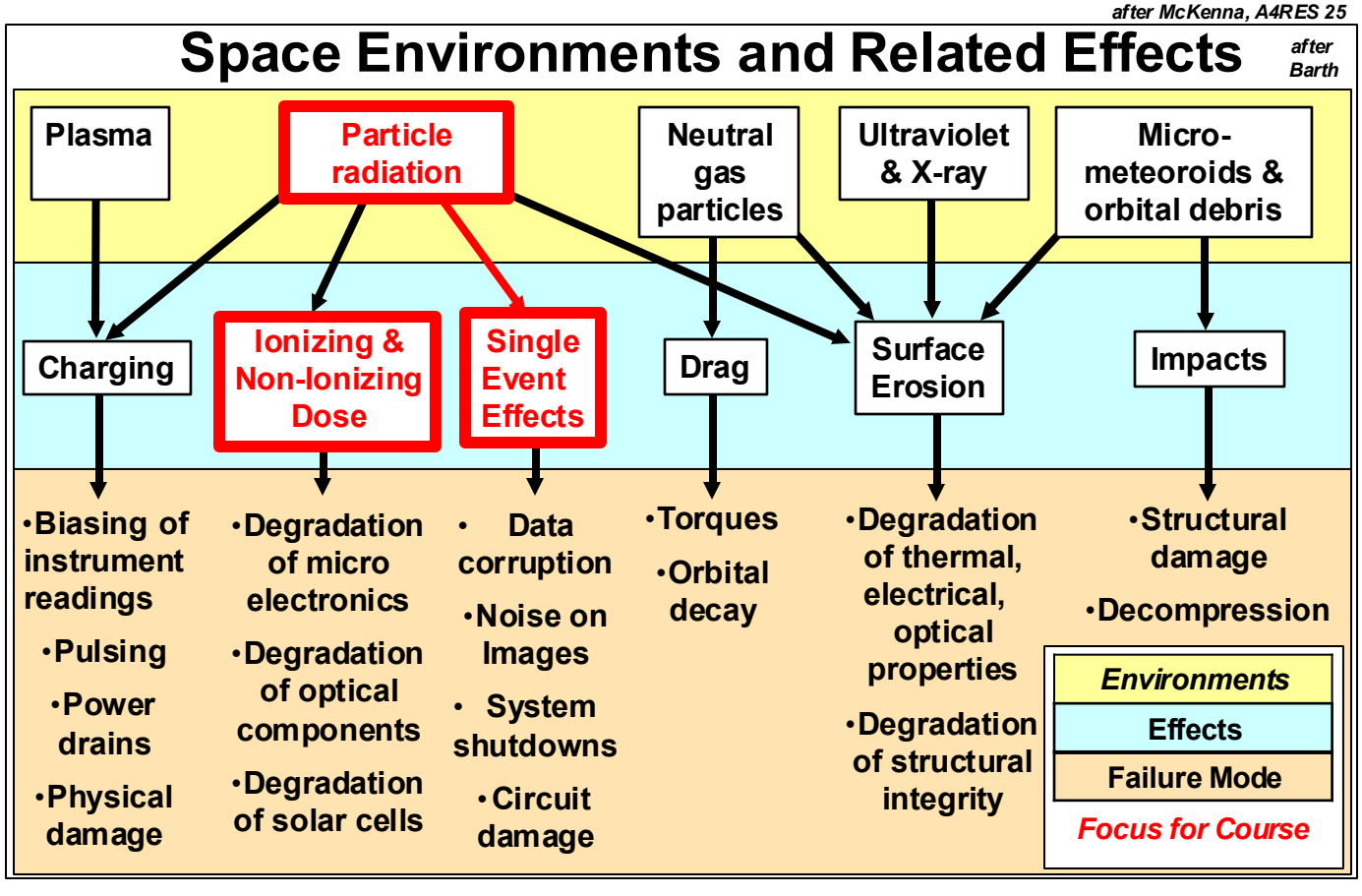
02 – The Natural Space Radiation Environment

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)



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

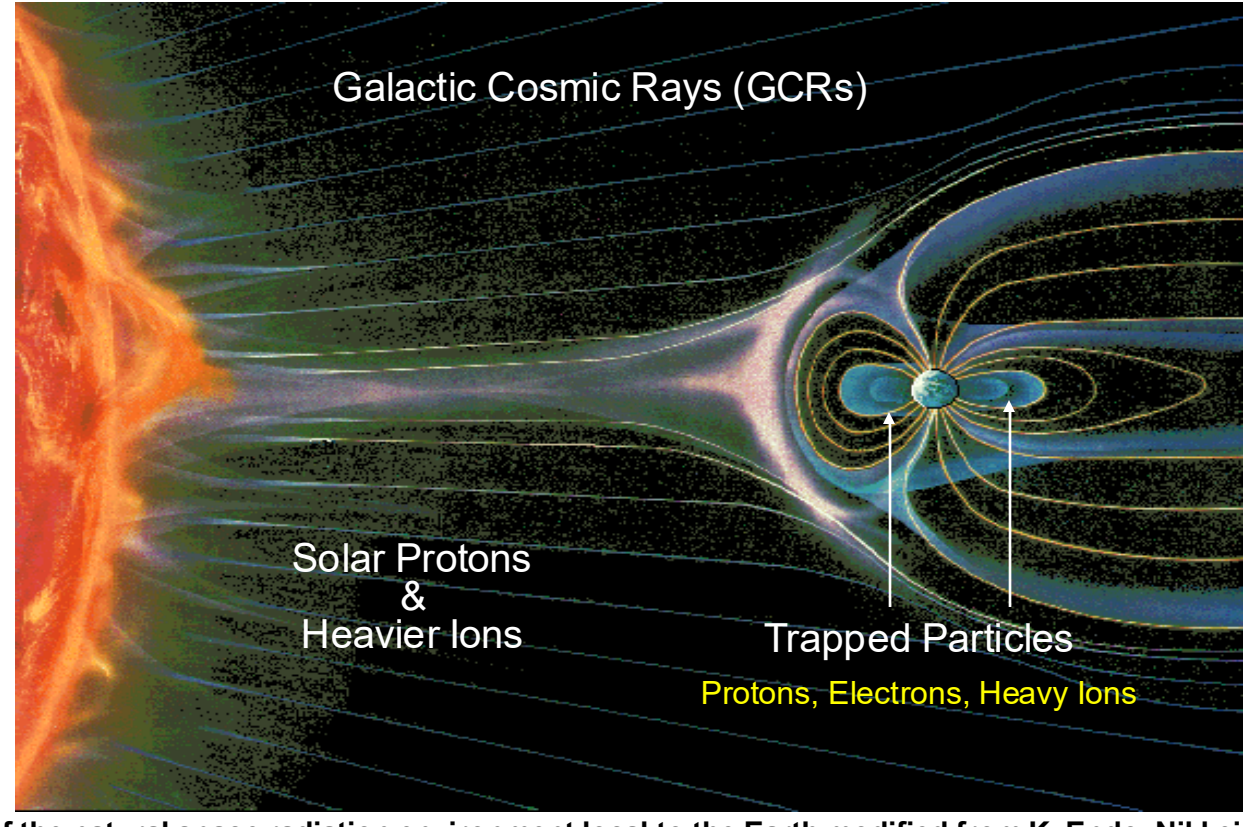
Section Topics/Outline

- 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

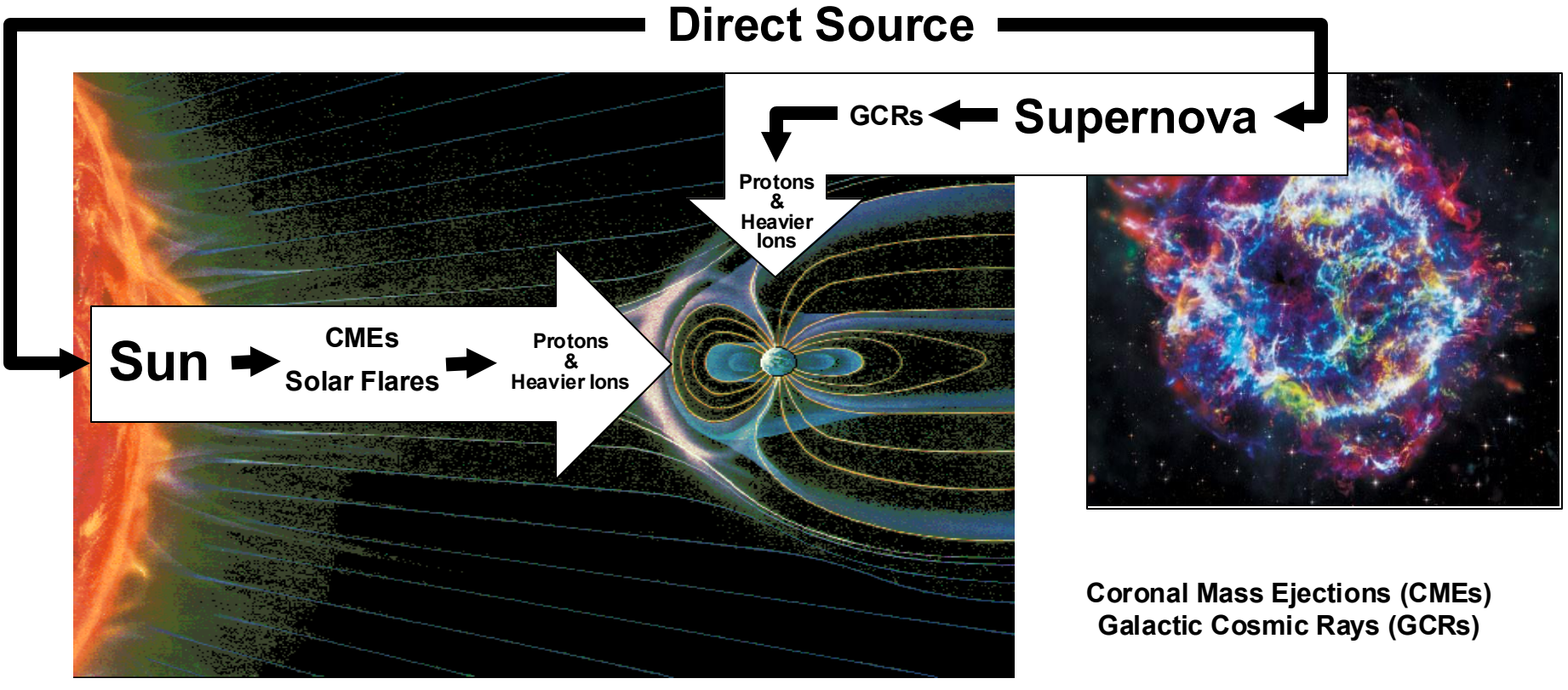
- What are the sources of the natural space radiation environment?
  - Direct Sources (Solar Particles, Galactic Cosmic Rays)
  - Indirect Sources (Trapped Radiation)
- What role does the Sun play on these environments?
- Why do environments matter?
- Summary

