02 – The Natural Space Radiation Environment

ENGR-E 399/599
Microelectronics Radiation Effects and Reliability

Context

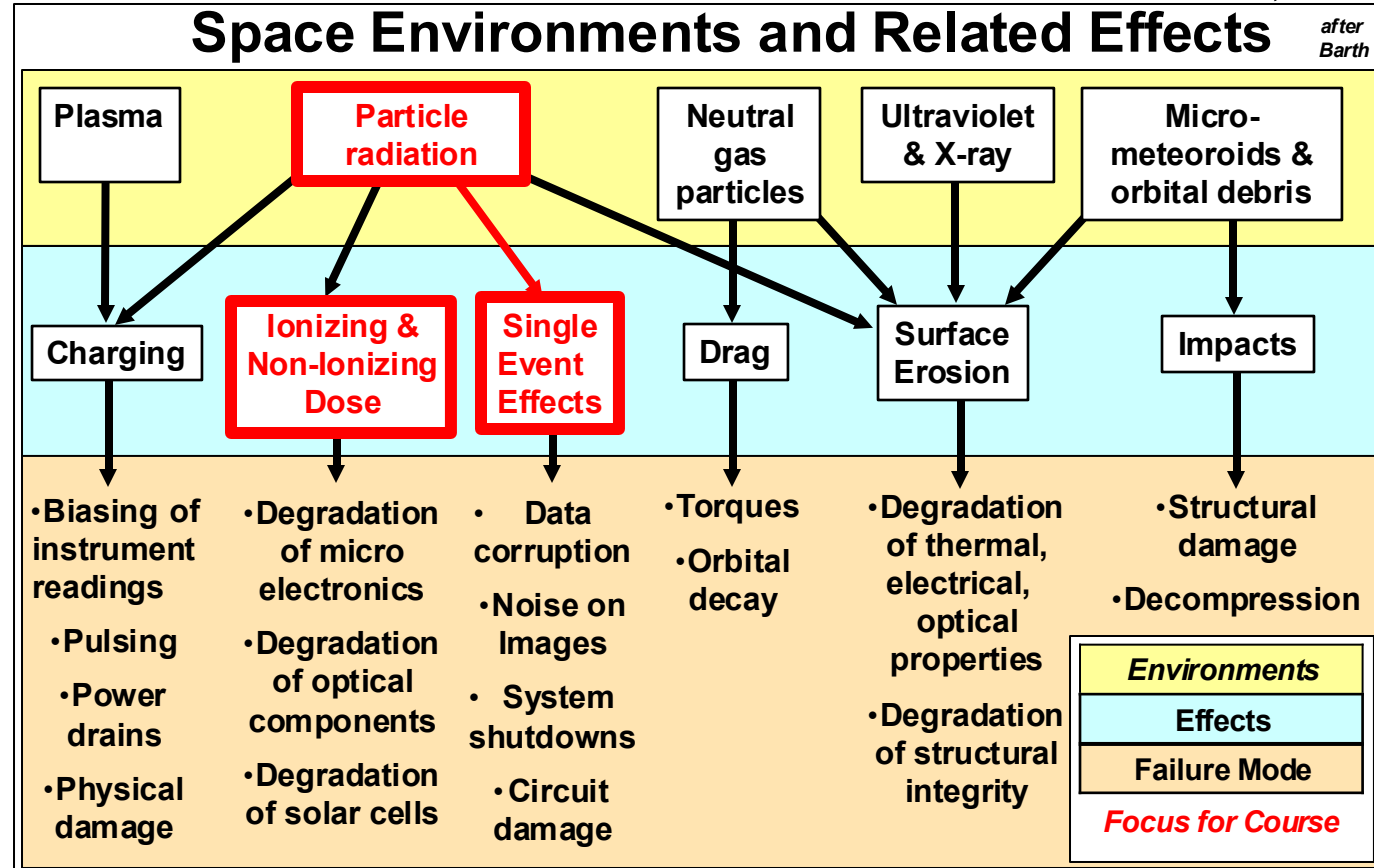- **This presentation is only focused on the natural space exoatmospheric radiation environment around Earth**
  - **Focus of this presentation will specifically be on particle radiation, since those are the kind most likely to affect advanced electronics**
  - **Will not discuss Jovian or Cis Lunar environment (Jupiter, Saturn, Neptune, and Uranus)**

Space Environments and Related Effects

after Barth

Environments
Effects
Failure Mode
Focus for Course

Environments: Plasma | Particle radiation | Neutral gas particles | Ultraviolet & X-ray | Micro-meteoroids & orbital debris

Effects: Charging | Ionizing & Non-Ionizing Dose | Single Event Effects | Drag | Surface Erosion | Impacts

Failure Mode:
- 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

Learning Objectives

- Explain why environments are important in design
- Identify the direct and indirect sources of particle radiation that affect electronics
- Explain how the Sun impacts the environments that exist in space
- Identify different mission regimes and the environments that will impact those missions
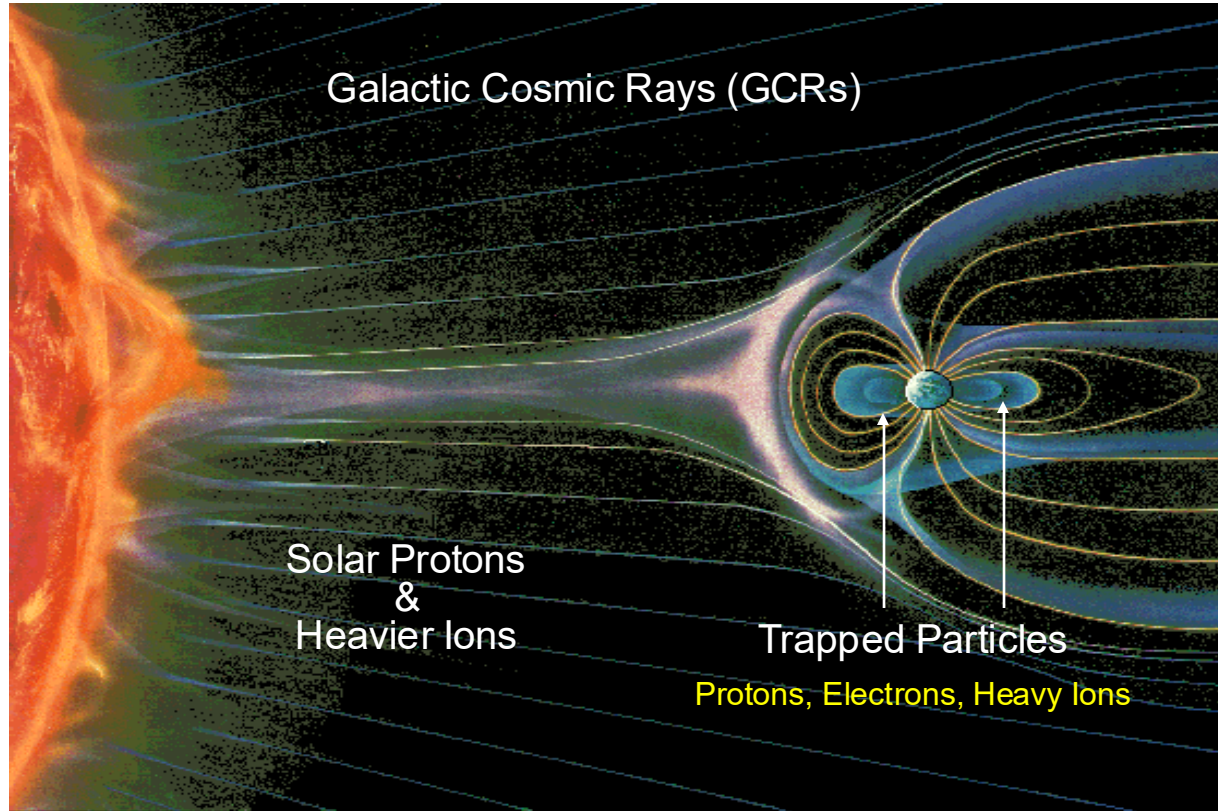
Section Topics/Outline

- What are the sources of the natural space radiation environment?
- What role does the Sun play on these environments?
- Why do environments matter?
- Summary

Section Topics/Outline

- **What are the sources of the natural space radiation environment?**
  - **Direct Sources (Solar Particles, Galactic Cosmic Rays)**
  - **Indirect Sources (Trapped Radiation)**
- **What role does the Sun play on these environments?**
- **Why do environments matter?**
- **Summary**

The Natural Space Radiation Environment

Galactic Cosmic Rays (GCRs)

Solar Protons & Heavier Ions

Trapped Particles

Protons, Electrons, Heavy Ions

Depiction of the natural space radiation environment local to the Earth modified from K. Endo, Nikkei Science Inc. of Japan and J. L. Barth
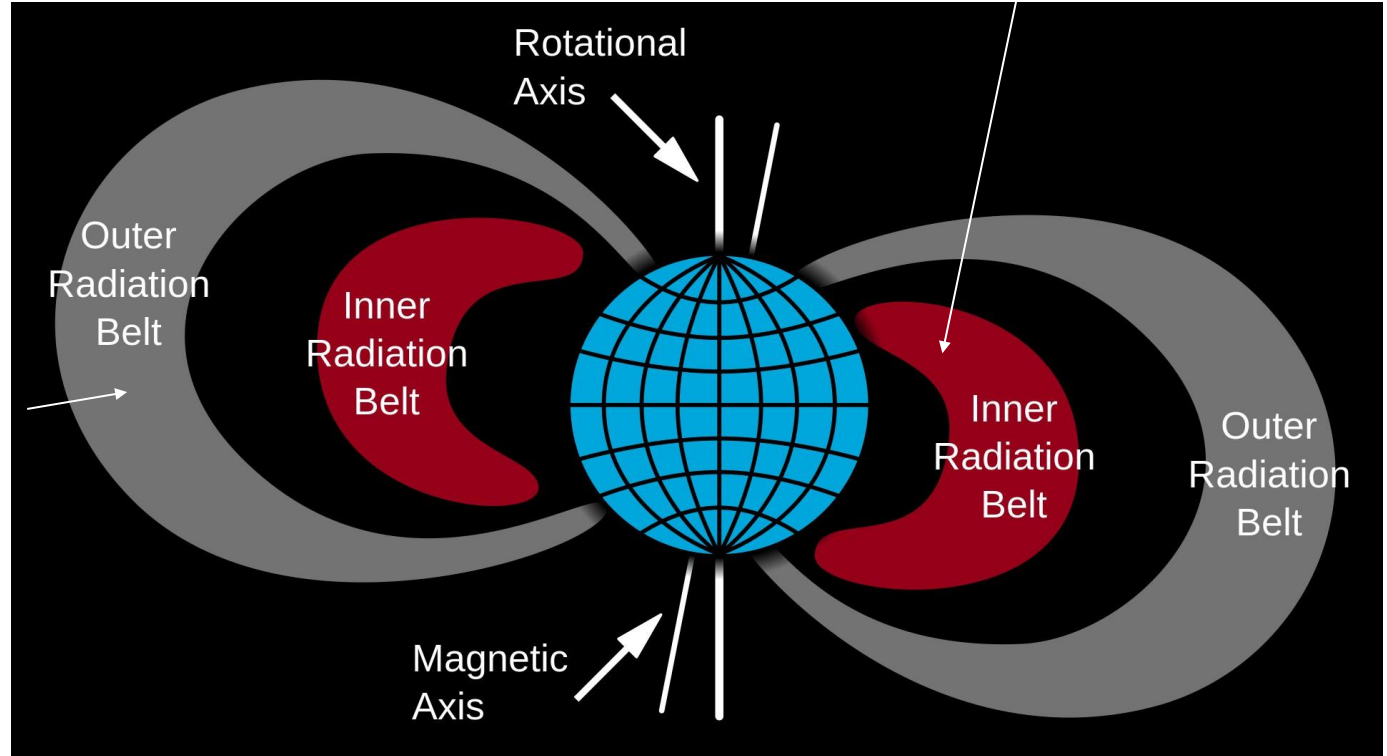
Sources of Natural Space Radiation Environment

