# 02 – The Natural Space Radiation Environment

## ENGR-E 399/599
## Microelectronics Radiation Effects and Reliability

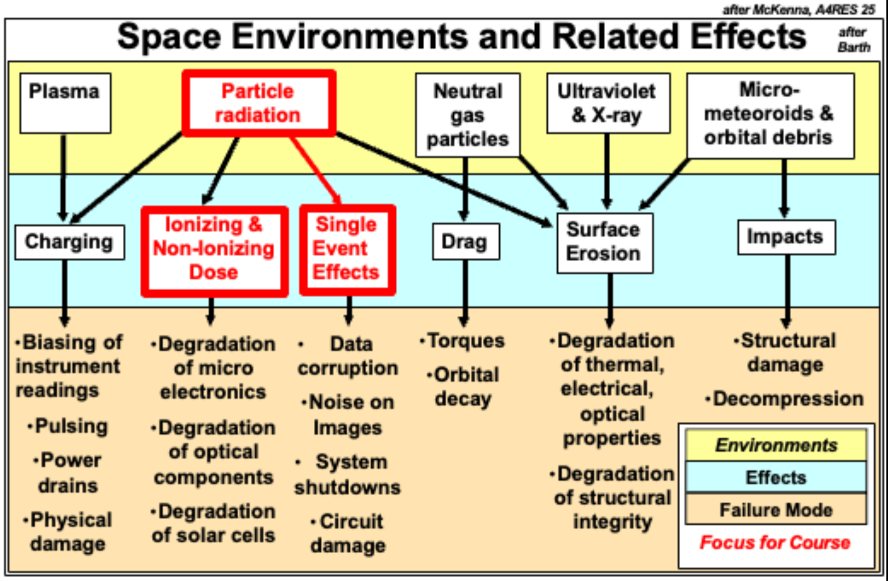
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

SCALE
SCalable Asymmetric Lifecycle Engagement

# 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)

*after McKenna, A4RES 25*

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Spacecraft must endure a number of environmental hazards, including high-energy particle radiation, x-ray and ultraviolet radiation, and low-energy plasma