The Natural Space Radiation Environment



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



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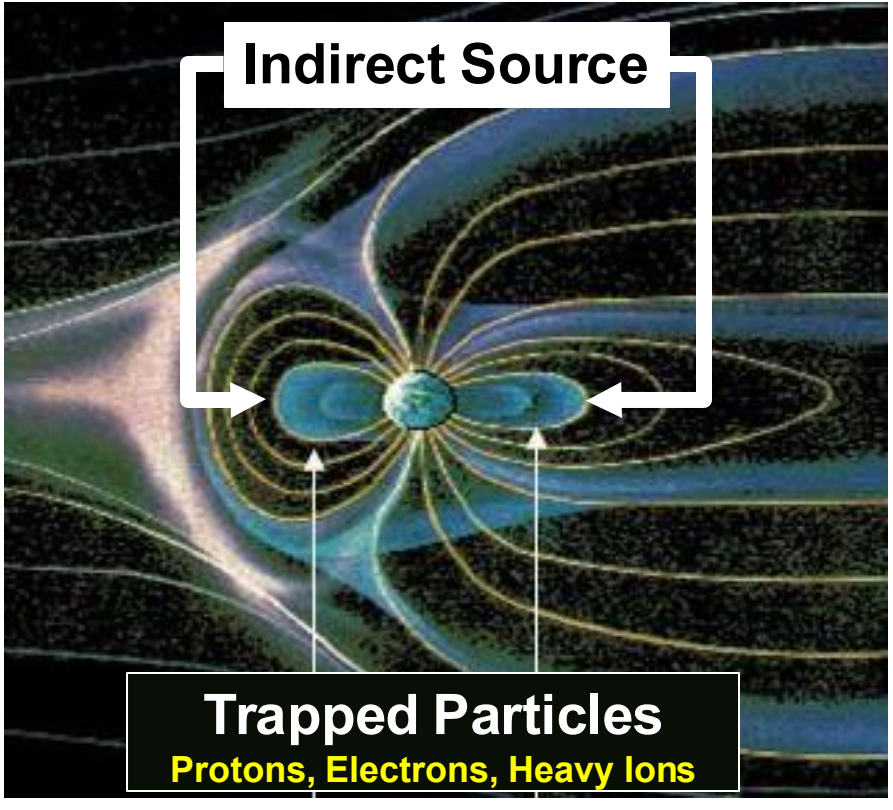
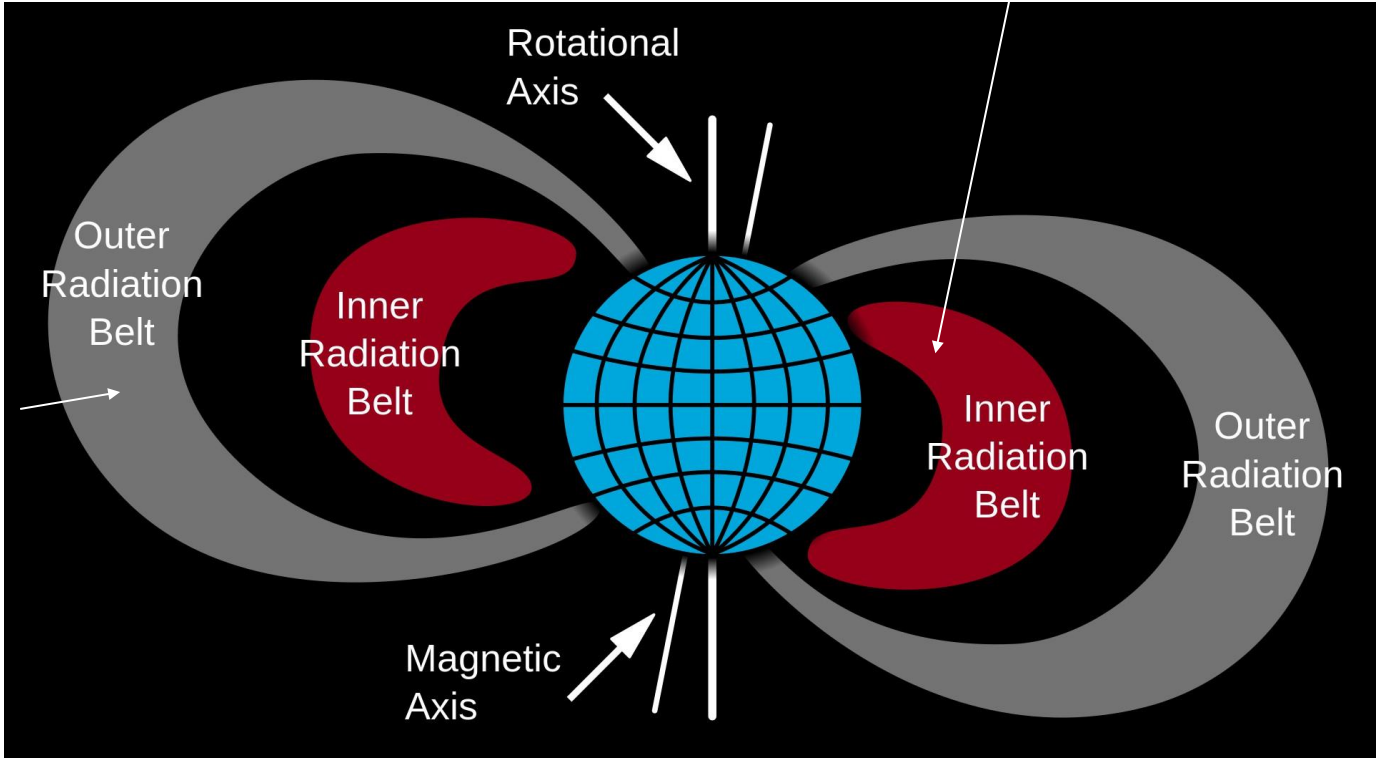


Depiction of the natural space radiation environment local to the Earth modified from K. Endo, Nikkei Science Inc. of Japan and J. L. Barth

