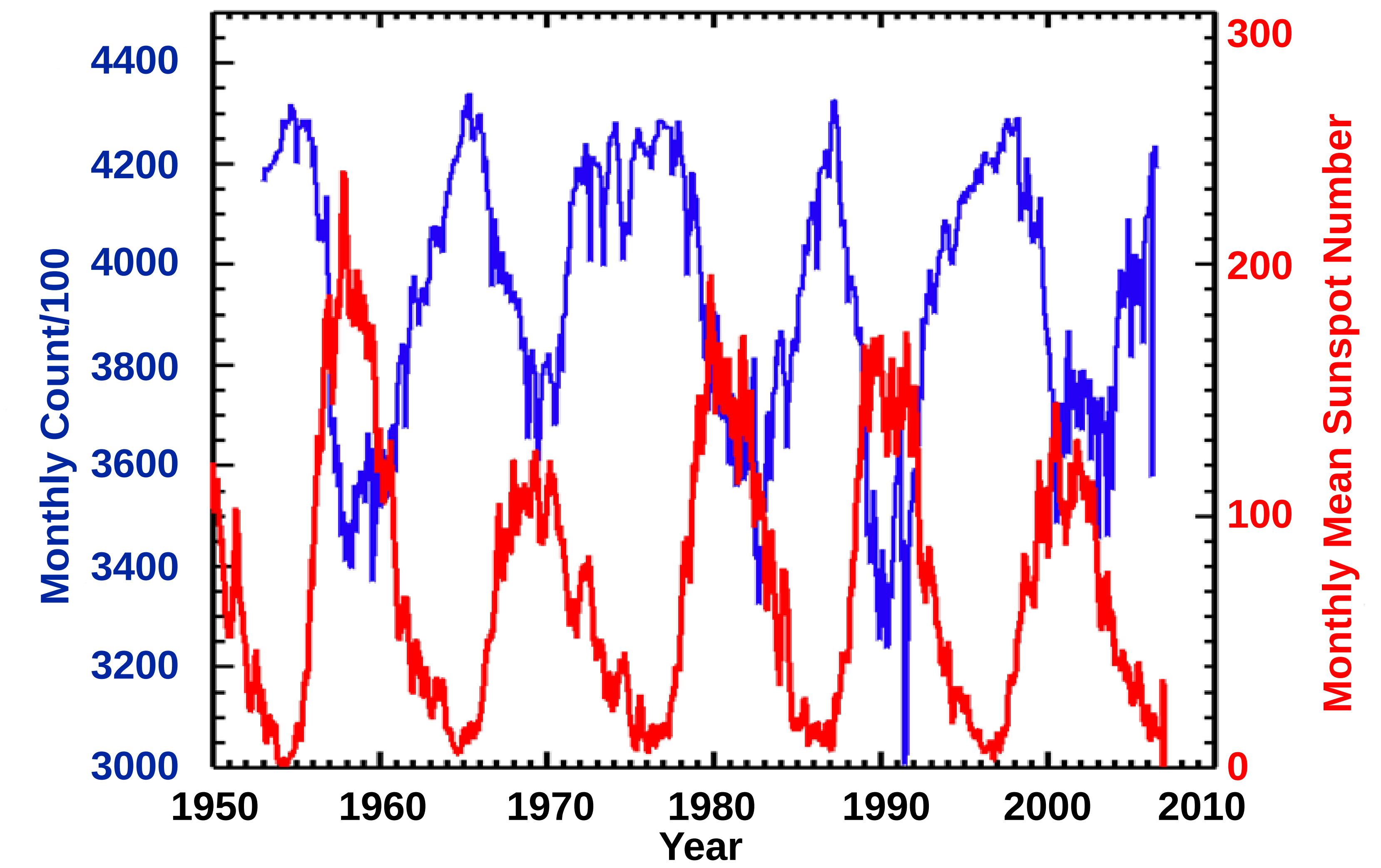
Boeing Neutron Model





Solar Cycle Effects: Ground Neutrons

Climax Neutron Monitor

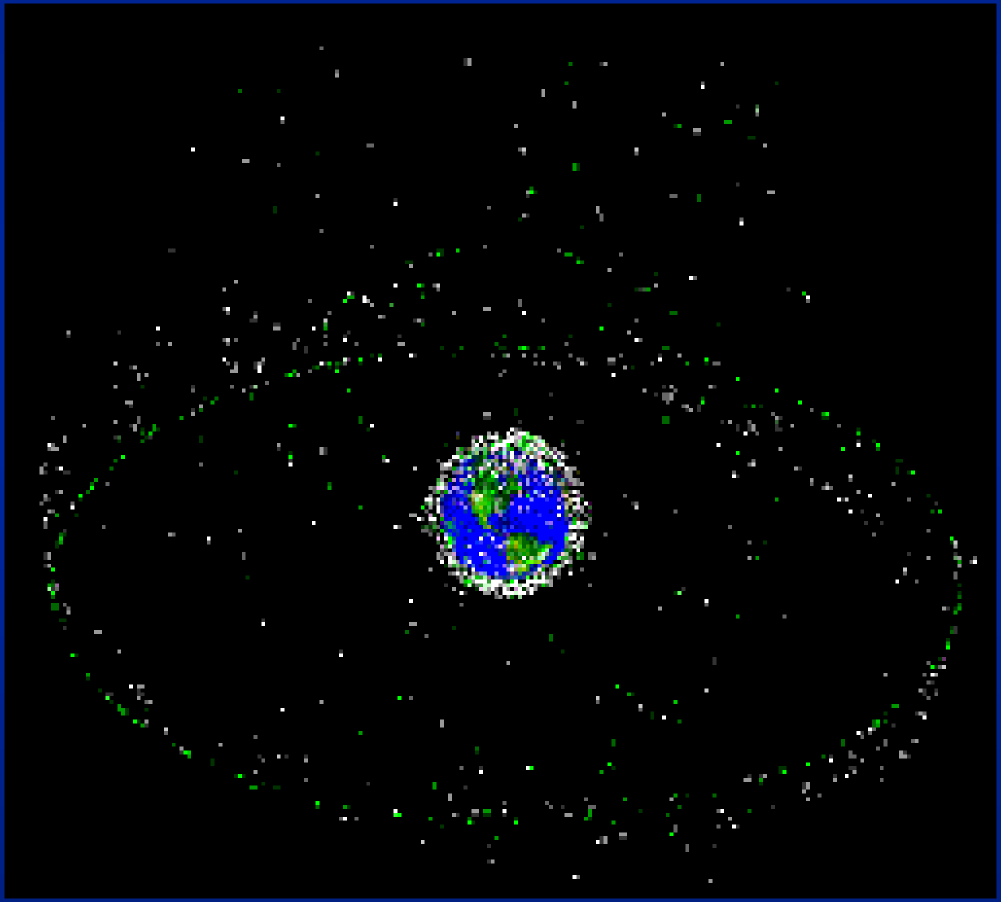


NOAA

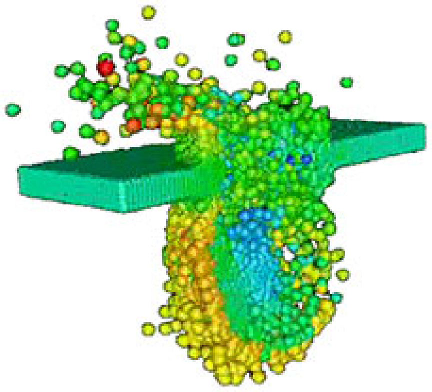
Meteoroid/Orbital Debris

- Meteoroids
  - Primarily remnants of comet orbits
    - Several times a year - Earth intersects a comet orbit
    - Other planets
  - Asteroid belt
    - Daily - Sporadic particles released
- Debris
  - Operational payloads, spent rockets stages, fragments of rockets and satellites, other hardware and ejecta
  - USAF Space Command tracks over 7,000 > 10 cm objects in LEO
  - Tens of thousands smaller objects