Direct Source

GCRs ← **Supernova**

Protons & Heavier Ions

Sun → CMEs Solar Flares → Protons & Heavier Ions

Coronal Mass Ejections (CMEs)
Galactic Cosmic Rays (GCRs)

Depiction of the natural space radiation environment local to the Earth modified from K. Endo, Nikkei Science Inc. of Japan and J. L. Barth

Sources of Natural Space Radiation Environment

Indirect Source

Trapped Particles
Protons, Electrons, Heavy Ions
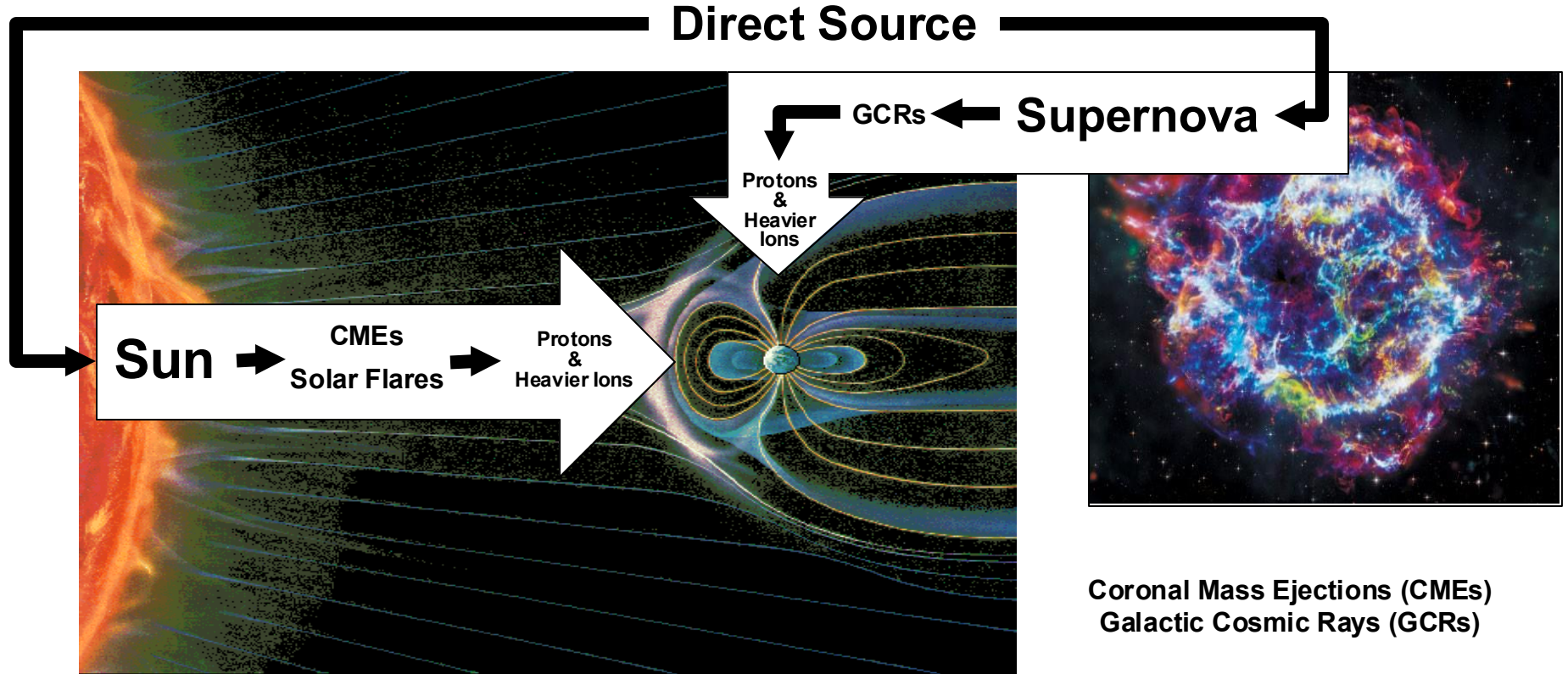
Depiction of the natural space radiation environment local to the Earth modified from K. Endo, Nikkei Science Inc. of Japan and J. L. Barth

Radiation Belts

Trapped

Energetic Protons
Very stable over time

Rotational
Axis

Energetic Electrons
Dynamic: varies on
weekly/monthly timescales

Outer
Radiation
Belt

Inner
Radiation
Belt

Inner
Radiation
Belt

Outer
Radiation
Belt

Magnetic
Axis

Courtesy Wikipedia

Different Orbits will sample different parts of the trapped environment
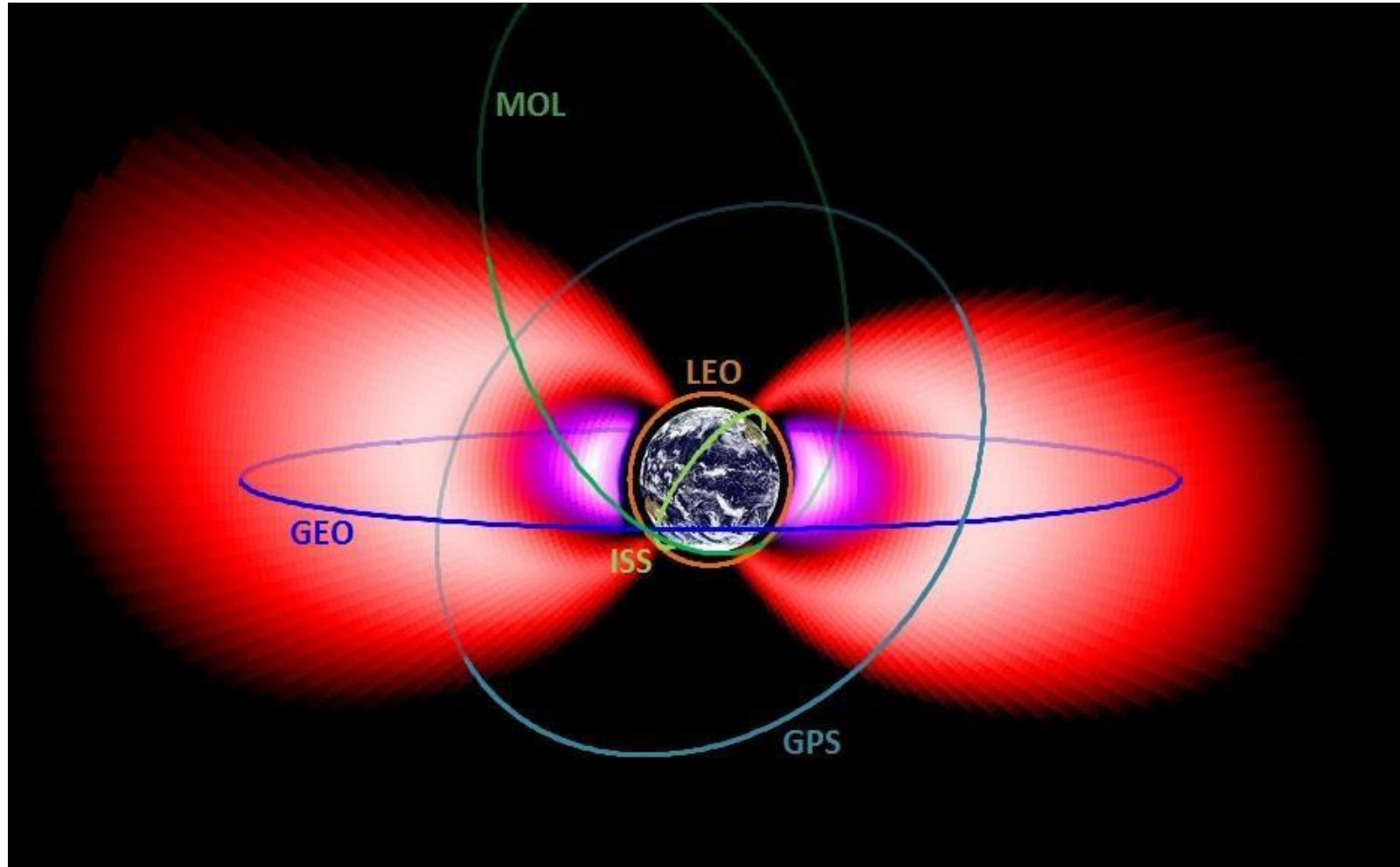
Radiation Belts

Section Topics/Outline

- **What are the sources of the natural space radiation environment?**
- **What role does the Sun play on these environments?**
  - **Source vs. Modulator**
  - **Sunspots**
  - **Solar Cycle**
- **Why do environments matter?**
- **Summary**

Effects of the Sun on Space Environment

- **The Sun's serves as both a producer and modulator of particles in the space environment**
  - **Direct Source of:**
    - *Protons and heavy ions*
  - **Indirect Source of:**
    - **Protons and electrons in Van Allen belts**
  - **Modulator of:**
    - **Galactic Cosmic Ray fluxes entering solar system**

- **The solar cycle determines the frequency of solar events and which environments are most dominant**

Source

Modulator
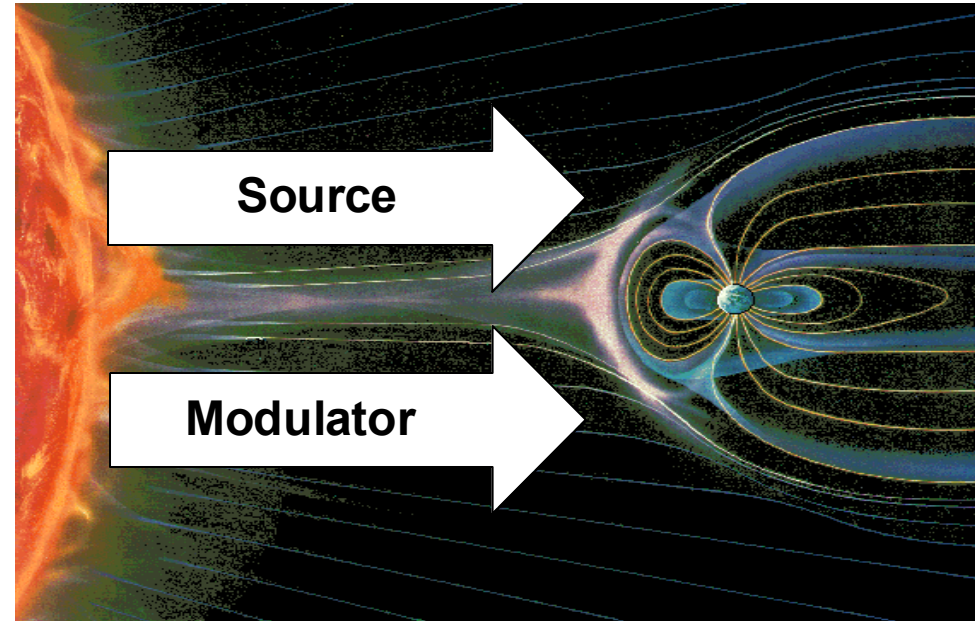
The Sun and It's Effect on the Natural Space Environment
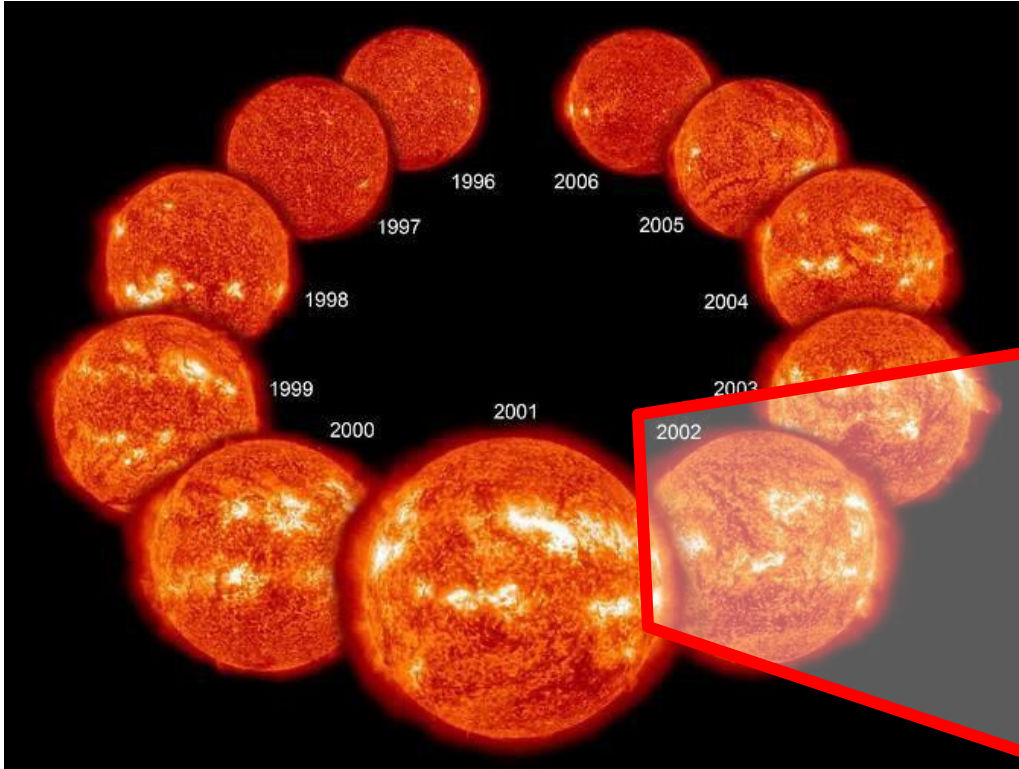
Credit: NASA