Radiation Belts

Trapped

Energetic Protons
Very stable over time

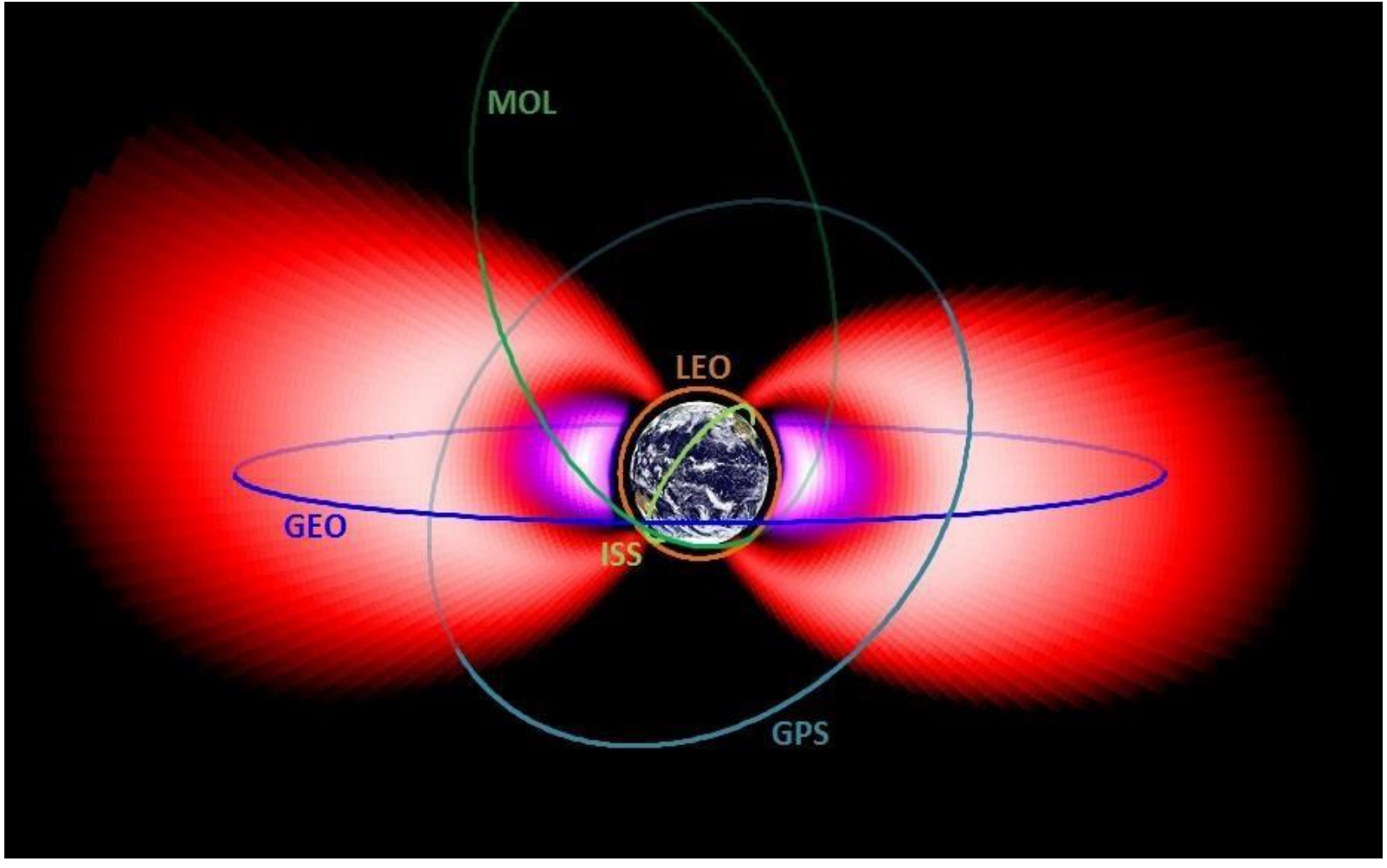


Energetic Electrons
Dynamic: varies on weekly/monthly timescales

Courtesy Wikipedia

Different Orbits will sample different parts of the trapped environment

Radiation Belts

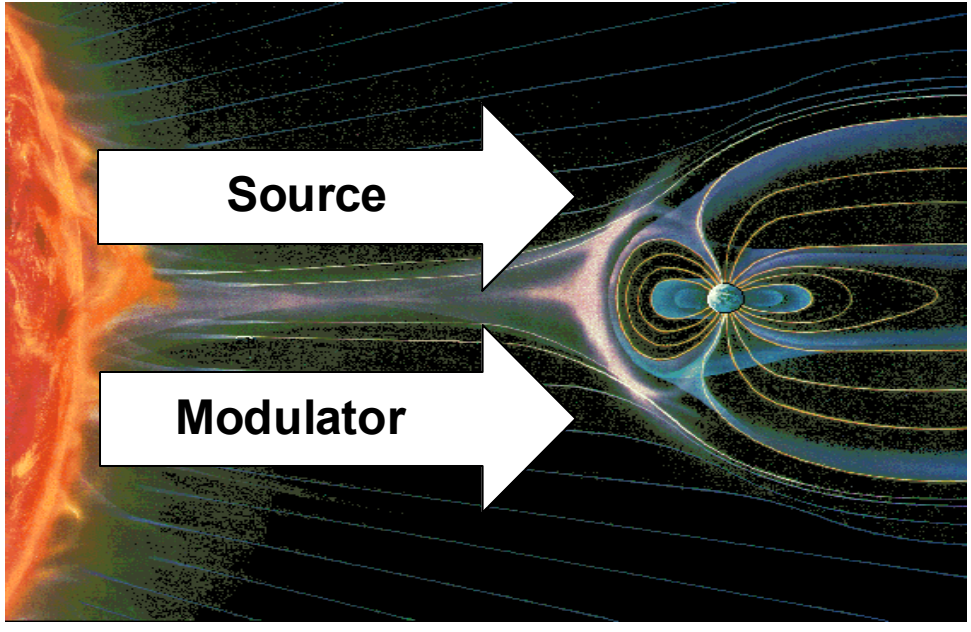


Section Topics/Outline

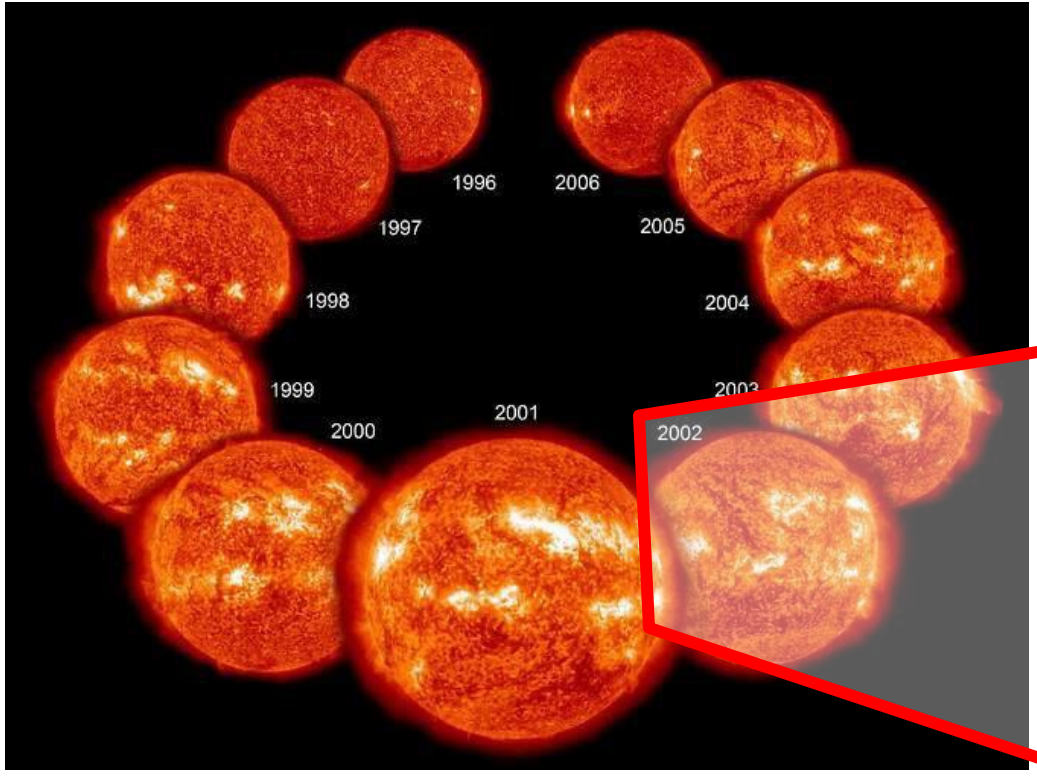
- What are the sources of the natural space radiation environment?
- What role does the Sun play on these environments?
  - Source vs. Modulator
  - Sunspots
  - Solar Cycle
- Why do environments matter?
- Summary

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

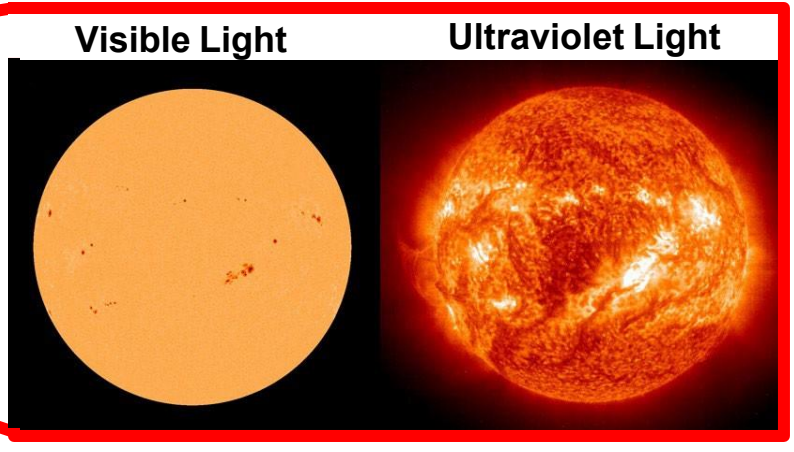


The Sun and It's Effect on the Natural Space Environment



Credit: NASA

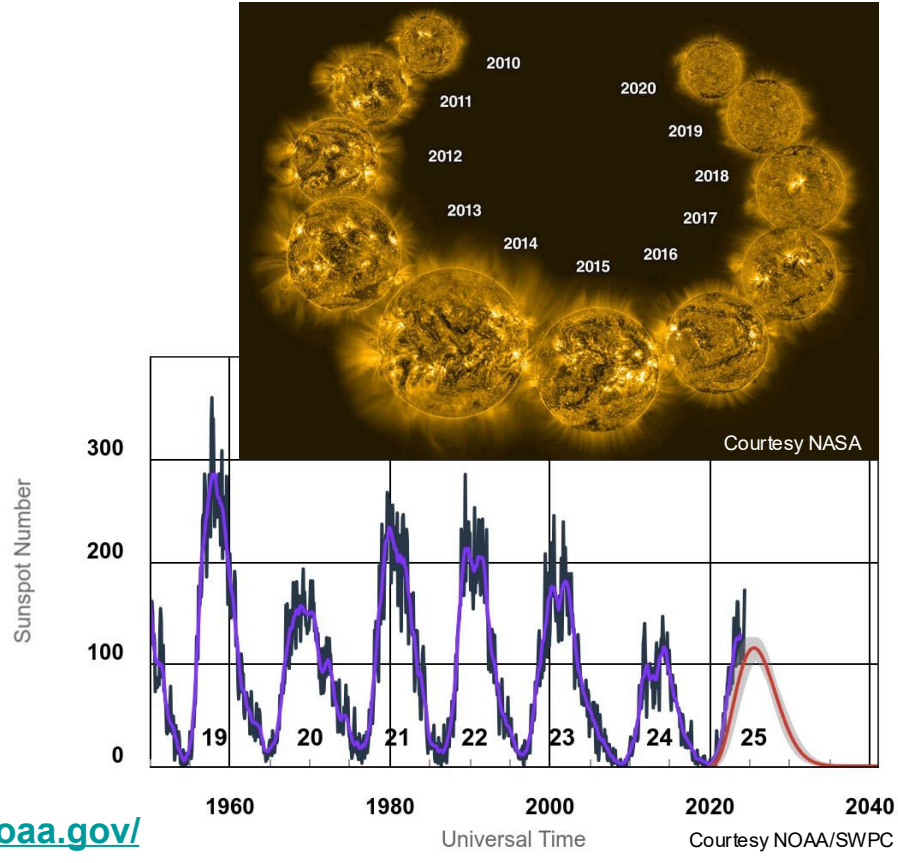
- Sun is very active
  - Sunspots are viewed as a proxy to solar activity
- Region is cooler and appears darker when viewed in visible light



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



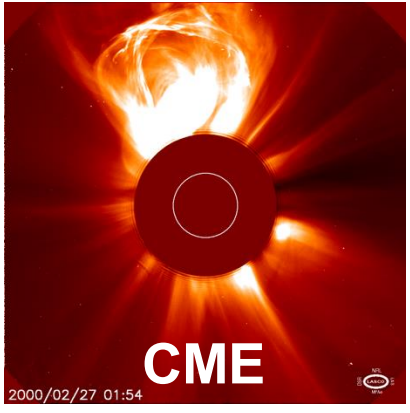
https://www.swpc.noaa.gov/

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



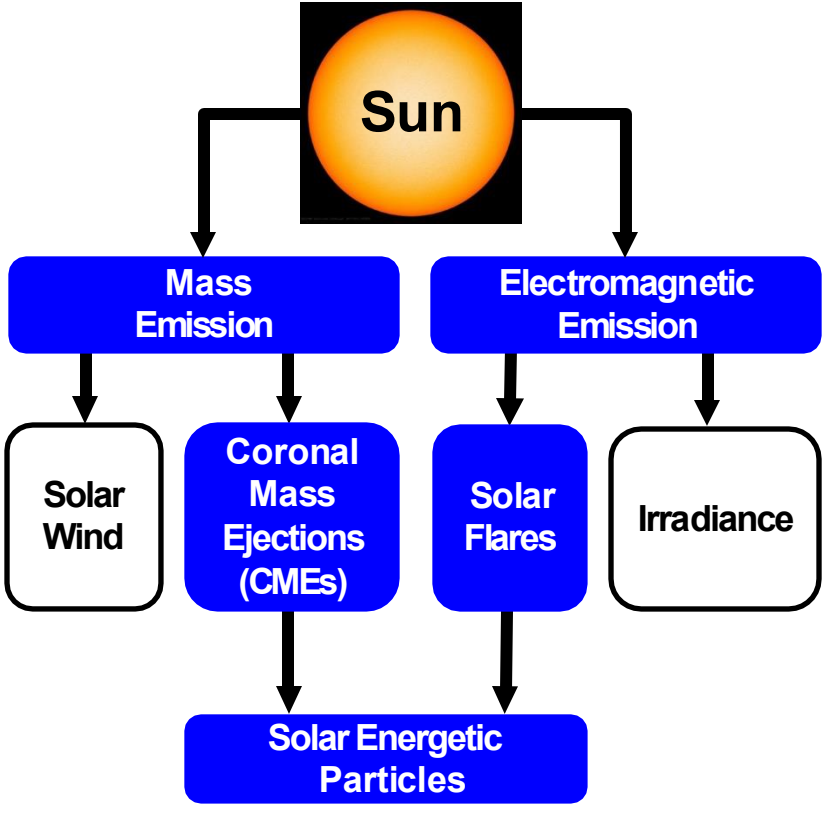
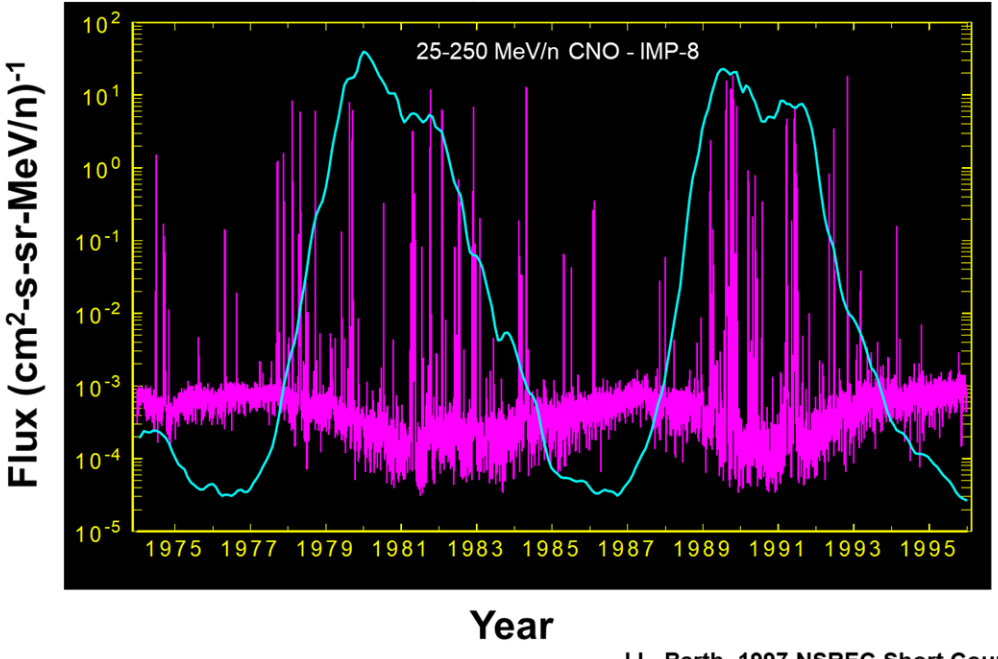