Satellite & Debris Tracking



USAF
Space Command
NORAD Tracking



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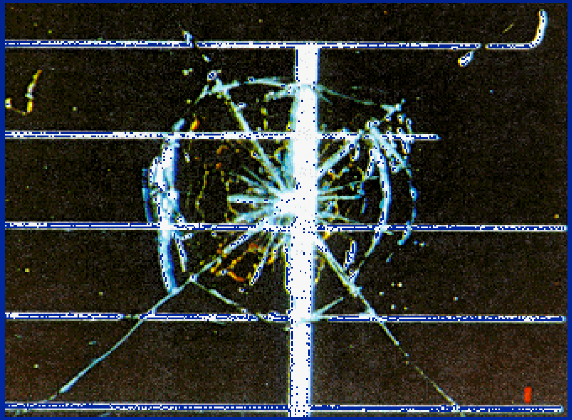
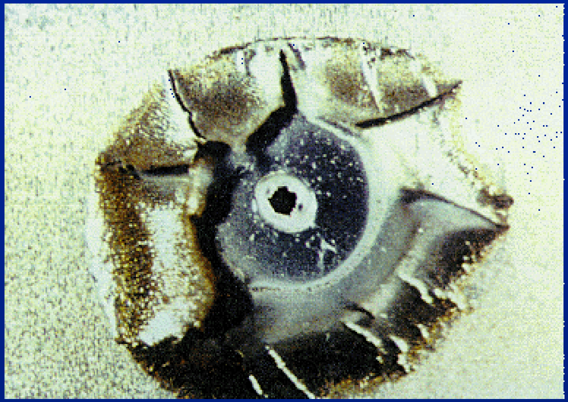
Micro-meteoroid & Orbital Debris Effects

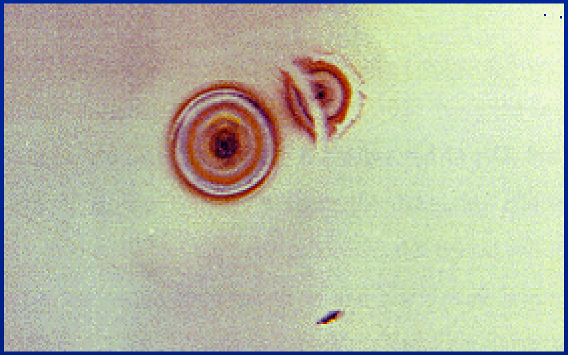
- Damage and decompression threat
  - Hypervelocity impacts from larger particles
  - Surface erosion from collisions with smaller objects
- Surface effects on thermal, electrical, and optical properties
- Increases contamination



Impact into solar-cell cover glass. Such impacts can degrade the power producing ability of such devices



Penetration through an aluminized Mylar foil



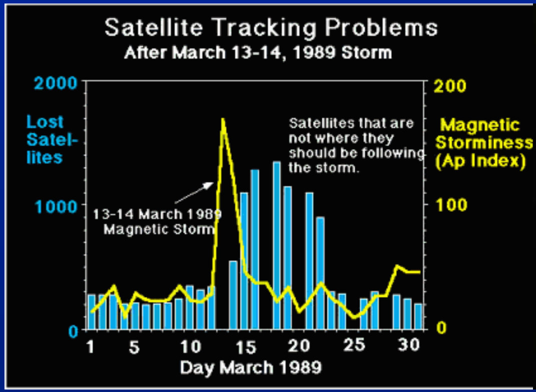
Penetrations, and commonly associated ringed structure, in silver-Teflon thermal blanket