- **Sun is very active**
  - **Sunspots are viewed as a proxy to solar activity**
- **Region is cooler and appears darker when viewed in visible light**

Visible Light   **Ultraviolet Light**
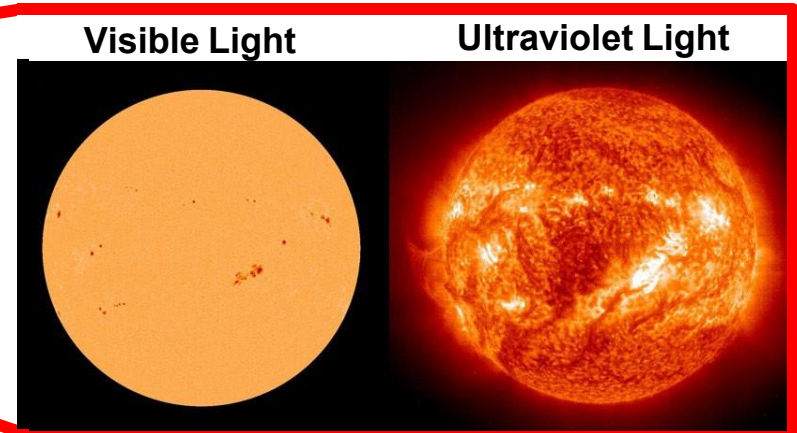
Images Taken Feb. 3, 2002 (Credit: ESA and NASA (SOHO))

The Sunspot Cycle

- **Sun's activity has a long-term, periodic behavior**

- **Sunspot cycle indicates the sun's magnetic activity levels**
  - **Approximately 11 year cycle but can vary in amplitude and duration**
  - **Solar maximum – typically 7-year period when activity levels are higher**
  - **Solar minimum – typically 4-year period when activity levels are lower**
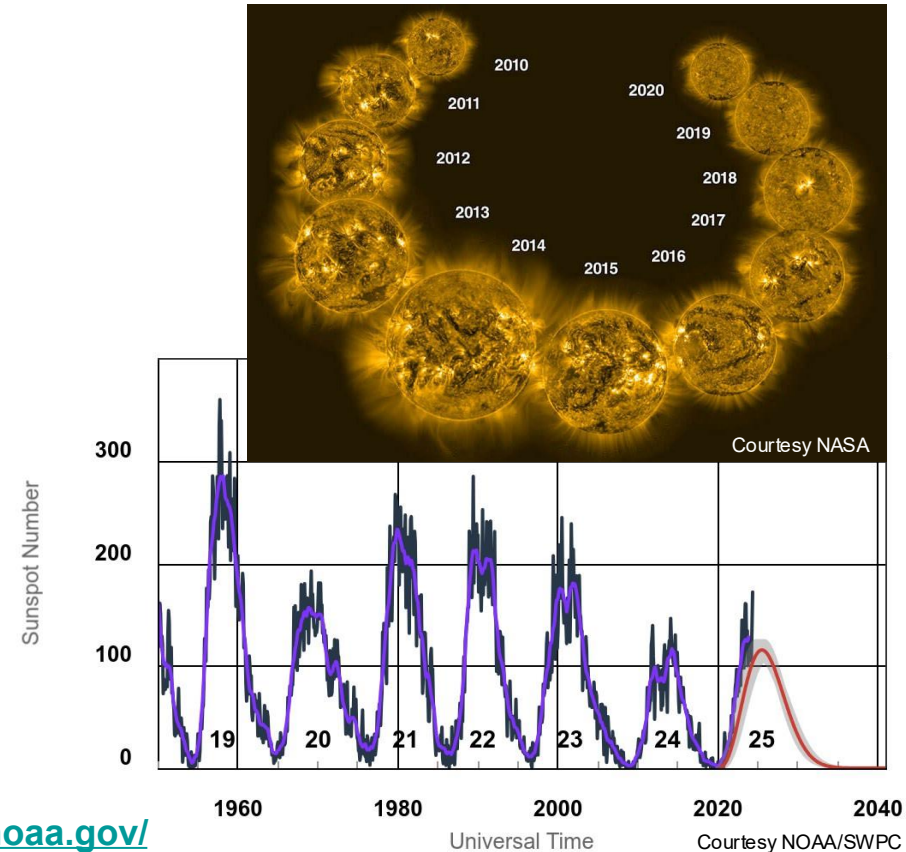
https://www.swpc.noaa.gov/

Courtesy NASA

Courtesy NOAA/SWPC

Section Topics/Outline

- What are the sources of the natural space radiation environment?
- **What role does the Sun play on these environments?**
  - **Active Environments (Solar Particle Events)**
- Why do environments matter?
- Summary

Solar Energetic Particles

- **Cyclical (Solar Max, Solar Min)**
  - **11-year average (9 to 13)**
  - **Solar Max is more active period**

- **Two types of events**
  - **Coronal Mass Ejections (CMEs)**
    - **More gradual**
    - **Proton rich – 96%**
    - **Responsible for major disturbances in Earth's magnetosphere and interplanetary space**
  - **Solar Flares**
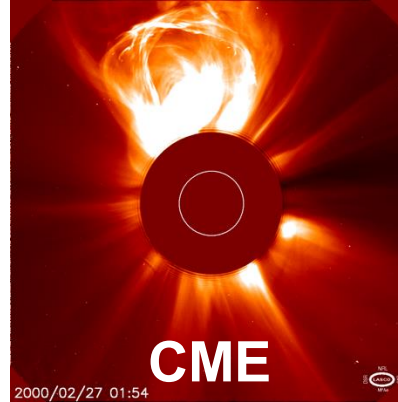   - **Heavy ion rich**
    - **Impulsive or spikes**

CME

2000/02/27 01:54

Solar Flare
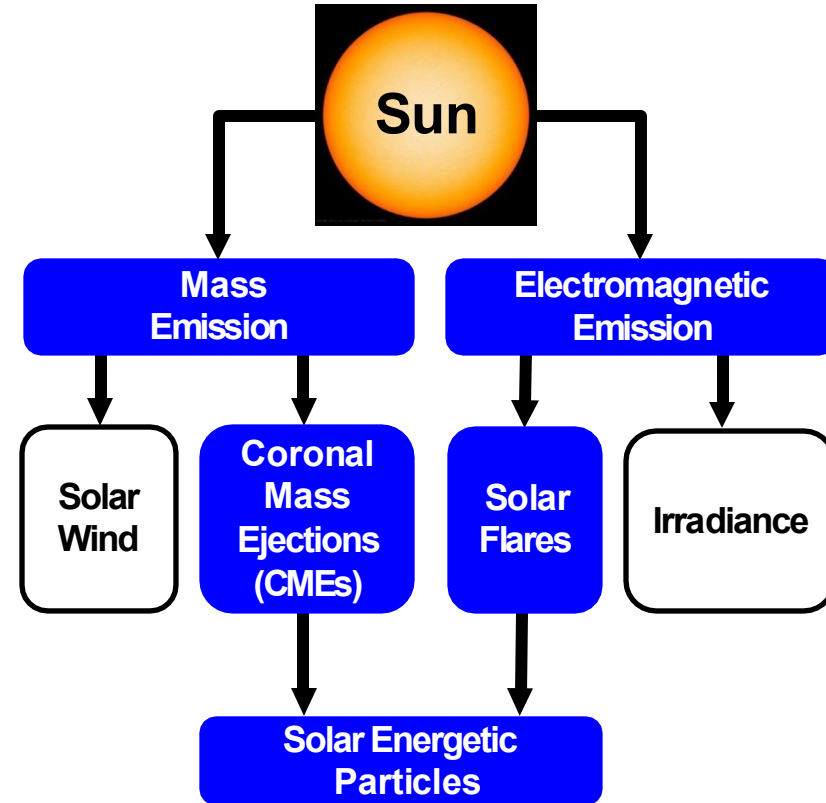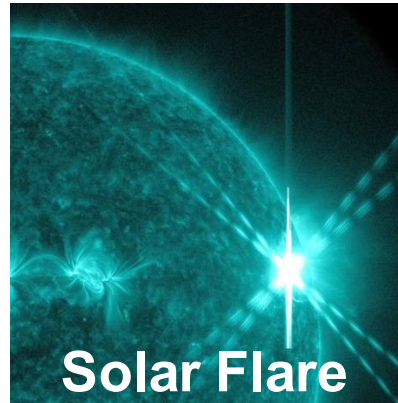
Image credits: NASA and ESA (SOHO and SDO)

Solar Cycle Dependence

- **Solar Maximum**
  - **Background (includes solar wind) levels lower**
  - **Solar Events More Frequent & Greater Intensity**
- **Solar Minimum**
  - **Background (includes solar wind) levels higher**
  - **Solar Events less frequent**
   - **Does not mean not happening**

25-250 MeV/n CNO - IMP-8

Flux (cm²-s-sr-MeV/n)⁻¹ vs Year
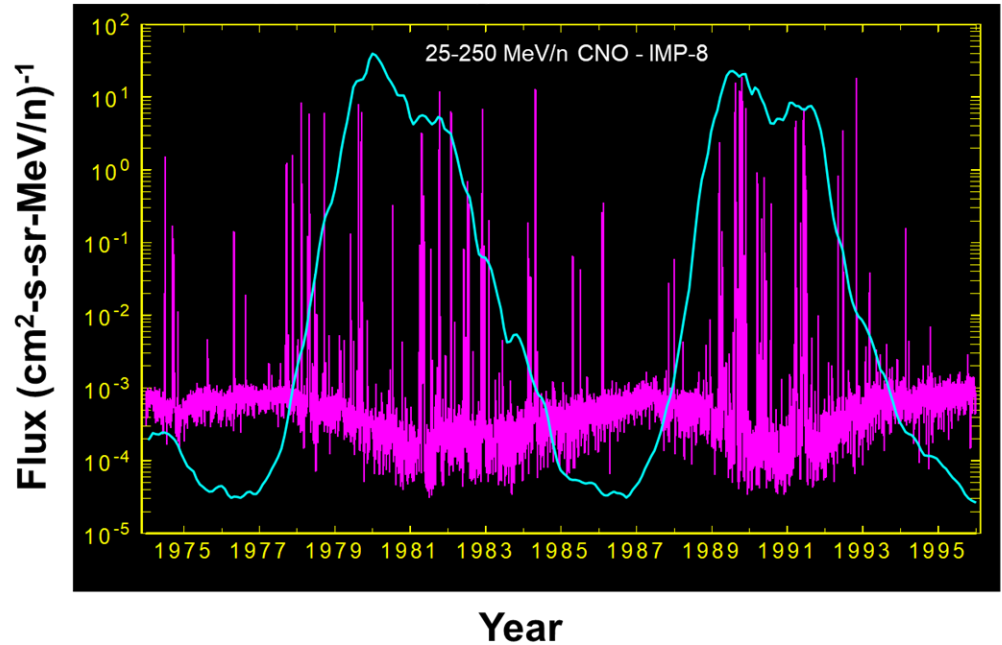
J.L. Barth, 1997 NSREC Short Course