Image credits: NASA and ESA (SOHO and SDO)

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

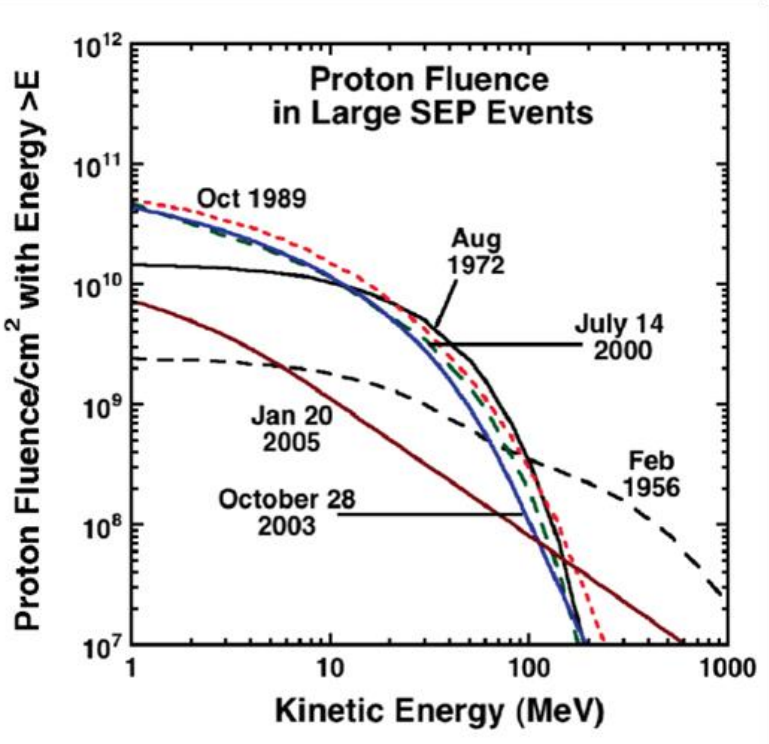


J.L. Barth, 1997 NSREC Short Course

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

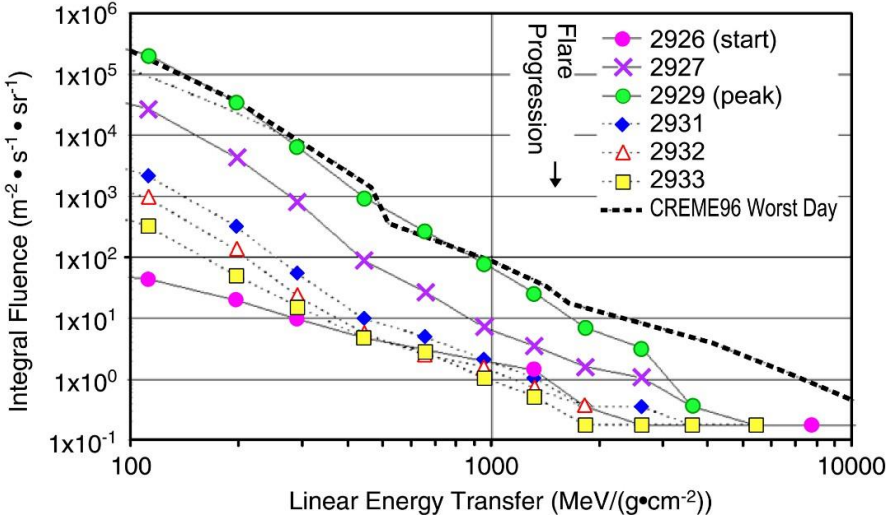


R.A Mewaldt et al., Radiat. Risks., 2007

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

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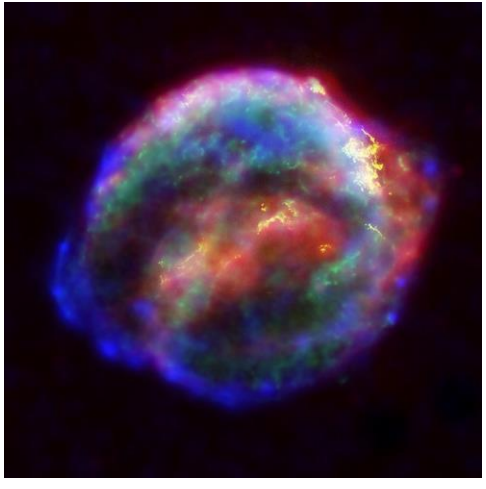
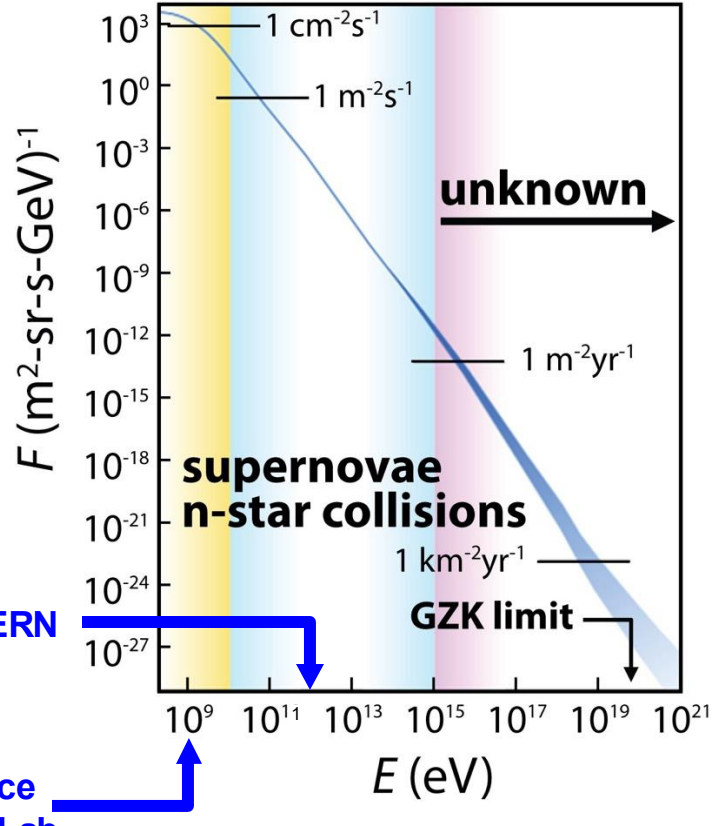
Kepler's 1604 Supernova Remnant