# 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

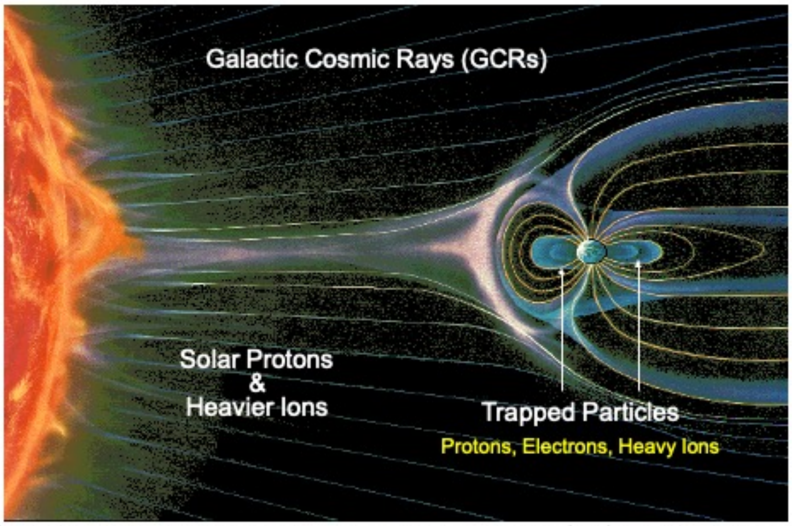
# Section Topics/Outline

- 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**

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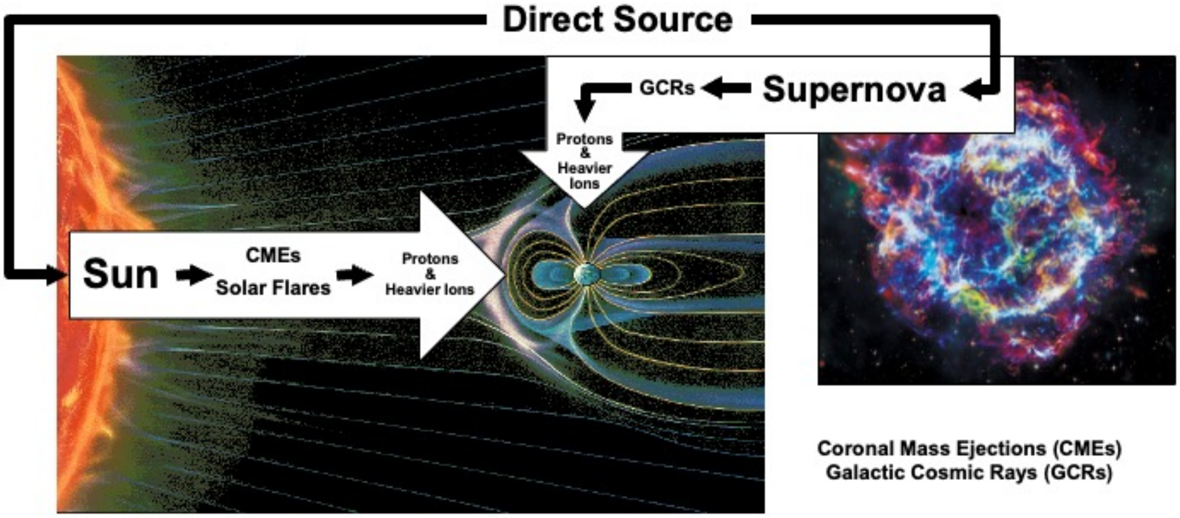
The natural space radiation environment is composed of solar particles, particles trapped in the Earth's magnetic field, and galactic cosmic rays (GCR). These particles include electrons, protons, and every naturally-occurring element in the periodic table (also called Heavy Ions).

There are three general categories of high-energy particles found in the natural space radiation environment: Particles that are emitted from the Sun during solar particle events like solar flares and coronal mass ejections (CMEs) Background ions that originates outside our solar system, called galactic cosmic rays (GCR)

# Sources of Natural Space Radiation Environment




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

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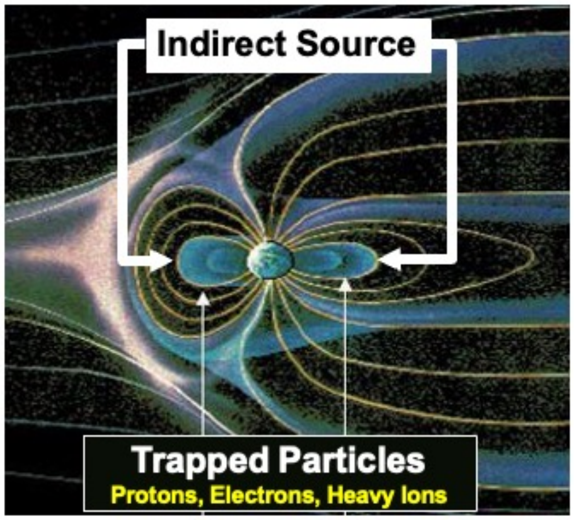
# Sources of Natural Space Radiation Environment




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

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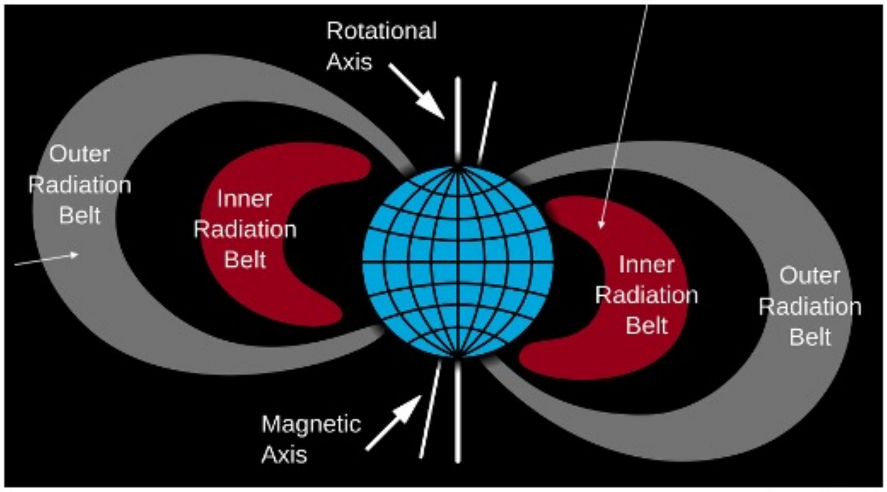
# Radiation Belts