Sun is a source of particle events

Worst Case Solar Particle Events

- **Most common approach is to design to a well-known large event**

- **Events most often considered:**
  - **October 2003**
  - **October 1989**
  - **August 1972**
  - **Carrington Event 1859**
    - **Published ice core data not a reliable indicator of solar proton event magnitudes**
    - **Not used in design**
    - **First example being linked to impacts on the earth**

- **Refer to Aerospace TOR-2022-00016 for best practices for generating space environment specifications with modern tools**
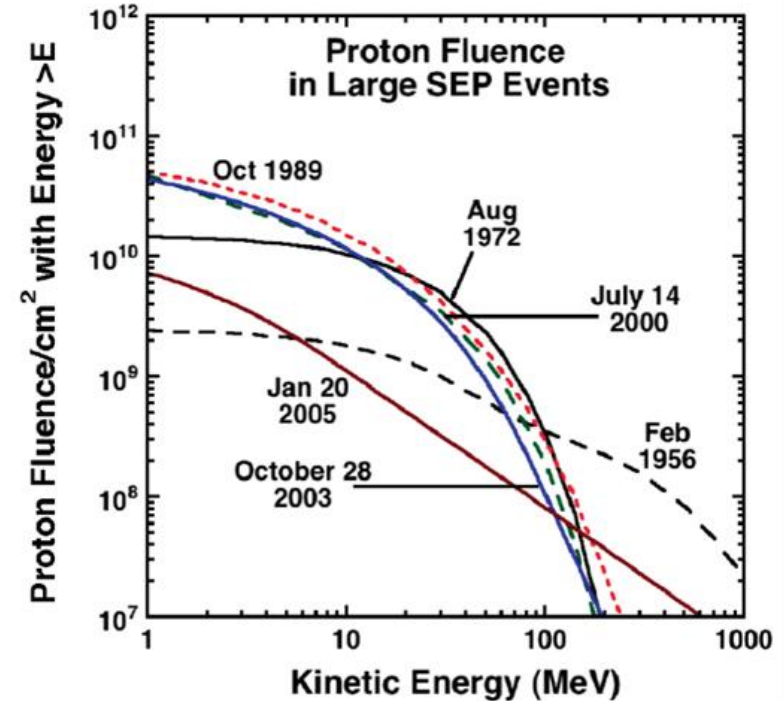
R.A Mewaldt et al., Radiat. Risks., 2007

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**
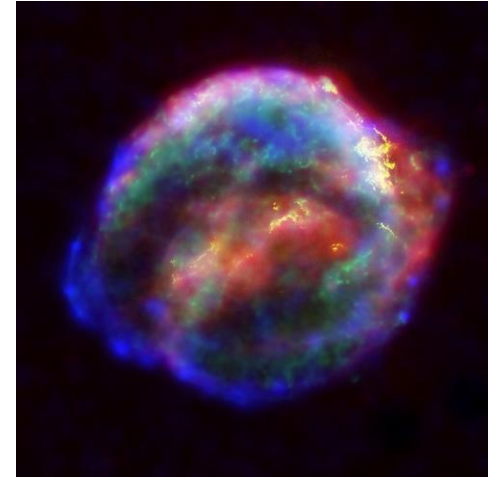- **Useful for both protons and heavy ions**
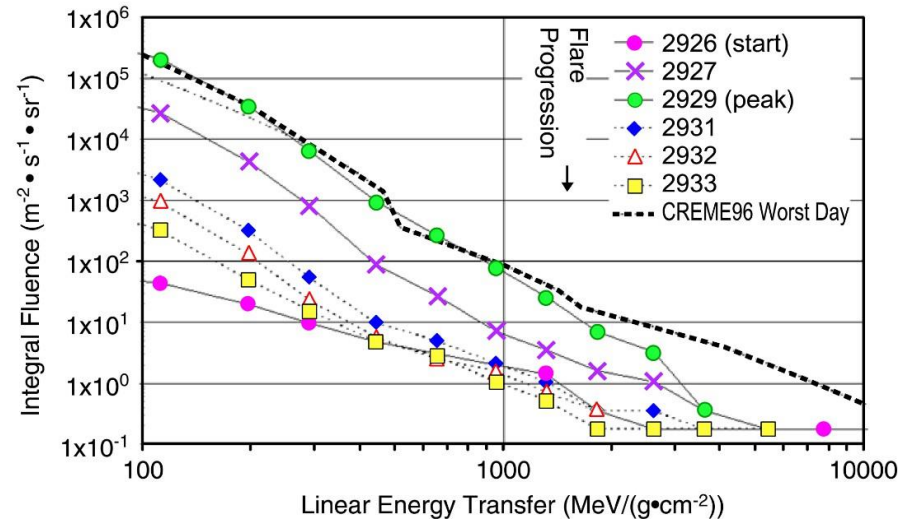
C.S. Dyer et al., IEEE TNS, Dec. 2002

Section Topics/Outline

- ~~What are the sources of the natural space radiation environment?~~
- **What role does the Sun play on these environments?**
  - **Quiet Environments (Galactic Cosmic Rays)**
- ~~Why do environments matter?~~
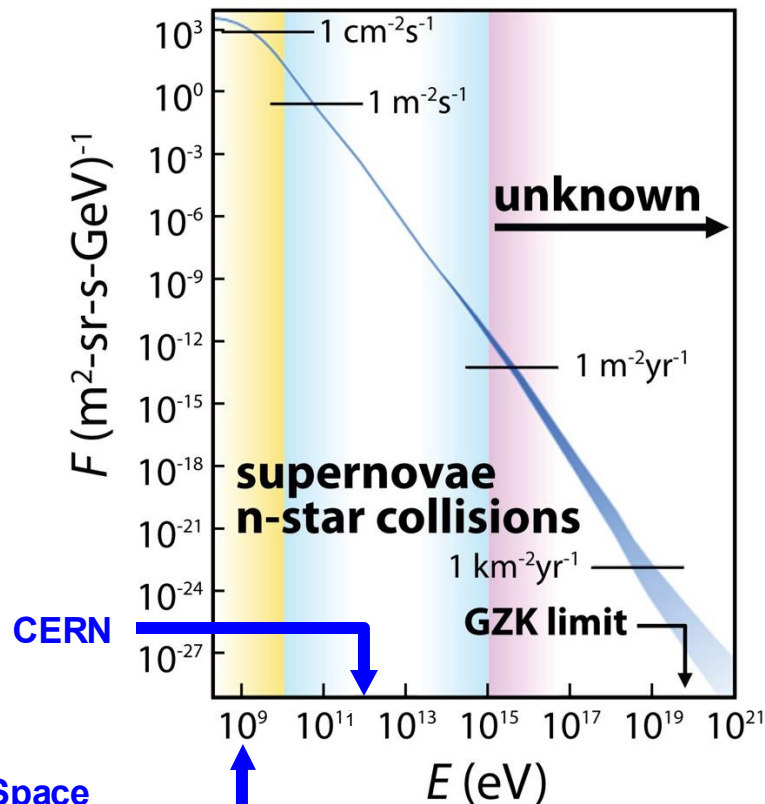- ~~Summary~~

Kepler's 1604 Supernova Remnant

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

Galactic Cosmic Rays

- **Composed of all naturally occurring elements**
  - **90% hydrogen**
  - **9% helium**
  - **1% heavier ions**
- **For GCR energies < 10^{15} electronvolt (eV):**
  - **Mainly attributed to supernovae within Milky Way galaxy and neutron star collisions**
  - **Most significant for effects on electronics**
- **For GCR energies > 10^{15} eV:**
  - **Unknown origin, especially highest energies**
- **High energy ≠ bad**
  - **Energy loss by a particle in material is key metric not amount of energy**

Ground Simulators

1 cm^{-2}s^{-1}
1 m^{-2}s^{-1}

unknown

F (m^2-sr-s-GeV)$^{-1}$

1 m^{-2}yr^{-1}

supernovae
n-star collisions

1 km^{-2}yr^{-1}

GZK limit

CERN

NASA Space Radiation Lab

E (eV)
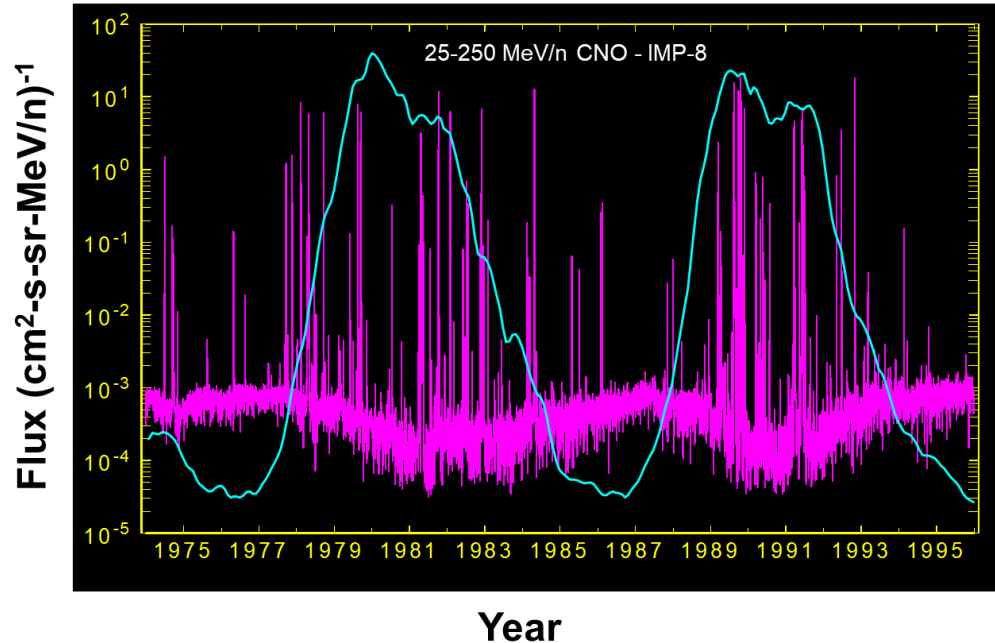
Data from S. Swordy, Space Sci. Rev., Oct. 2001

Solar Cycle Dependence

- **Solar Maximum**
  - **Background (includes solar wind + GCRs) levels lower**
- **Solar Minimum**
  - **Background (includes solar wind + GCRs) levels higher**

25-250 MeV/n CNO - IMP-8

Flux (cm²-s-sr-MeV/n)⁻¹ vs Year

J.L. Barth, 1997 NSREC Short Course

Sun modulates GCRs entering the solar system

Models

- **Two popular models are used for SEE that parameterize solar modulation using sunspot numbers**