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

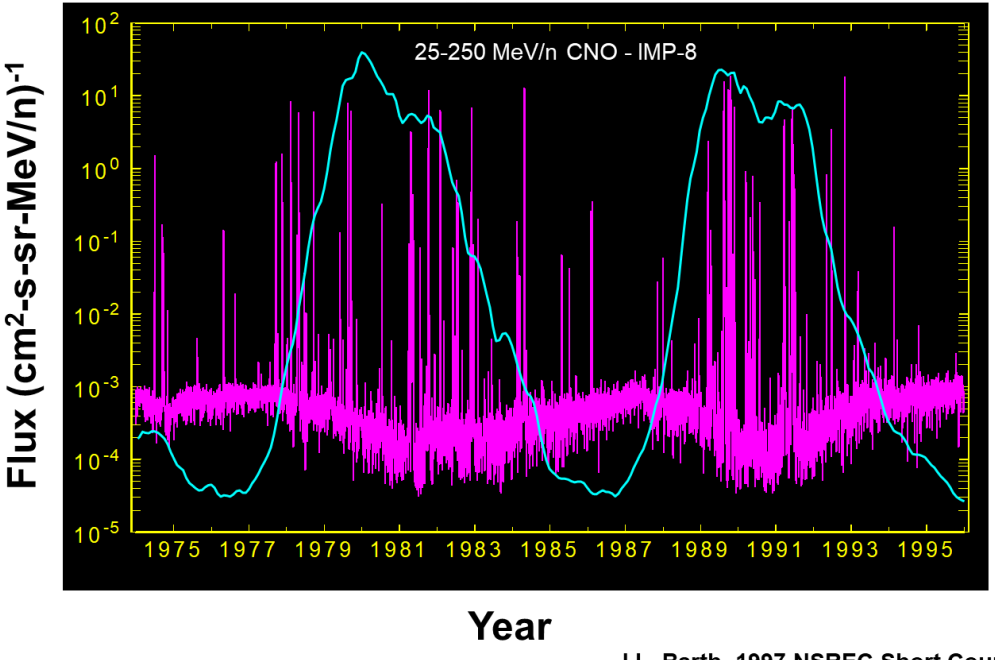


Data from S. Swordy, Space Sci. Rev., Oct. 2001

Ground Simulators

Solar Cycle Dependence

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

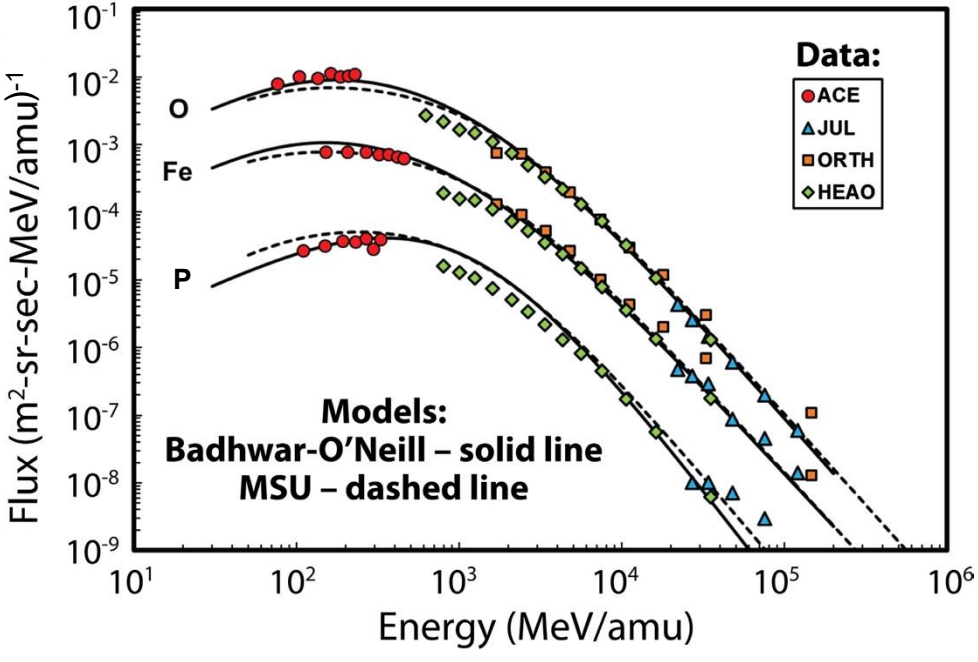


J.L. Barth, 1997 NSREC Short Course

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

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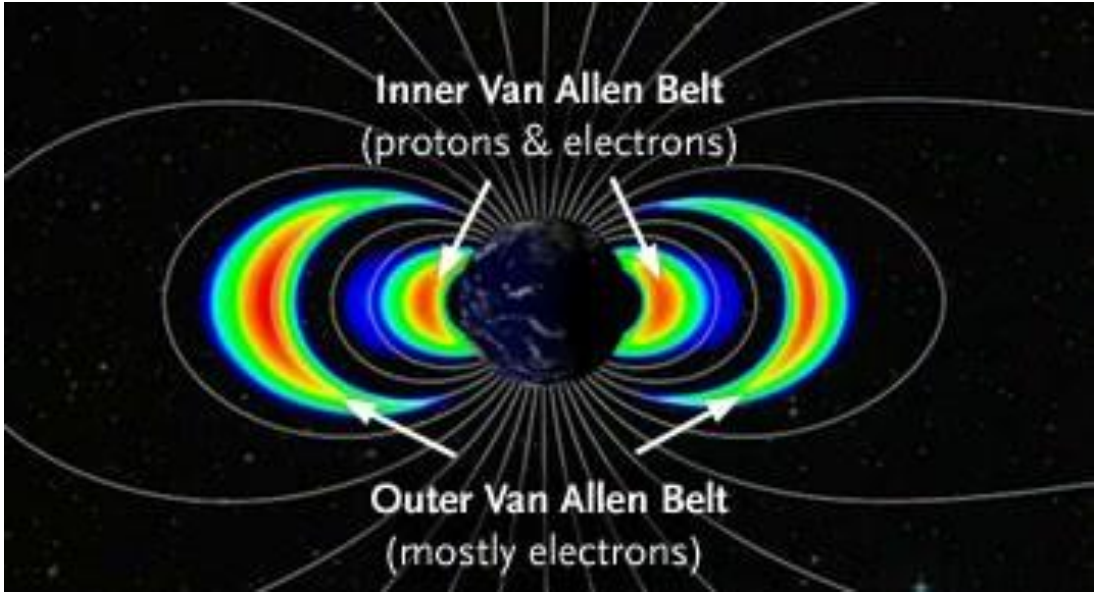
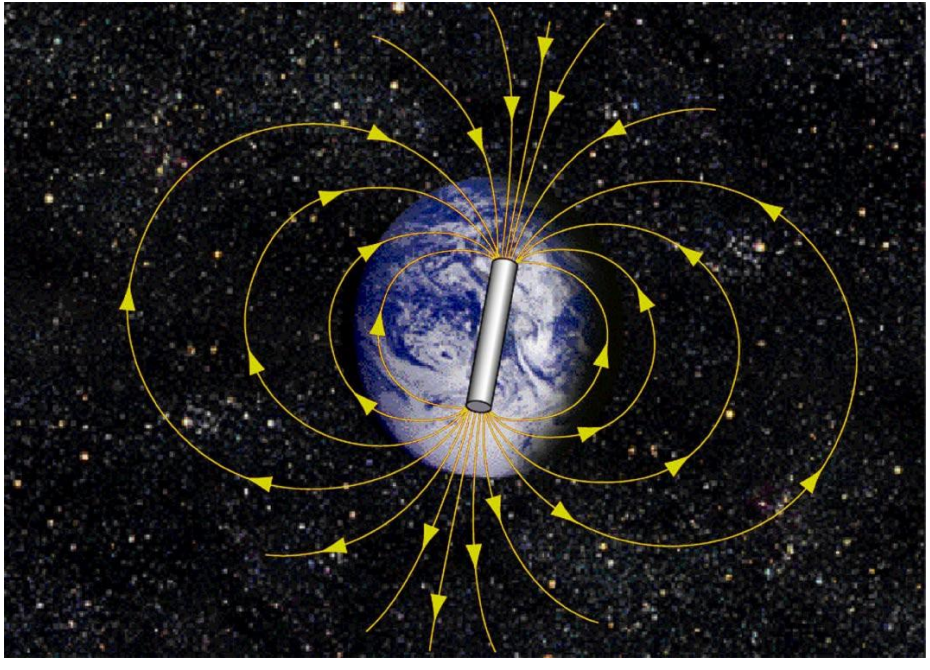


Earth's Internal Magnetic Field

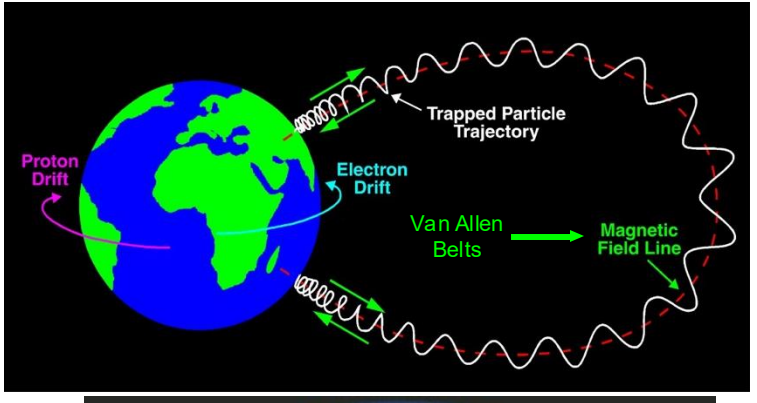
- The Earth has both internal and external magnetic fields that make up its magnetosphere
- Internal geomagnetic field is approximately dipolar for altitudes up to about 4 to 5 Earth radii
- Dipole axis is not same as geographic North-South axis
  - 11.5 degree tilt
  - ~500 km displacement
- Trapped particle populations conveniently mapped in dipole coordinate systems

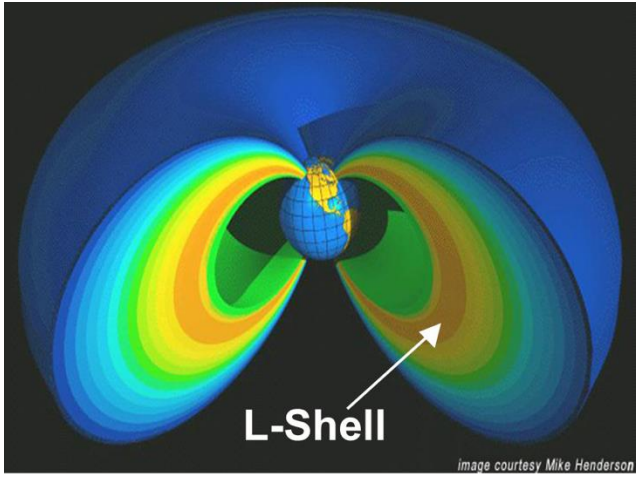


The internal magnetic field of the Earth is approximately a dipole field, which can trap both protons and electrons

Trapped Charged Particle Motion and L-Shells

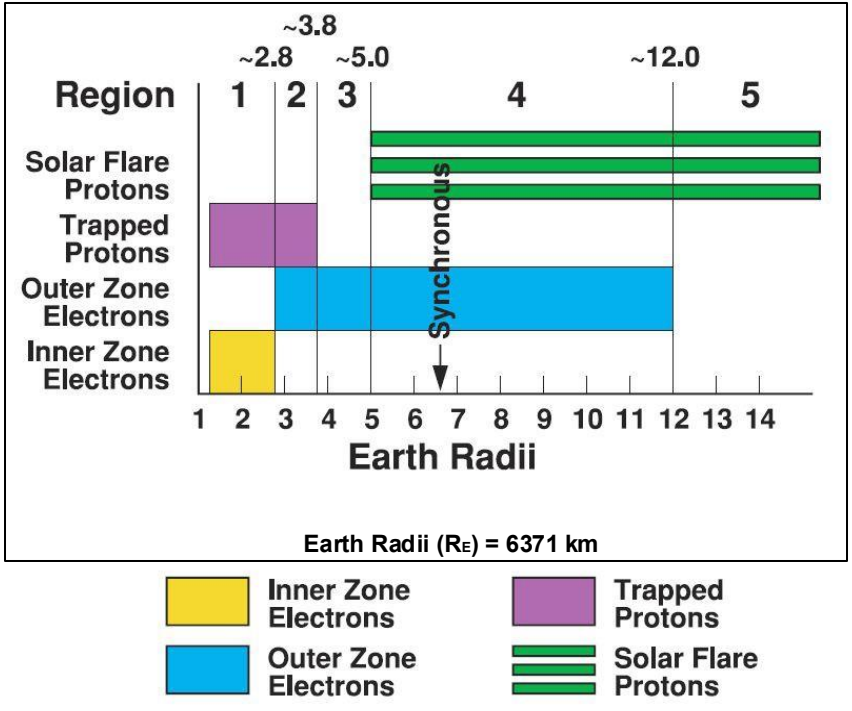
- Protons and electrons trapped in these magnetic field lines drift around the Earth and spiral along these field lines
  - A complete azimuthal rotation of particle is called a drift shell or L-shell
- L-shell parameter indicates magnetic equatorial distance from Earth's center in number of Earth radii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





Charged Particle Distribution

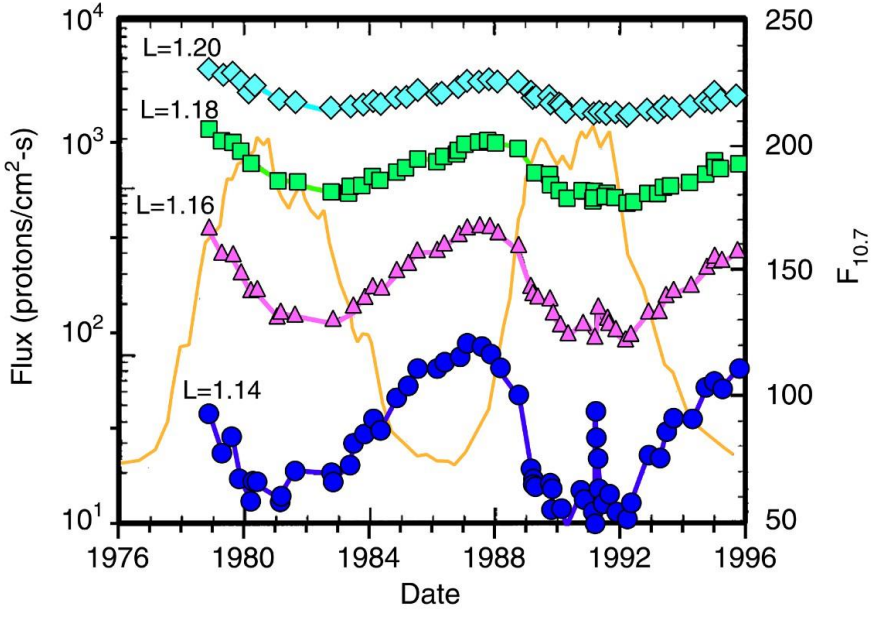
- An L-shell contains a subset of trapped particles peaked at a certain energy moving throughout this shell
  - Provides convenient global parameterization for a complex population of particles
- Each L-shell has a unique environment that must be accounted for in the design of a system