Trapped

**Energetic Protons**
Very stable over time

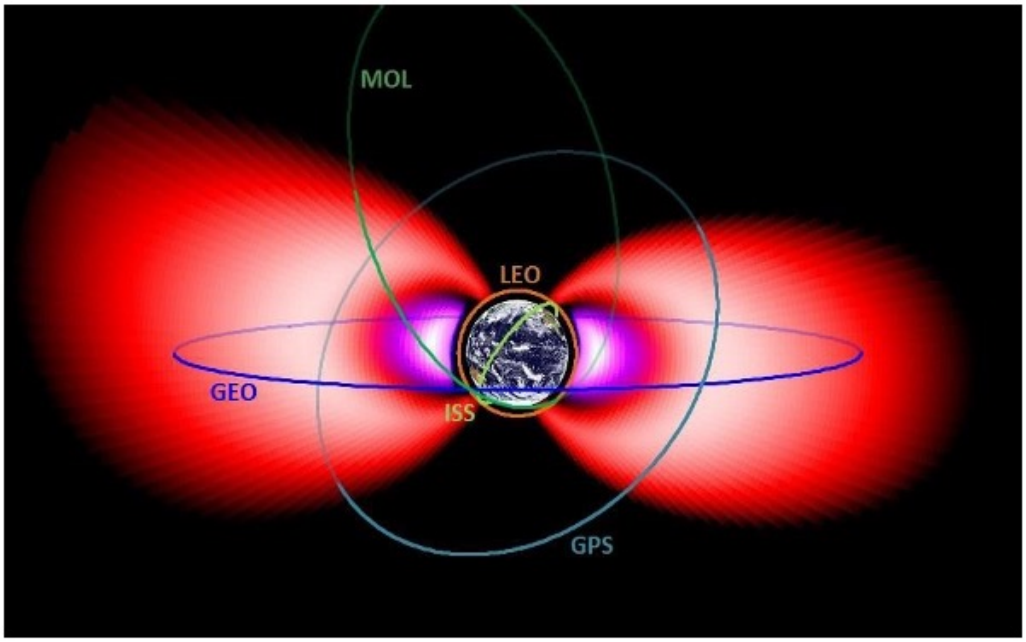
**Energetic Electrons**
Dynamic: varies on weekly/monthly timescales