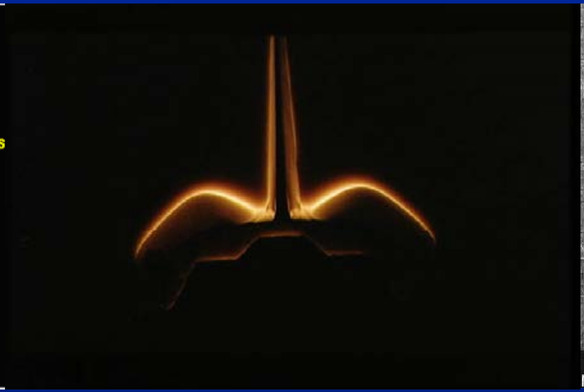
Neutral Gas/Thermosphere

- Definition
  - Neutral portion of the atmosphere
  - Composed of neutral gas particles
  - 90 – 600 km
- Variations
  - Altitude - Atomic mass
    - Lower altitude – Atomic oxygen (AO) (200 - 400 km)
    - Higher altitude – Hydrogen & Helium
  - Heating
    - Solar cycle effects due to absorption of solar extreme ultraviolet radiation (EUV)
    - Proxy measurement with 10.7-cm radio flux (F10.7)
  - Solar storms

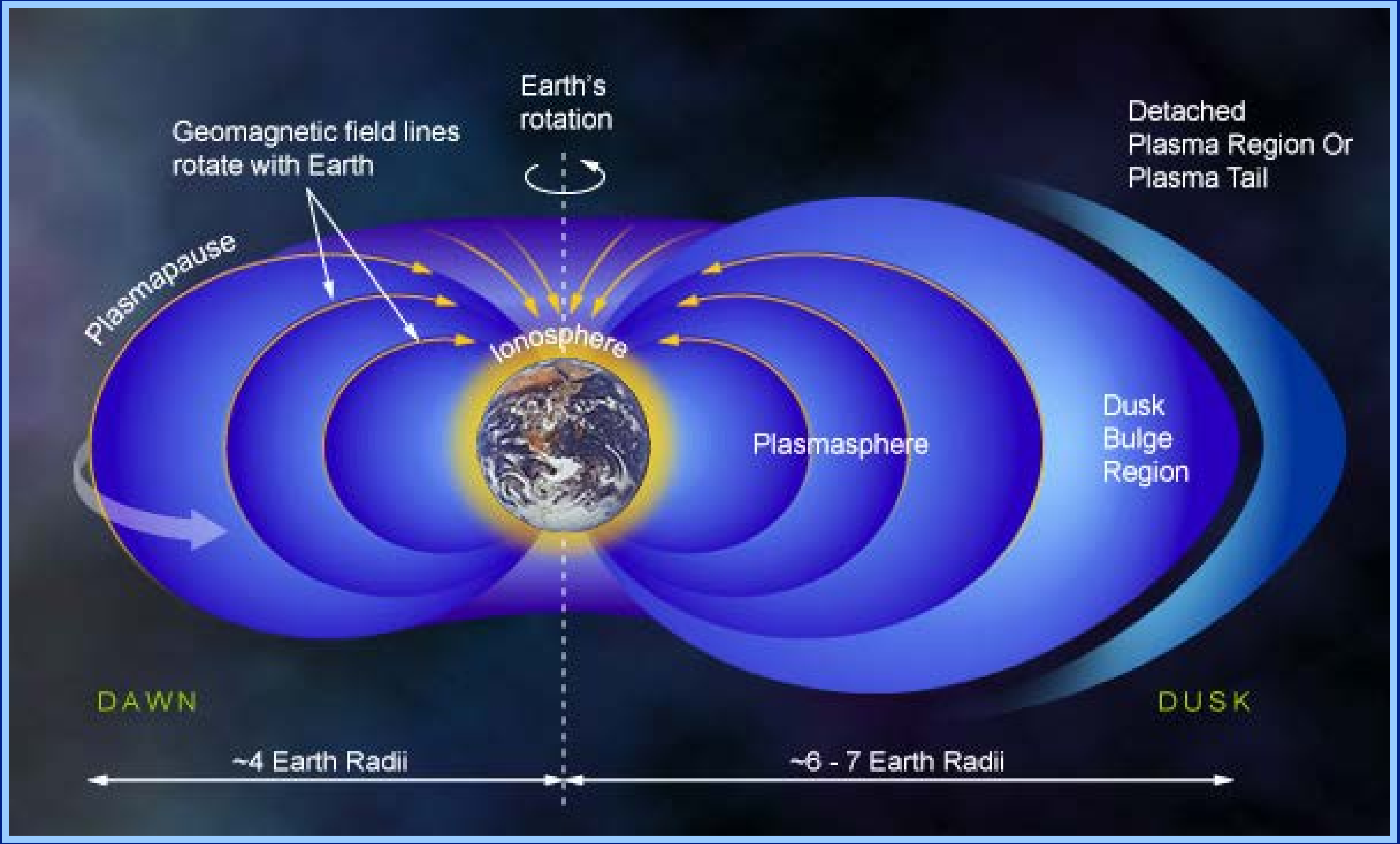
Neutral Gas Effects

- Degradation of surface materials
  - Atomic oxygen in synergy with plasma and UV
- Spacecraft drag
- Spacecraft glow





Plasmasphere

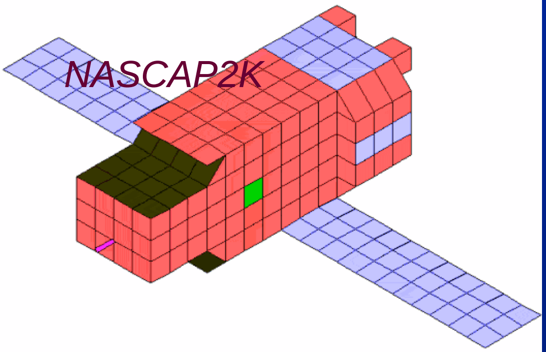


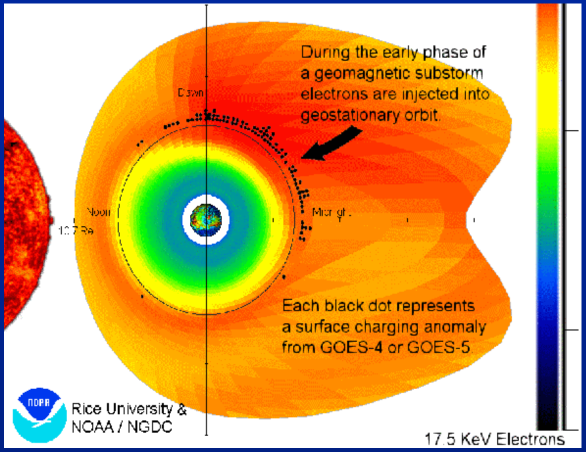
Plasma Environments

- Energy < 100 keV - No radiation effects
- Ionized gas where electron and ion densities are approximately equal
- Sources
  - Ionosphere
    - Electrically charged portion of the atmosphere
    - Low energy (eV)/High Density
  - Plasmasphere - Magnetosphere
    - Source - ionosphere and solar wind
    - High energy (keV)/Low density
    - Storms - Geomagnetic substorm activity
  - Solar Wind
    - Sun’s corona
    - Seen at > 10 Billion km from the Sun by Pioneer 10

Plasma Effects

- Surface charging – can be destructive
- Solar array coupling to plasma
  - Current drain
- Contamination
  - Dense pressure of atmosphere in LEO
- Generation and emission of plasma waves





During the early phase of a geomagnetic substorm electrons are injected into geostationary orbit.

Each black dot represents a surface charging anomaly from GOES-4 or GOES-5.

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