- **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**

- **Badhwar – O'Neill 2020 Model**
 - **Incorporates broader and more recent data base**
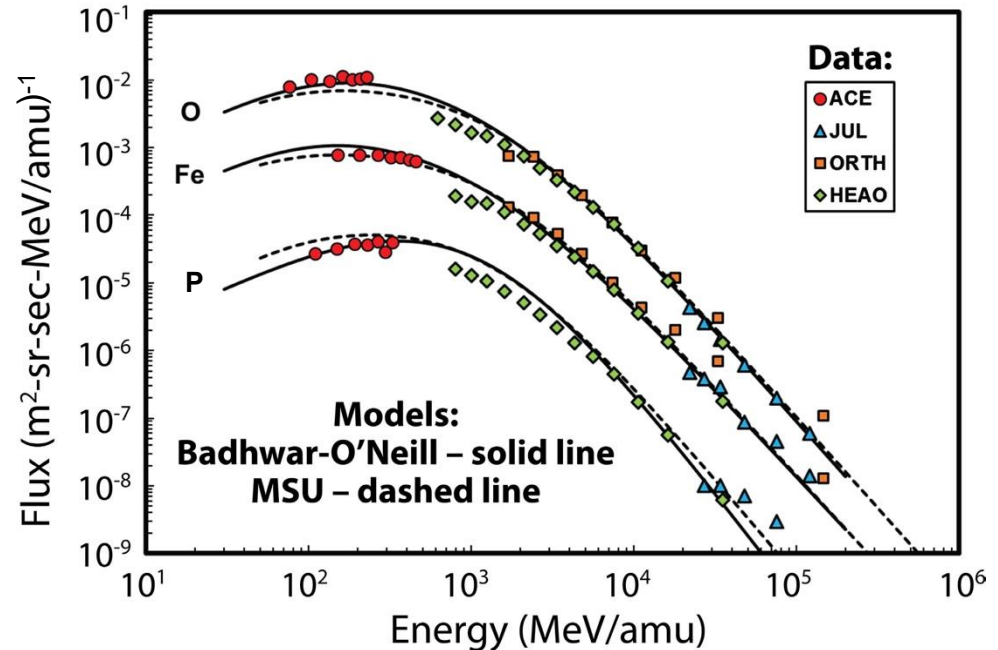
P.M. O'Neill, S. Golge and T.C. Slaba, NASA Tech. Paper, March 2015

Section Topics/Outline

- What are the sources of the natural space radiation environment?
- **What role does the Sun play on these environments?**
  - **Quiet Environments (Trapped Radiation)**
- Why do environments matter?
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Inner Van Allen Belt
(protons & electrons)

Outer Van Allen Belt
(mostly electrons)
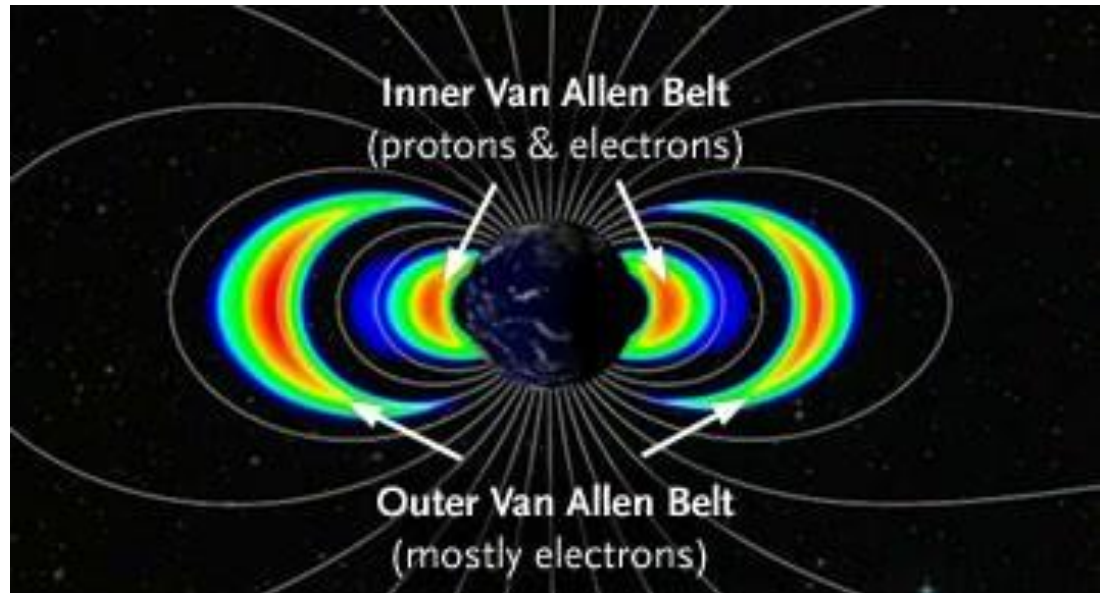
Earth's Internal Magnetic Field

- **The Earth has both internal and external magnetic fields that make up its magnetosphere**
- **Internal 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**
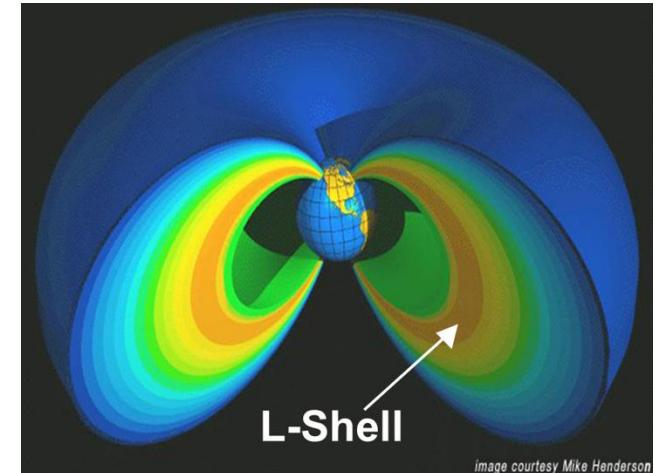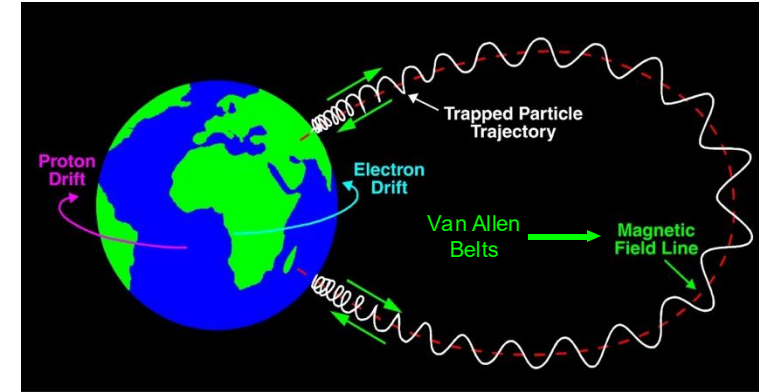- **Trapped particle populations conveniently mapped in dipole coordinate systems**
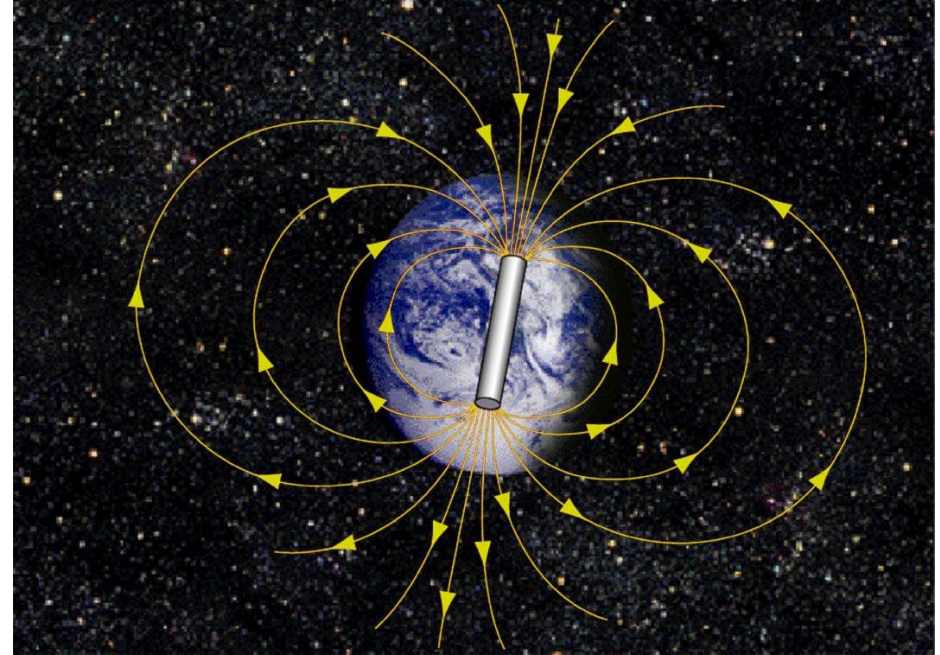
The internal magnetic field of the Earth is approximately a dipole field, which can trap both protons and electrons

# Trapped Charged Particle Motion and L-Shells

- **Protons and electrons trapped in these magnetic field lines drift around the Earth and spiral along these field lines**
  - **A complete azimuthal rotation of particle is called a drift shell or L-shell**
- **L-shell parameter indicates magnetic equatorial distance from Earth's center in number of Earth radii (6371 km) and represents the entire drift shell**

image courtesy Mike Henderson

Charged Particle Distribution

- **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*
- **Each L-shell has a unique environment that must be accounted for in the design of a system**


Earth Radii (R_E) = 6371 km
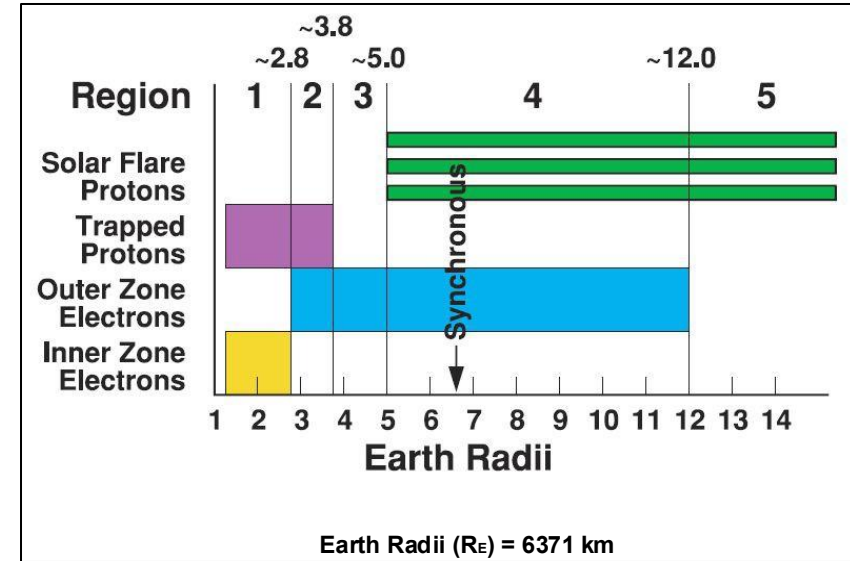
Charged particle distribution in the magnetosphere as a function of Earth radii. This figure was adapted by J. R. Schwank and colleagues after the original