Courtesy Wikipedia

**Different Orbits will sample different parts of the trapped environment**

# Radiation Belts

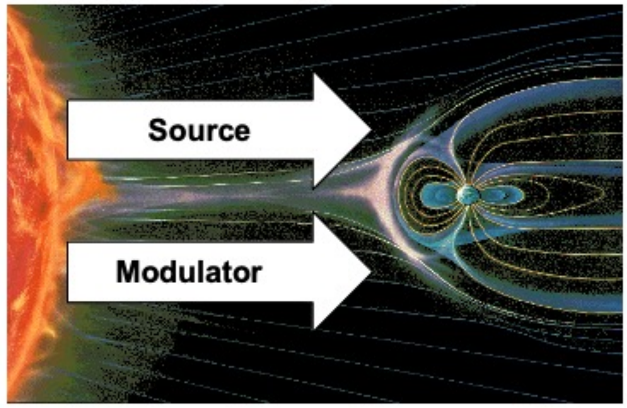


# Section Topics/Outline

- 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

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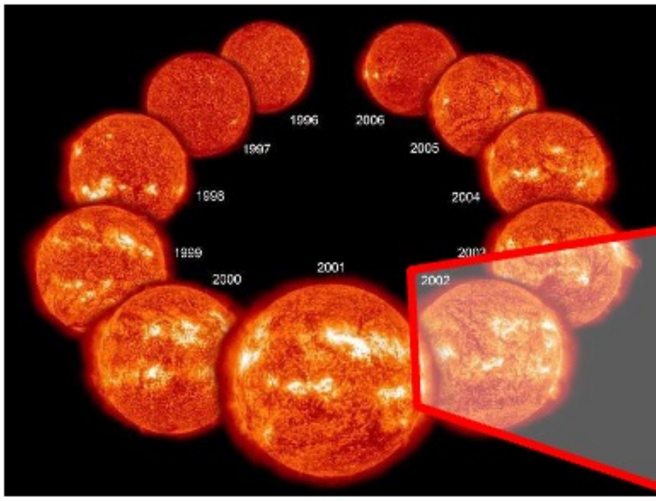
As previously discussed, the sun acts as both a direct and indirect source of particle radiation. However, the sun's magnetic activity also plays a significant effect on the radiation environment that earth experiences. The sun's activity acts as a modulator of all energetic particles in the near earth region. What this means is that the sun's solar activity not only determines the frequency of solar events such as solar flares but as also almost "regulates" which environment (GCRs or Solar Events) are most dominant. This makes the near earth portion of the space environment very dynamic at times.

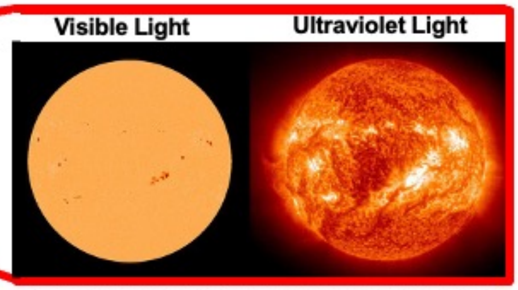
The space environment's dynamic behavior complicates environmental predictions for space missions and is one of the primary reasons that design margin is a necessity. Next

# 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))

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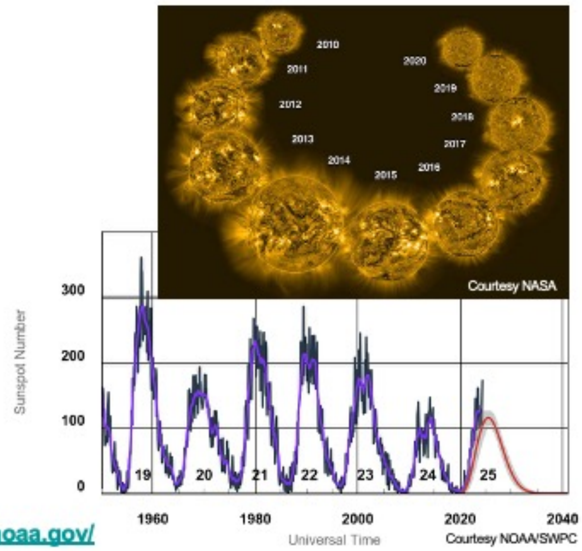
Sunspots are viewed as an indicator or proxy of solar activity. So, the more sunspots, the more active the sun is and vice versa.

The magnified image on the left was taken in visible light and you can see the sunspots as the darker spots. The image on the right was taken in ultraviolet light and this shows the active regions. When you compare two images, you see that the active regions correspond almost exactly to the regions of the sunspots. Next

# 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/**

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Solar activity has a fairly consistent periodic behavior. The solar cycle is approximately 11 years in duration. When the sun is most active this is called the solar maximum and lasts typically for 7 years. When the sun is less active this is called the solar minimum which lasts for about 4 years.

Fun fact, as you can see on the graph, we are at the peak of the solar maximum currently. And an even funner fact, is that Codie let me know that apparently there is supposed to be a large solar storm impacting earth tonight that should be visible in Indiana. So if you can find an area without light pollution you might be able to see the Auroa Borealis. I haven't mentioned this yet but the Auroa Borealis or Northern Lights are the lights we can see when radiation particles (mainly electrons and protons) interact with the upper atmosphere. You can visit the space weather website for more details. Next