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**

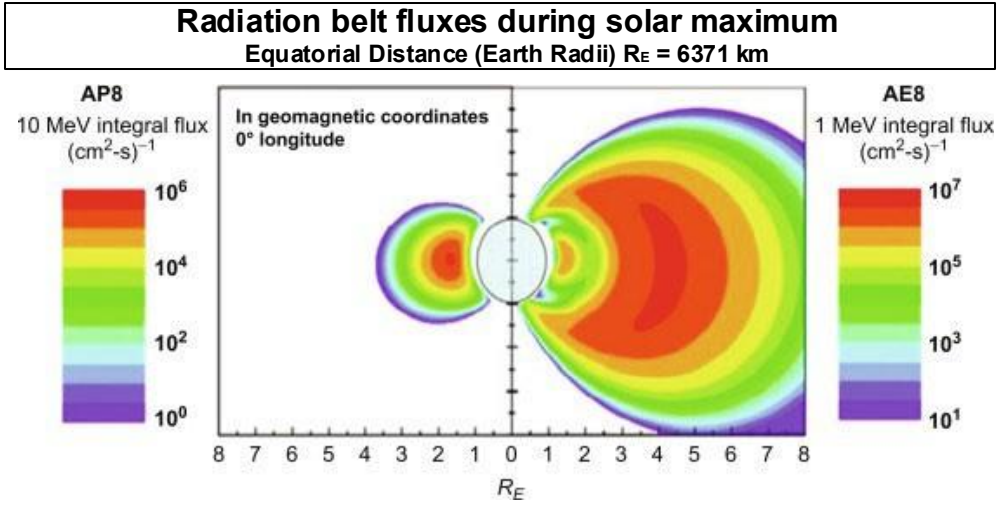


S.L. Huston and K.A. Pfitzer, IEEE TNS, Dec. 1998

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.



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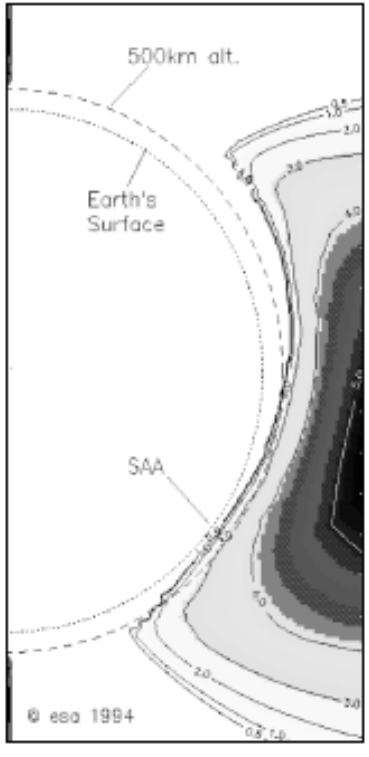
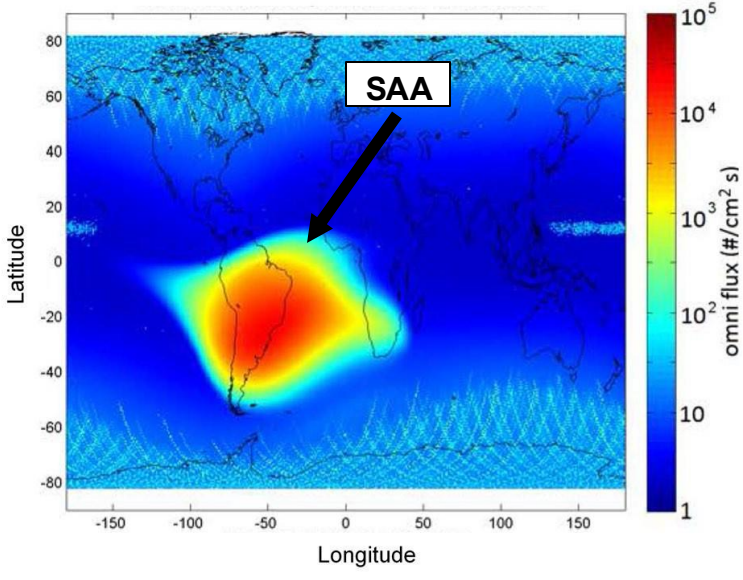
Trapped Proton Properties

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

- 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

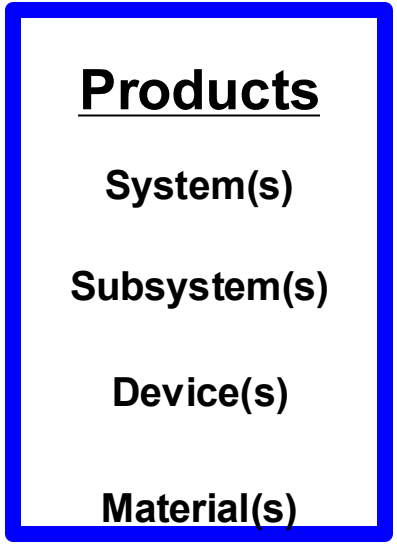
Trapped Environment Models

- 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

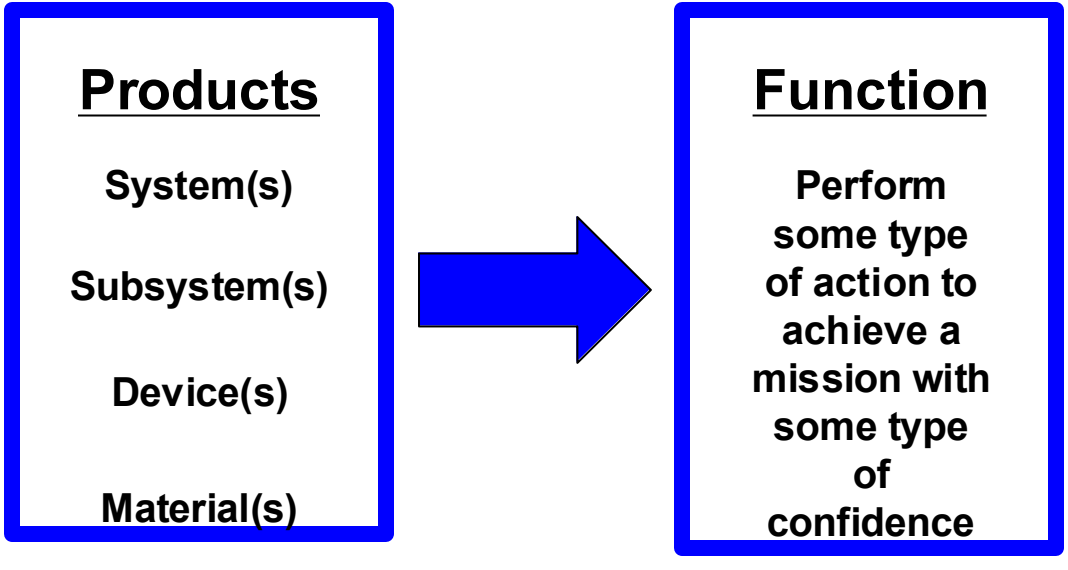
Section Topics/Outline

- 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?



Why do environments matter?



Why do environments matter?

Environments

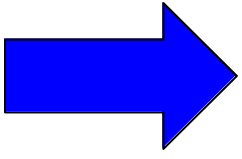
Products

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)

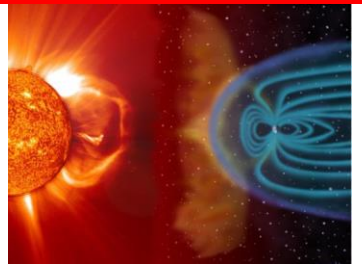
Device(s)

Material(s)

Function

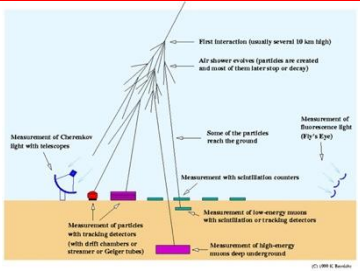
Perform some type of action to achieve a mission with some type of confidence

Exoatmospheric



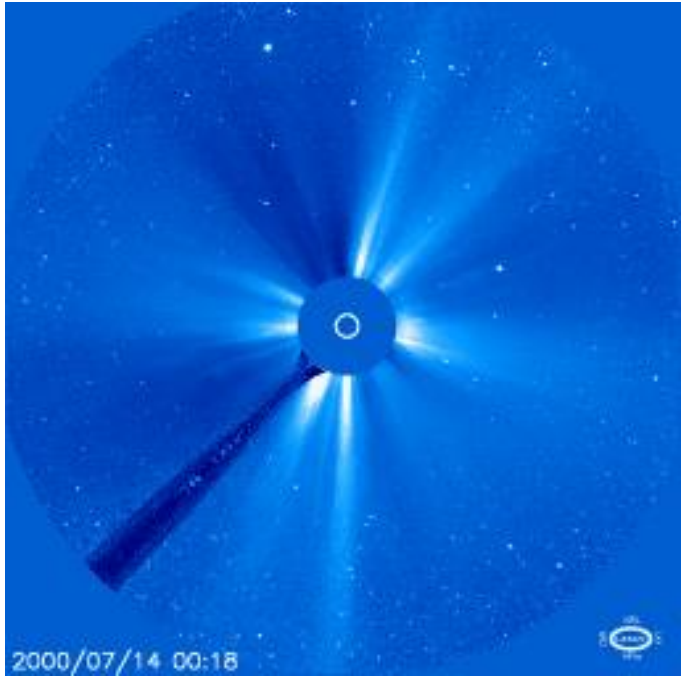
~100 km

Endoatmospheric

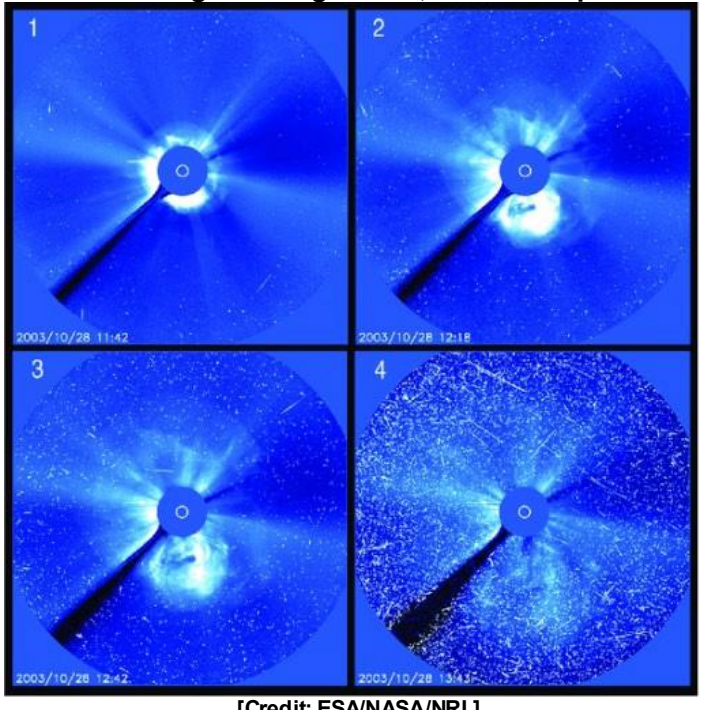


Why do environments matter?