Solar Cycle Dependence

- **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**
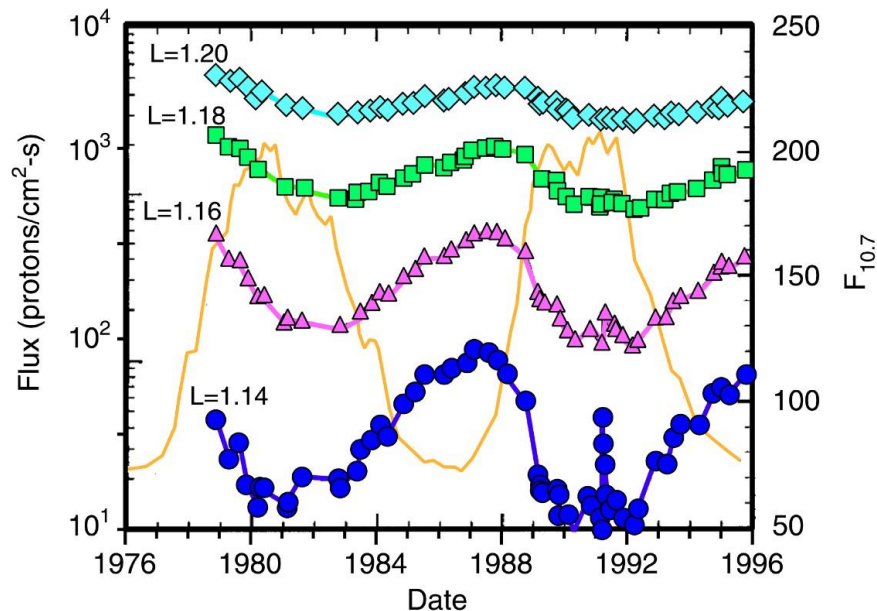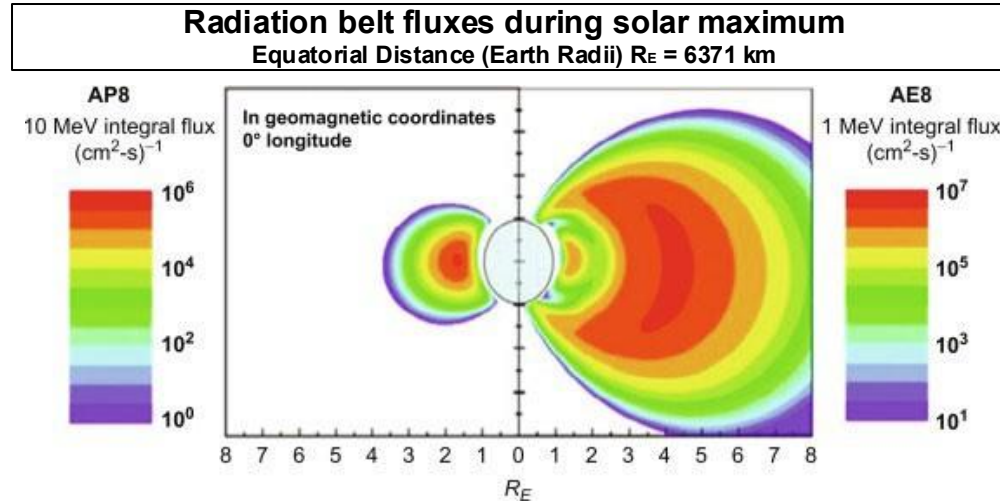

S.L. Huston and K.A. Pfitzer, IEEE TNS, Dec. 1998

Trapped Proton and Electron Properties

Protons

- **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**
- **Nuclear reaction products from incident protons can have LET values up to 20 MeV-cm2/mg.**

Radiation belt fluxes during solar maximum
Equatorial Distance (Earth Radii) R_E = 6371 km

Electrons

- **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**
- **Nuclear reaction products from incident protons can have LET values up to 20 MeV-cm2/mg.**

Trapped Proton Properties
- South Atlantic Anomaly -
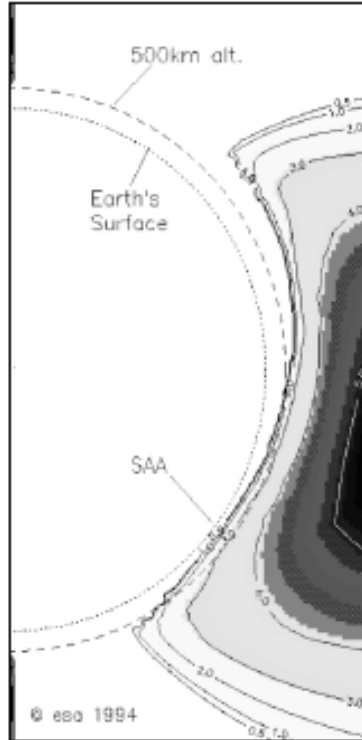
- **Phenomenon caused by tilt and shift of geomagnetic axis relative to rotational axis**

- **Inner edge of proton belt is at lower altitudes in vicinity of South America**

- **Generally dominates the radiation environment for altitudes less than about 1000 km**
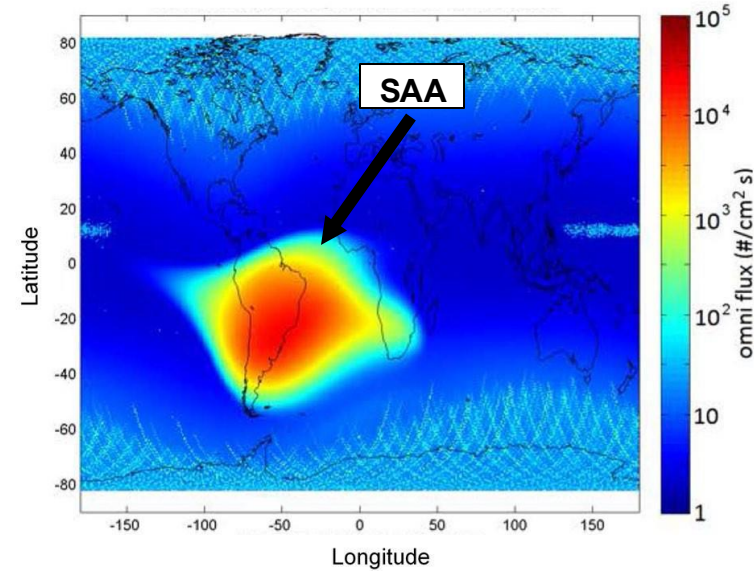
W.R. Johnston et al., IEEE TNS, Dec. 2015

Trapped Proton and Electron Models

Modeling Tool

SPENVIS
The Space Environment Information System

- **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**

Trapped Environment Models

- **AP8/AE8**
  - **Static model for mean environment**
  - **Based on data from 1960s and 1970s**
  - **Approximate solar cycle dependence**
    - **Solar maximum**
    - **Solar minimum**
- **AP9/AE9/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 – present**
    - **~10x that of AP8 based on instrument years**
  - **Output averaged over solar cycle**

Module Topics

- What are the sources of the natural space radiation environment?
- What role does the Sun play on these environments?
  - Active Environments
  - Quiet Environments
- **Why do environments matter?**
- Summary

Why do environments matter?

Products
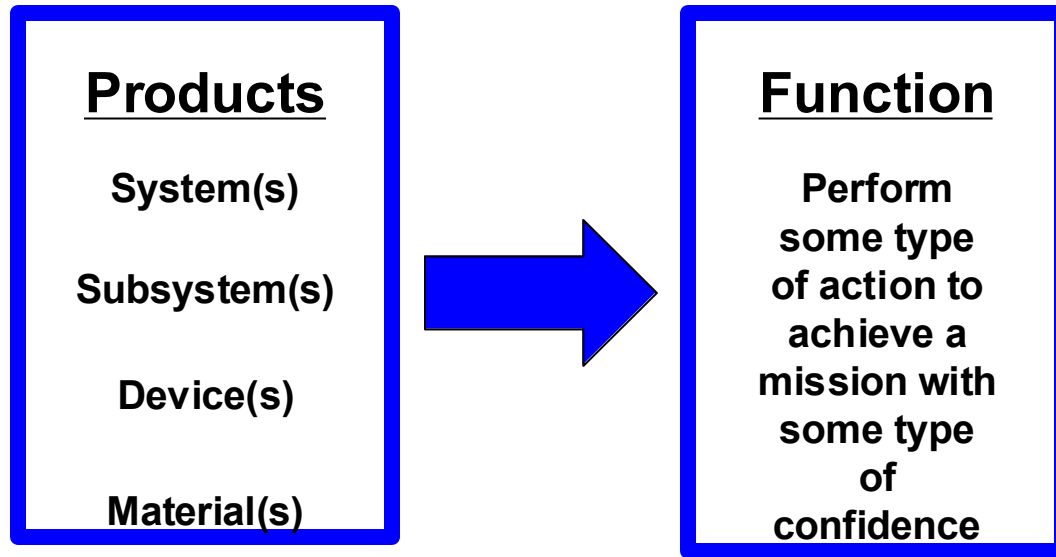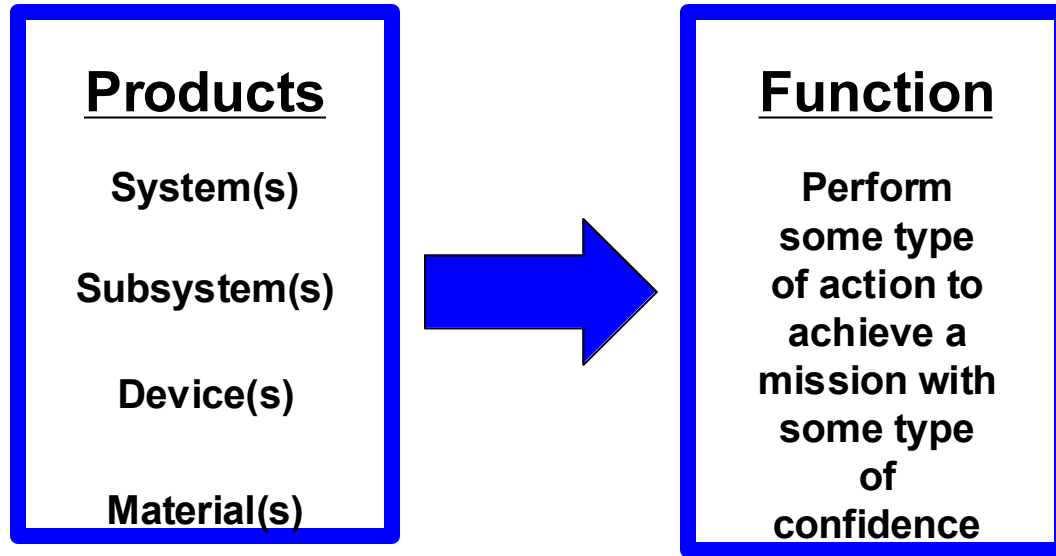
System(s)

Subsystem(s)

Device(s)

Material(s)

Why do environments matter?

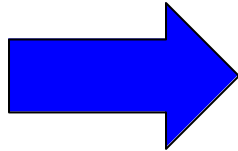# Why do environments matter?

Environments

Products

System(s)

Subsystem(s)

Device(s)

Material(s)

Function

Perform some type of action to achieve a mission with some type of confidence

A products mission (and its criticality) determines environments of interest

Why do environments matter?

Environments

Products

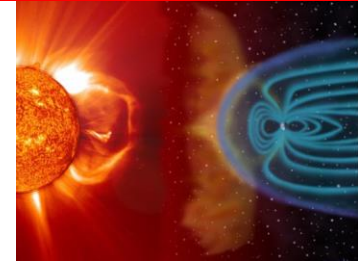System(s)

Subsystem(s)

Device(s)

Material(s)

Function

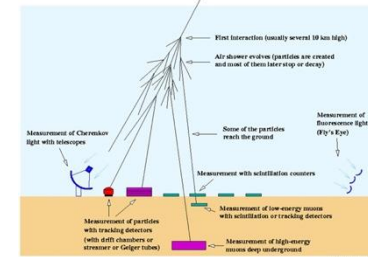Perform some type of action to achieve a mission with some type of confidence