# 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



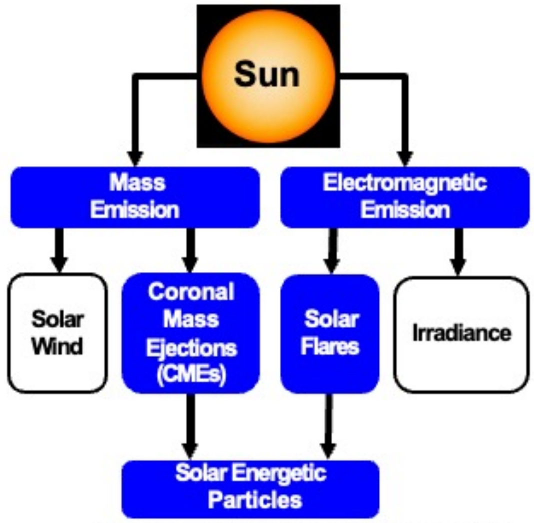


Image credits: NASA and ESA (SOHO and SDO)

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The sun produces mass emissions, namely Solar wind and Coronal Mass Ejections, and electromagnetic emissions, namely Solar Flares and Irradiance.

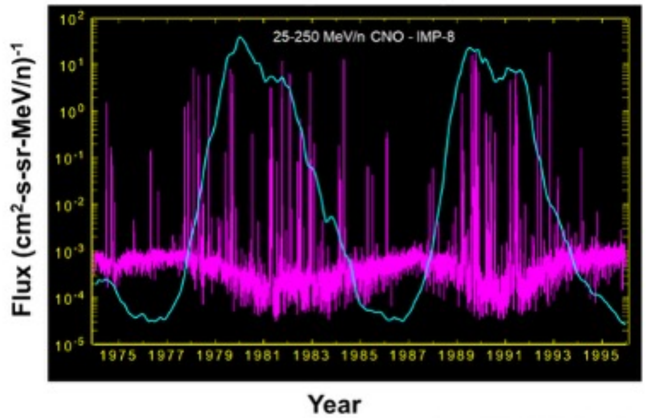
Coronal Mass Ejections and Solar Flares are the two types of solar events that are responsible for producing solar energetic particles which are primarily responsible for impacting electronics. Coronal Mass Ejections are proton rich -> are more gradual emissions -> and typically take hours to a few days to reach Earth

Solar flares are heavy ion rich and typically impulsive Next

Solar wind is always in the background, and then you have storms which can result in increased proton flux
Irradiance is photons, all others particles

# 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**

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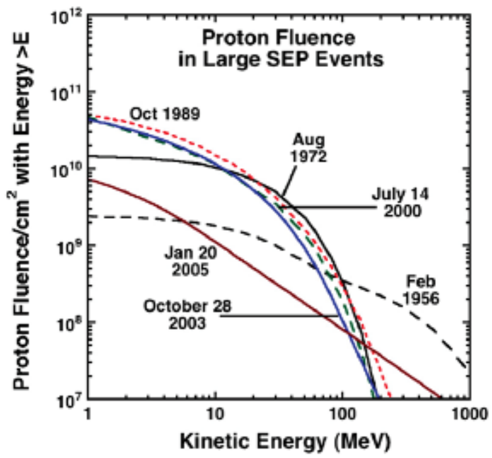
As discussed previously the sun's activity or solar cycle plays a role in determining the frequency of solar energetic particles. The graph shows the solar cycle, in blue, overlayed on top of particle events, in pink.

I hope you can see that during the Solar Maximum there is an increase in solar events and during Solar Minimum, there are fewer. However, I'd like to point out that just because the sun is less active, does not mean events aren't happening. It's also worth mentioning now that not all "big" events are earth facing.

We previously also talked about the Sun being a modulator. This graph shows what I meant. The more consistent pink concentration along the bottom is the background or Quiet environment, which is composed of Galactic Cosmic Rays and solar wind. You can see the increase in GCR influence in the environment during Solar Minimum and decrease during Solar Maximum. Next

# 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

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I previously stated that the space environment's dynamic behavior is one of the primary reasons that design margin is a necessity.

The most common approach when thinking about margin is to design to a well known large or Worst Case event. The graph on the right shows several events that are most often considered. Out of this list the October 2003 event is particularly interesting as it is the "most modern space age" event on this list, meaning the most satellites in orbit with the most advanced technology to date, hence comparatively lots of anomalies. You'll note I've also listed the Carrington Event of 1859 on this list. Click. However, it is not used when determining design margin. I've listed it because it's fascinating to me as one of the first recorded examples of a solar storm impacting earth. You should google it.