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



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

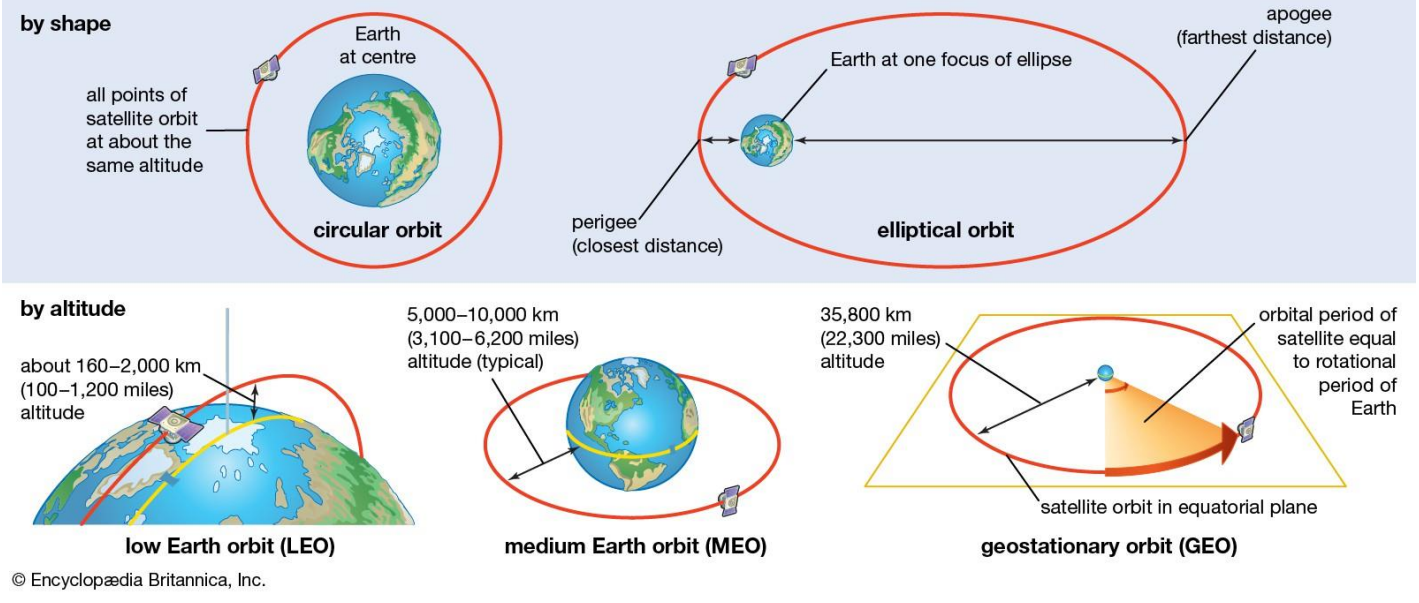


[Credit: ESA/NASA/NRL]

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

Section Topics/Outline

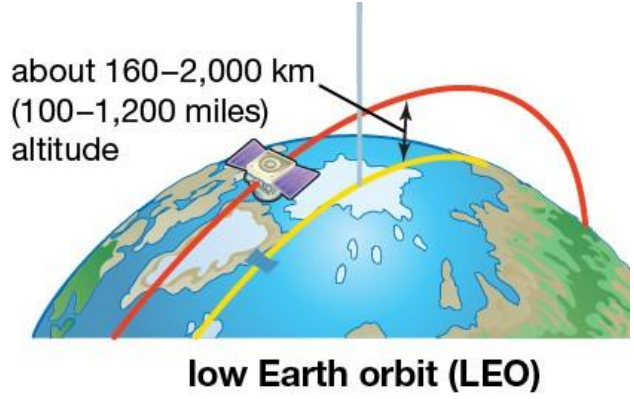
- What are the sources of the natural space radiation environment?
- What role does the Sun play on these environments?
- **Why do environments matter?**
  - **Environmental impacts on common orbit regimes**
- Summary

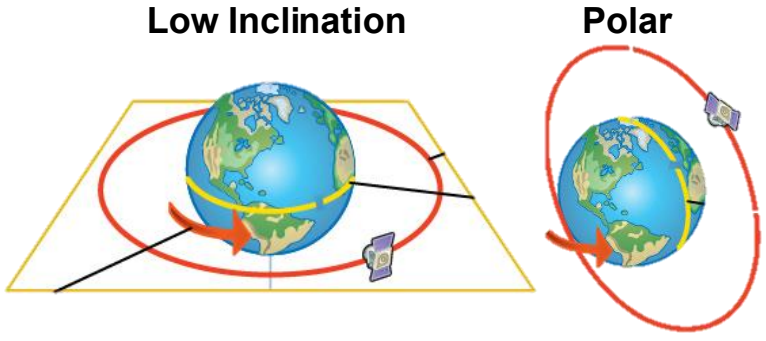


Effect of the Environment on Mission

Low Earth Orbit (LEO)

	Levels		Orbits	
Env	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



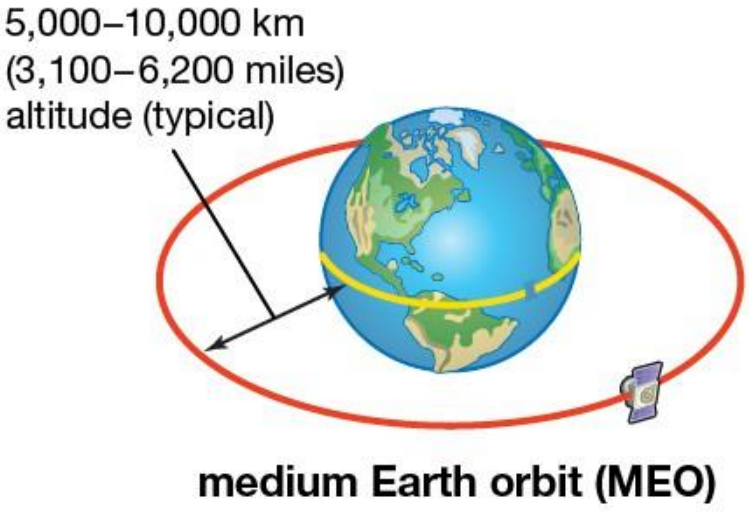


Modeling and simulation is required to specify the environments

Effect of the Environment on Mission

Medium Earth Orbit (MEO)

	Levels		Orbits
Env	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

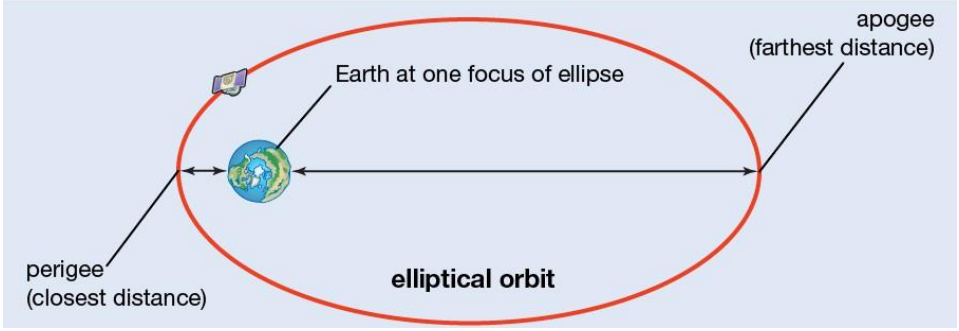


Modeling and simulation is required to specify the environments

Effect of the Environment on Mission

Highly Elliptical Orbit (HEO)

	Levels		Orbits
Env	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

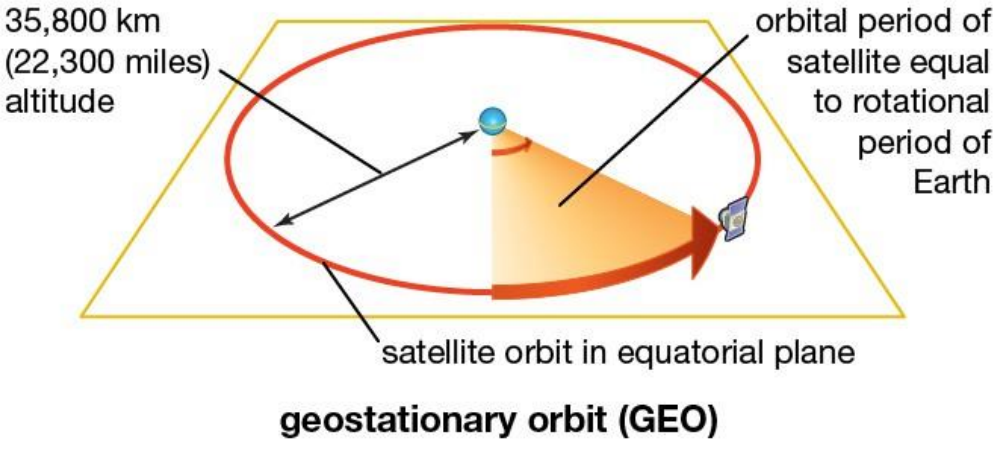


Modeling and simulation is required to specify the environments

Effect of the Environment on Mission

Geosynchronous Orbit (GEO)

	Levels		Orbits
Env	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



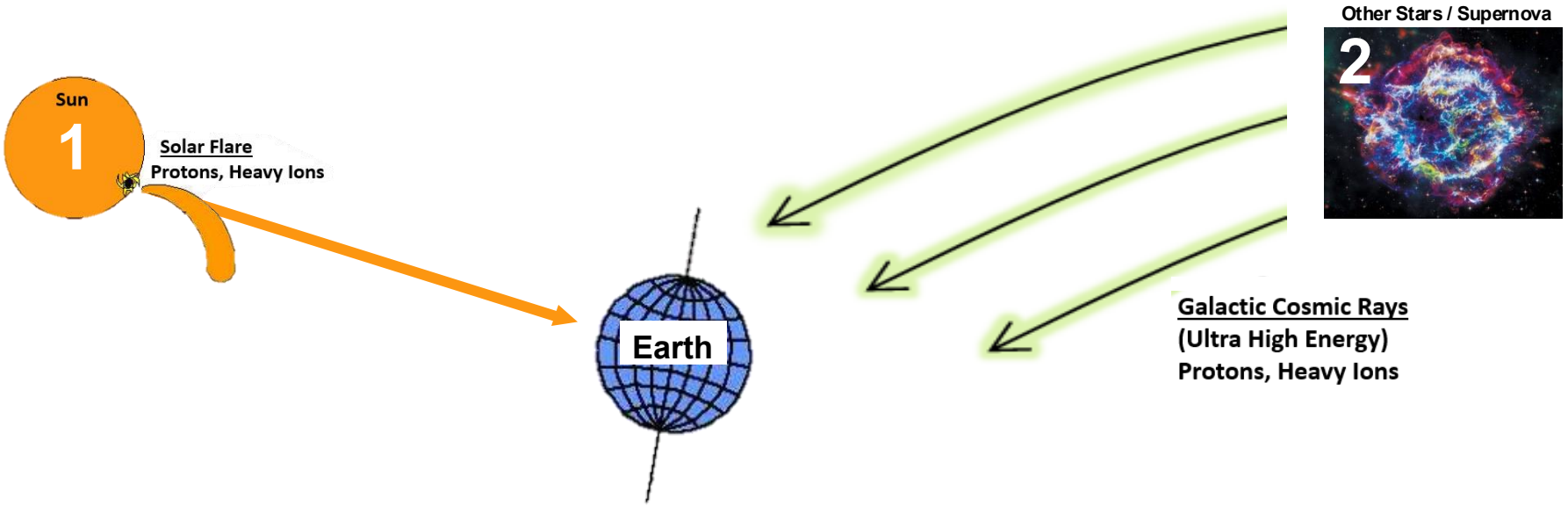
Modeling and simulation is required to specify the environments