Exoatmospheric

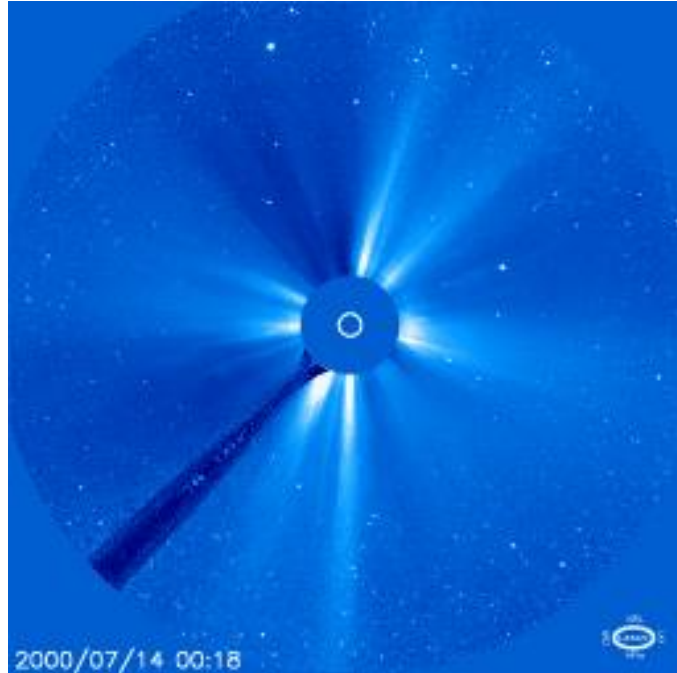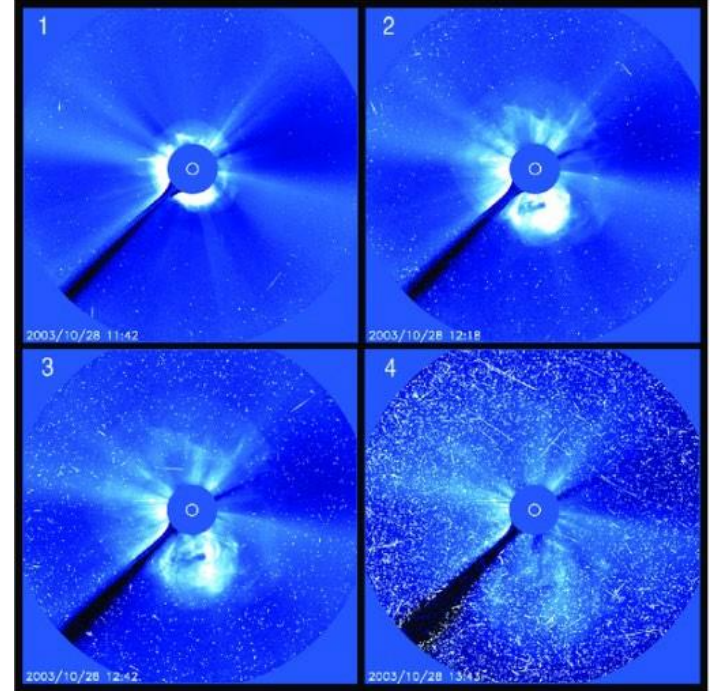**~100 km**

Endoatmospheric

Why do environments matter?

SOHO/LASCO imager during Jul 14, 2000 solar particle event

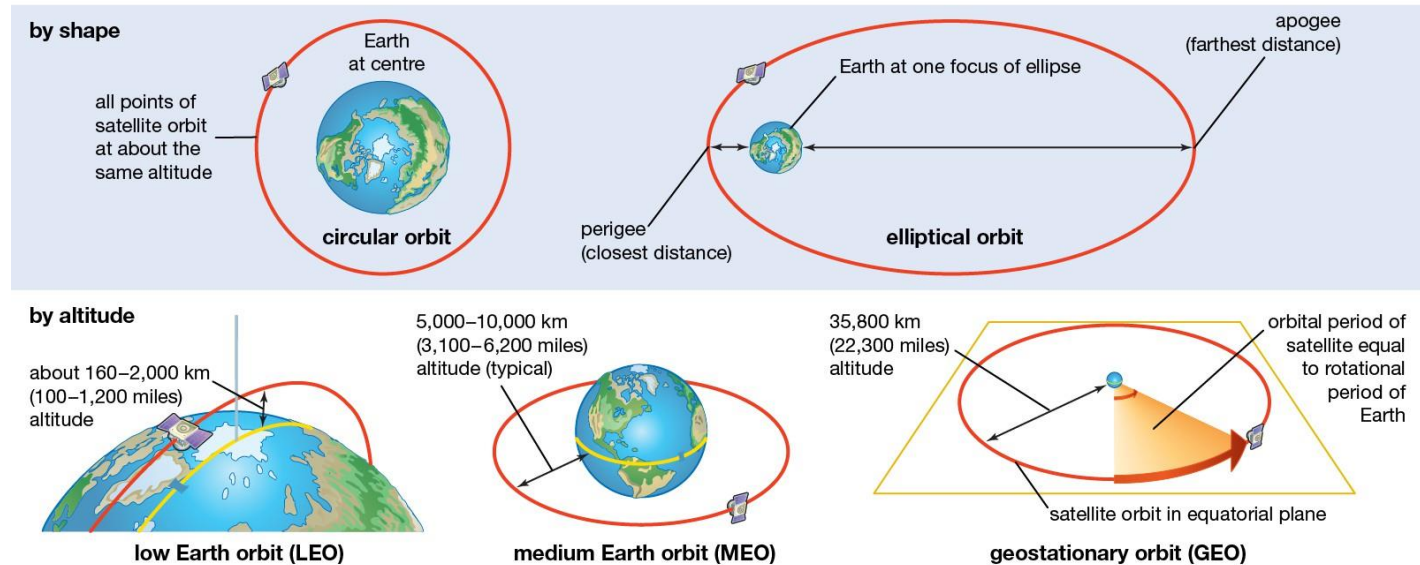**SOHO/LASCO imager during Oct 28, 2003 solar particle event**

[Credit: ESA/NASA/NRL]

Environments -> produce effects -> can cause malfunctions -> impact mission success?

Module Topics

- What are the sources of the natural space radiation environment?
- What role does the Sun play on these environments?
- **Why do environments matter?**
 - **Environmental impacts on common orbit regimes**
- Summary

by shape

all points of satellite orbit at about the same altitude

Earth at centre

circular orbit

Earth at one focus of ellipse

apogee (farthest distance)

perigee (closest distance)

elliptical orbit

by altitude

about 160–2,000 km (100–1,200 miles) altitude

low Earth orbit (LEO)

5,000–10,000 km (3,100–6,200 miles) altitude (typical)

medium Earth orbit (MEO)

35,800 km (22,300 miles) altitude

orbital period of satellite equal to rotational period of Earth

satellite orbit in equatorial plane

geostationary orbit (GEO)

© Encyclopædia Britannica, Inc.

Effect of the Environment on Mission
- Low Earth Orbit (LEO) -

Env	Levels		Orbits	
	Solar Max	Solar Min	LEO (Low Inc)	LEO (Polar)
Trapped Electron	Higher	Lower	Moderate	Moderate
Trapped Protons	Lower	Higher	Yes	Yes
Solar Particle	More Frequent	Less Frequent	No	Yes
GCRs	Lower	Higher	Moderate	Yes
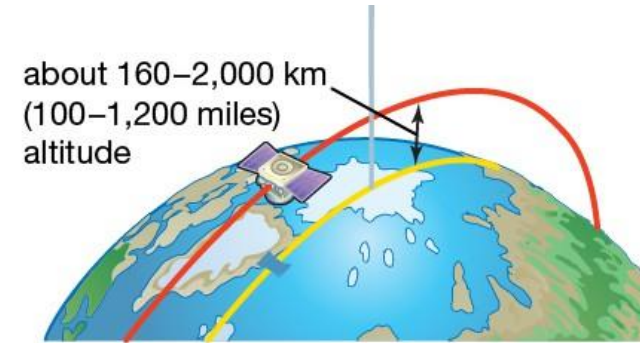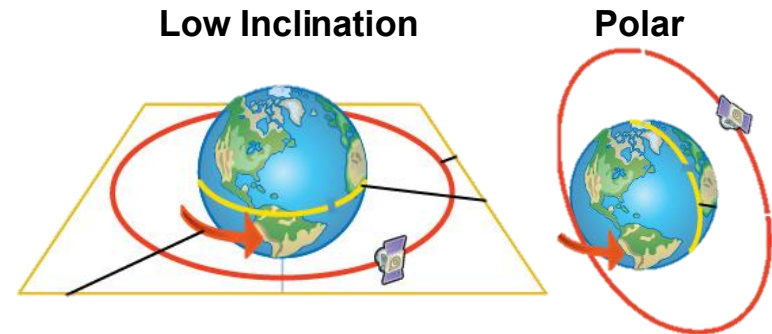
about 160–2,000 km (100–1,200 miles) altitude
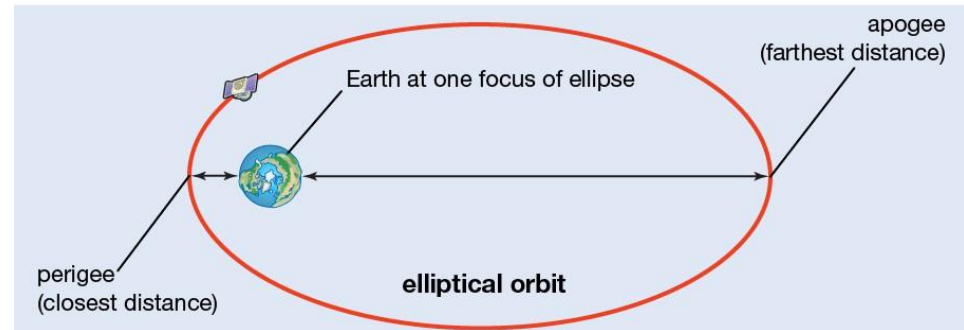
low Earth orbit (LEO)

Low Inclination

Polar

Modeling and simulation is required to specify the environments

Effect of the Environment on Mission
- Medium Earth Orbit (MEO) -

Env	Levels		Orbits
	Solar Max	Solar Min	MEO
Trapped Electron	Higher	Lower	Severe
Trapped Protons	Lower	Higher	Severe
Solar Particle	More Frequent	Less Frequent	Yes
GCRs	Lower	Higher	Yes

5,000–10,000 km
(3,100–6,200 miles)
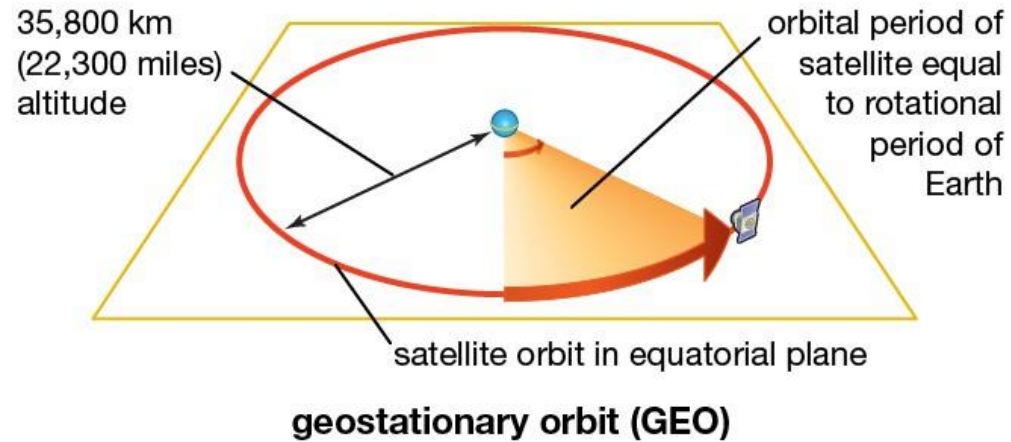altitude (typical)

medium Earth orbit (MEO)

Modeling and simulation is required to specify the environments

Effect of the Environment on Mission
- Highly Elliptical Orbit (HEO) -

Env	Levels		Orbits
	Solar Max	Solar Min	HEO
Trapped Electron	Higher	Lower	Yes
Trapped Protons	Lower	Higher	Yes
Solar Particle	More Frequent	Less Frequent	Yes
GCRs	Lower	Higher	Yes

**Modeling and simulation is required to specify the environments**

Effect of the Environment on Mission
- Geosynchronous Orbit (GEO) -

Env	Levels		Orbits
	Solar Max	Solar Min	GEO
Trapped Electron	Higher	Lower	Severe
Trapped Protons	Lower	Higher	No
Solar Particle	More Frequent	Less Frequent	Yes
GCRs	Lower	Higher	Yes

35,800 km (22,300 miles) altitude

orbital period of satellite equal to rotational period of Earth

satellite orbit in equatorial plane

geostationary orbit (GEO)