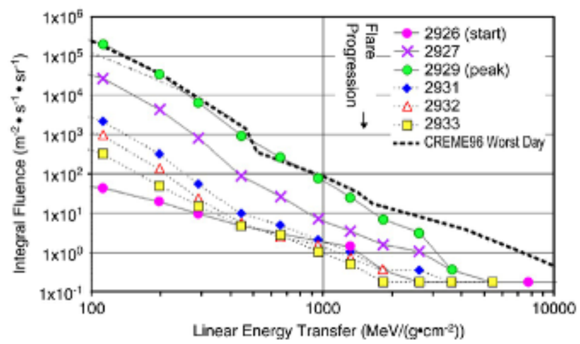
Finally, for far more detail on best practices for generating space environment specifications I'd recommend referring to the Aerospace TOR "Best Practices for Generating Space Environment Specifications with Modern Tools" Next

Design margins are tied less to environment than mission classification (more to come)

Design margin = Confidence level around the environment (I'm 95% confident I won't exceed) + margin on the technology using ->

# 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

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The most common model used to model solar particle events is called CREME96.

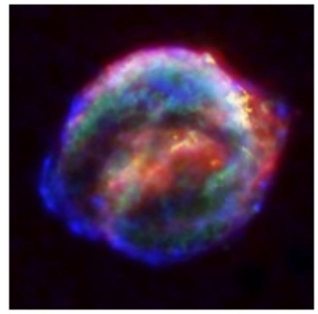
This model is based on the October 1989 event and helps determine various worst cases (peak 5 minutes, worst day, worst week, etc).

I'm not going to go very deep on this subject but I did want to make mention of this as the CREME96 model is what you will be using in the SPENVIS activities that follow this presentation today and later in the week. Next

# 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**

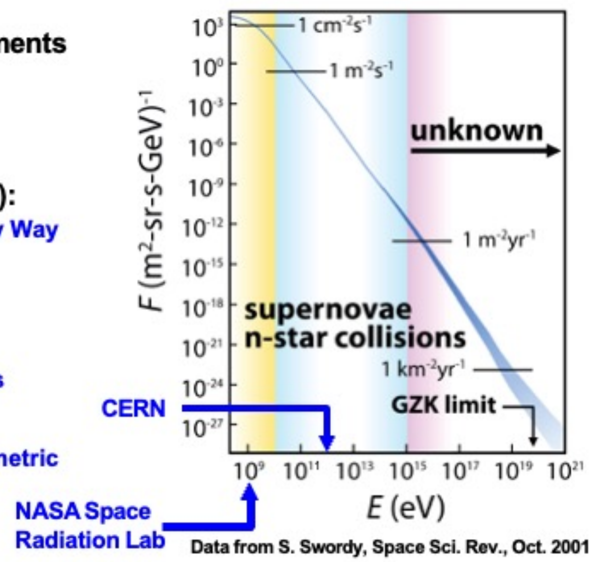


Credit: NASA, ESA & JHU APL (Chandra, Hubble and Spitzer)

# 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**




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

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Once more, galactic cosmic rays are ions that originate outside of our solar system.

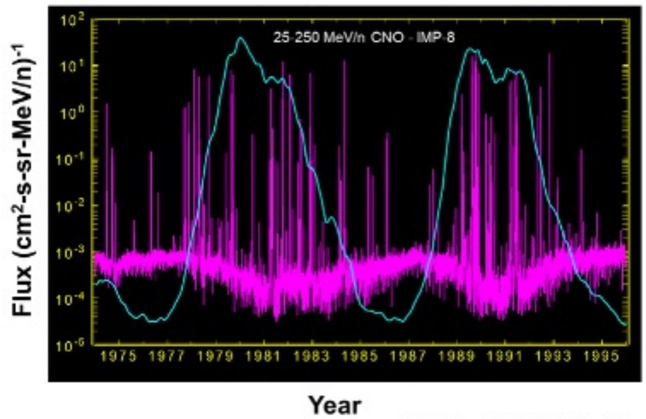
Galactic Cosmic Rays are primarily comprised of lighter ions such as protons (hydrogen) with only 1% being made up of heavier elements.