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**
  - **Environment Sources**
  - **Effect of the Sun on the Environments**
  - **Effect of the Environment on Missions**

Summary

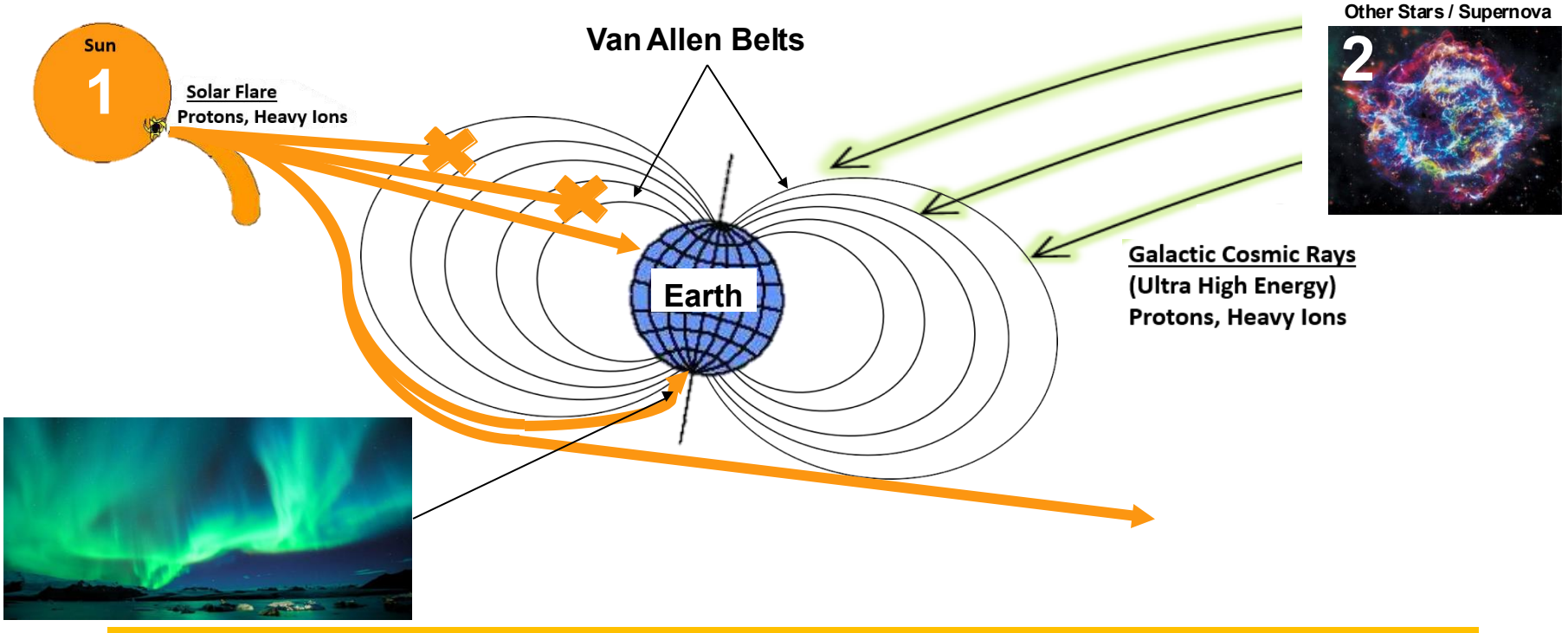
Sources of Radiation Near Earth



Radiation comes from the Sun and/or other stars/supernova in the galaxy

Summary

Sources of Radiation Near Earth



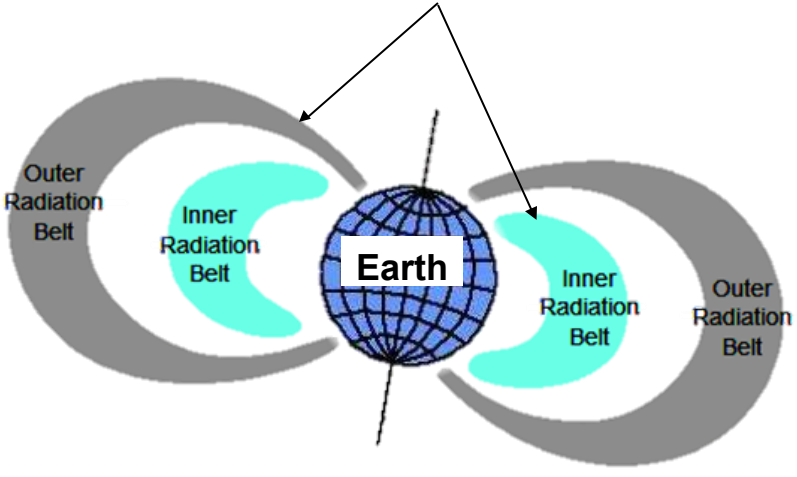
Earth is surrounded by a magnetic field called the Van Allen Belts that trap some radiation from the Sun and/or other stars

Summary

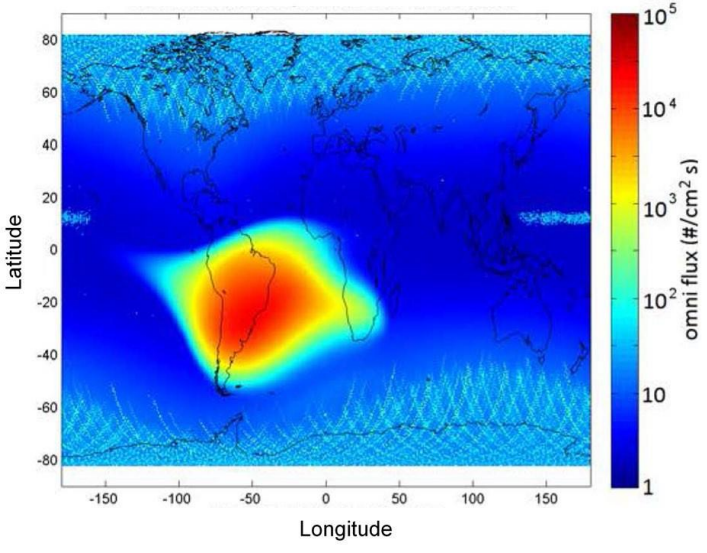
Sources of Radiation Near Earth

3 Trapped Radiation

Radiation Belts



South Atlantic Anomaly (SAA)



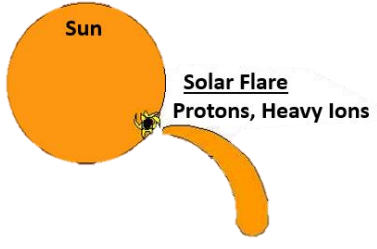
Trapped radiation comes in two forms: radiation trapped by the Van Allen Belts and the South Atlantic Anomaly

Summary

Effect of the Sun on Environment

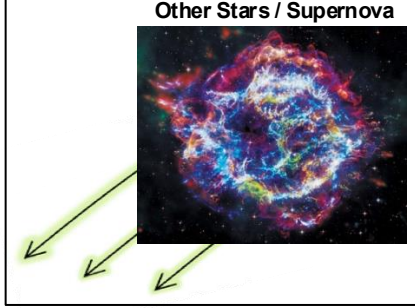
Episodic or "Active" Environment

1 Solar Energetic Particles (SEPs)



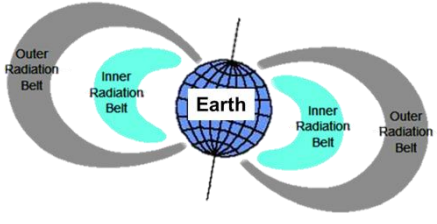
Continuous or "Quiet Time" Environment

2 Galactic Cosmic Rays (GCRs)

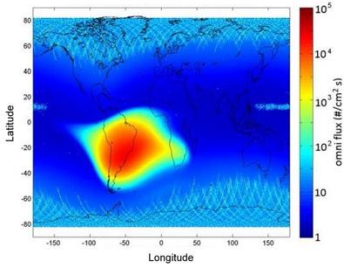


Trapped Radiation

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

	Levels		Orbits				
Env	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

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

Questions?

SCALE
SCalable Asymmetric Lifecycle Engagement

Why do environments matter?

Historical Examples

2022: A VERY EXPENSIVE STORM

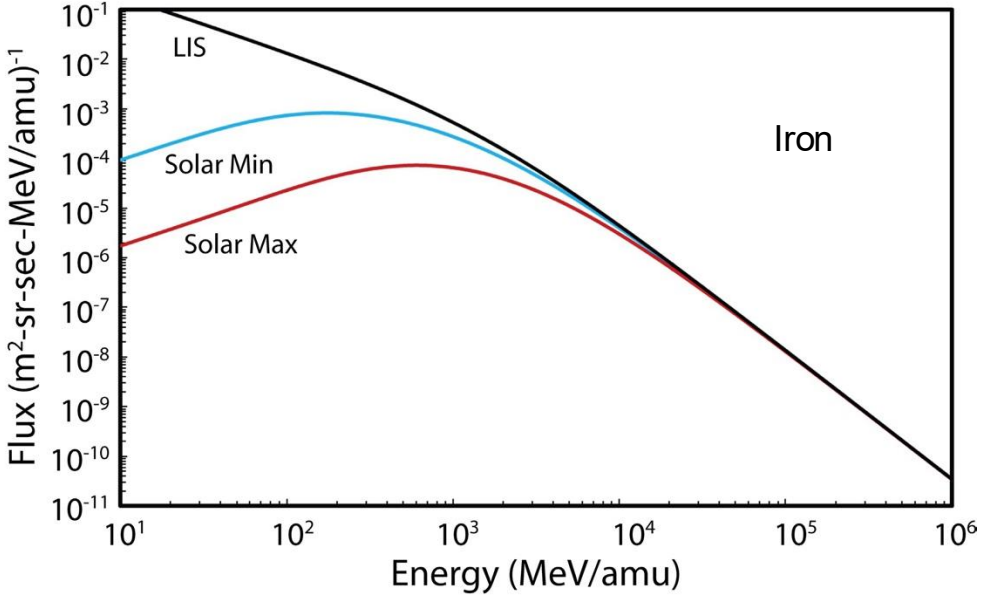
A view of SpaceX's first 60 Starlink satellites in orbit, still in stacked configuration, with the Earth as a brilliant blue backdrop on May 23, 2019. (Image credit: SpaceX)

In February 2022, SpaceX witnessed the destructive power of the sun when a geomagnetic storm destroyed up to 40 Starlink satellites worth over $50 million shortly after deployment.

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

Model 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