Modeling and simulation is required to specify the environments

Module Topics

- What are the sources of the natural space radiation environment?
- What role does the Sun play on these environments?
- Why do environments matter?
- **Summary**
  - **Environment Sources**
  - **Effect of the Sun on the Environments**
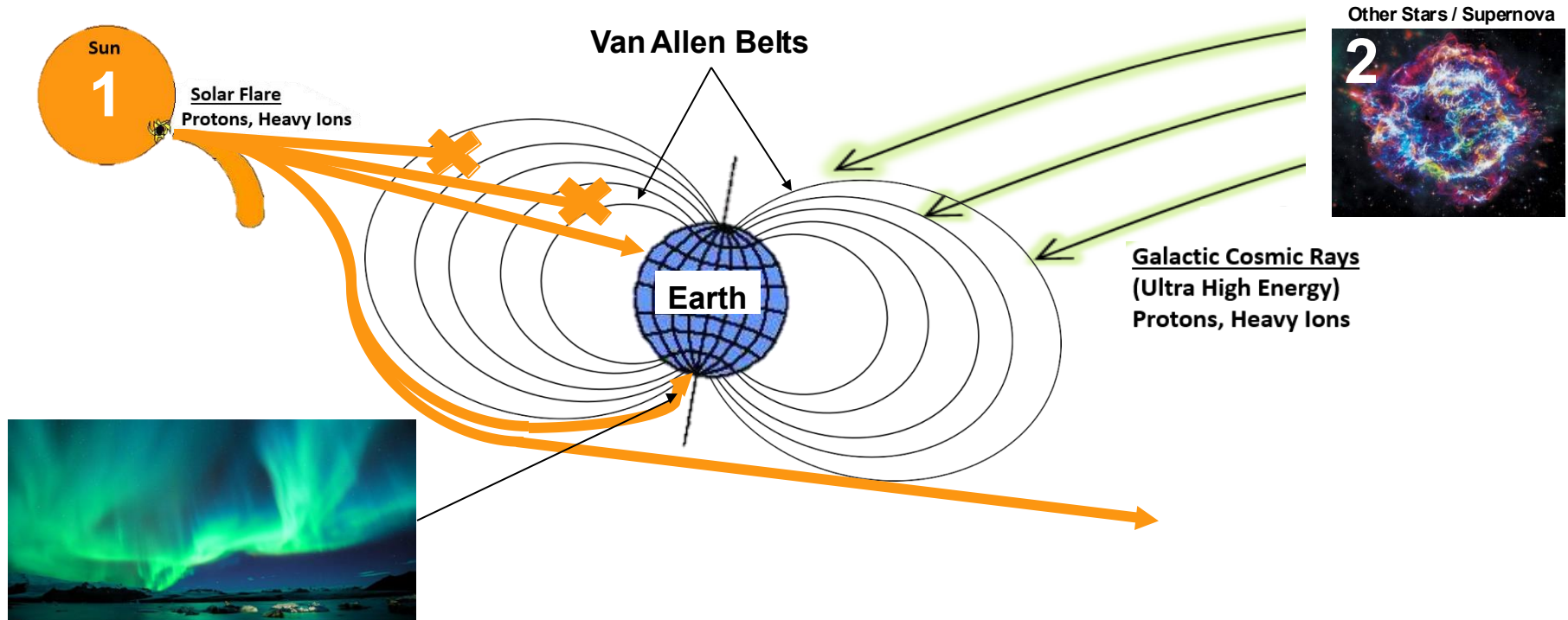 - **Effect of the Environment on Missions**

Summary
- Sources of Radiation Near Earth -
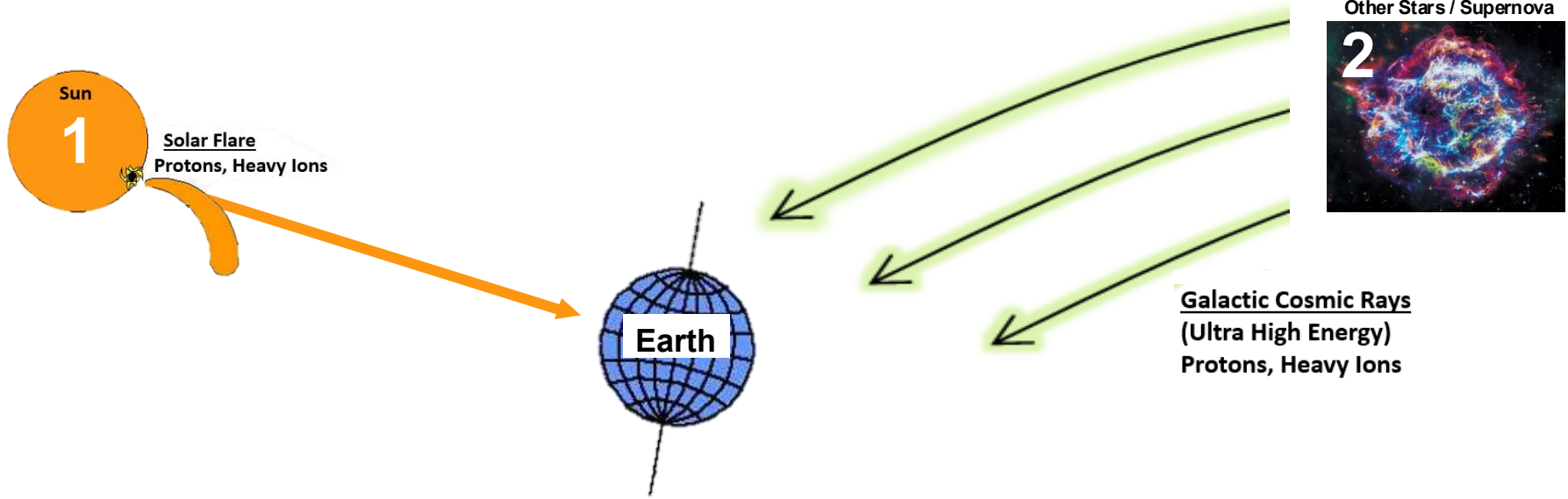
Radiation comes from the Sun and/or other stars/supernova in the galaxy

Summary
- Sources of Radiation Near Earth -

Sun 1

Solar Flare
Protons, Heavy Ions

Van Allen Belts

Other Stars / Supernova

2

Earth

Galactic Cosmic Rays
(Ultra High Energy)
Protons, Heavy Ions

Earth is surrounded by a magnetic field called the Van Allen Belts that trap some radiation from the Sun and/or other stars

Summary
- Sources of Radiation Near Earth -

3 Trapped Radiation

Radiation Belts

South Atlantic Anomaly (SAA)
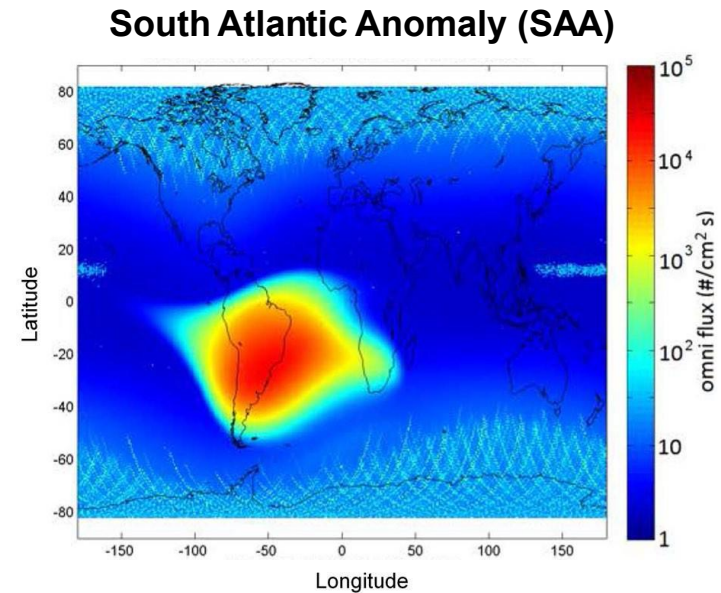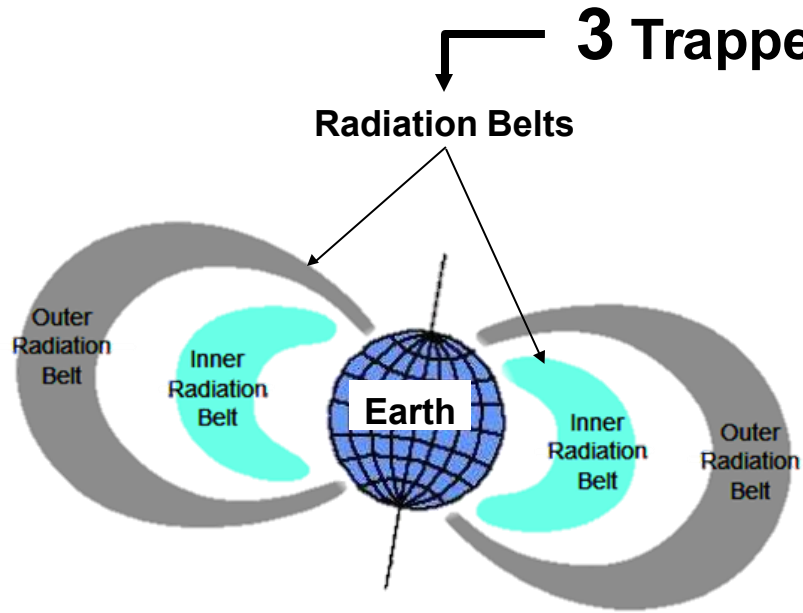
Trapped radiation comes in two forms: radiation trapped by the Van Allen Belts and the South Atlantic Anomaly
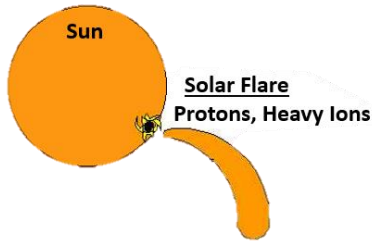
Summary
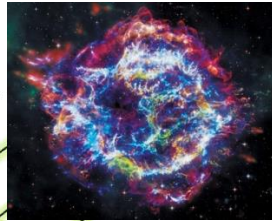# - Effect of the Sun on Environment -

Episodic or "Active" Environment
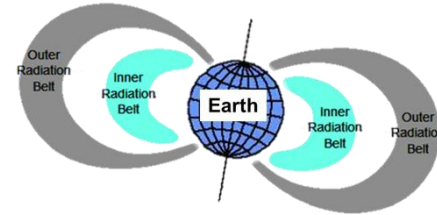
1 **Solar Energetic Particles (SEPs)**

Continuous or "Quiet Time" Environment

Trapped Radiation

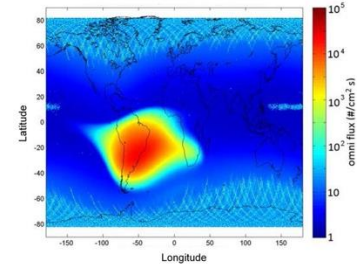**2** **Galactic Cosmic Rays (GCRs)**

Other Stars / Supernova

3 **Radiation Belts**

4 **South Atlantic Anomaly (SAA)**

The space environment is dynamic due to the solar cycle which determines environments that are most prominent around Earth

Summary
- Effect of the Environment on Mission -

Env	Levels		Orbits				
	Solar Max	Solar Min	LEO (Low Inc)	LEO (Polar)	MEO	HEO	GEO
Trapped Electron	Higher	Lower	Moderate	Moderate	Severe	Yes	Severe
Trapped Protons	Lower	Higher	Yes	Yes	Severe	Yes	No
Solar Particle	More Frequent	Less Frequent	No	Yes	Yes	Yes	Yes
GCRs	Lower	Higher	Moderate	Yes	Yes	Yes	Yes

Questions?

Modeling and simulation is required to understand HOW, not IF, the natural space environment will affect your system.

Why do environments matter?
- Historical Examples -

[Credit: T. Malik, July 20, 2022 The Worst Solar Storms in History]

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