Earlier I noted that GCRs originate from exploding stars, called supernova. I called these out because they are the most significant contributor to effects on electronics. But as you can see on the graph, there are GCRs that also originate from other start types called n-star as well as some origins being unknown.

On the graph you'll notice that I've added to Ground Simulators of radiation, the NASA Space Radiation Lab and CERN. I wanted to give some context to energy levels produced by GCRs in comparison to what these facilities can produce on Earth. The NASA Space Radiation Lab was designed and built to simulate the GCR spectrum and is the highest energy radiation facility in the country…Dr. Loveless will talk more on this subject on his facility basics brief. Next Flux is plotted on the y-axis (which is the rate of beam particles passing through a unit area)
Particle energy is plotted on the x-axis

# 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**

***Presenter Notes***

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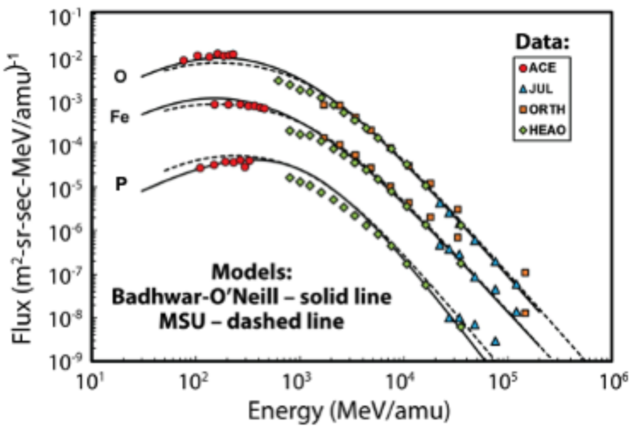
Just a quick reminder that the Sun modulates other environments and in this case Galactic Cosmic Rays.

Once more the thick pink line at the bottom of the graph shows this background or quiet environment which GCRs makes up. And once more during Solar Max, GCRs go down, and during Solar Min, GCRs go up.

Next

# 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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*2025-06-03 15:00:17*
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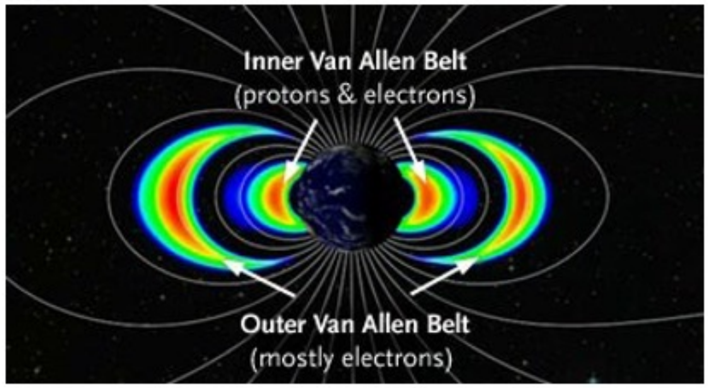
I'd like to briefly mention that there are are two popular  models used to model GCRs.

Once more CREME96 is one  and the other is the Badhwar – O'Neill 2020 Model which incorporates more recent data. For future activities in this workshop we will once more be using CREME96.

Next

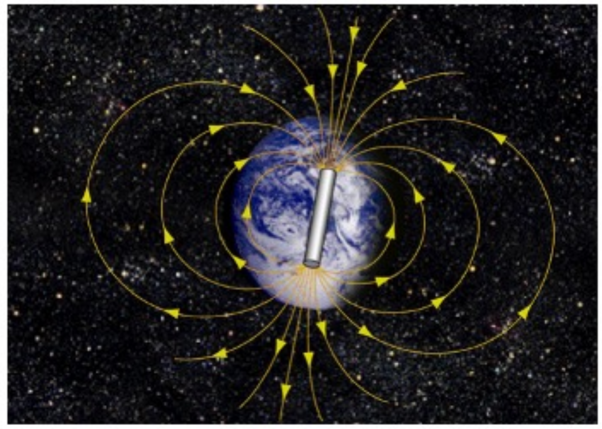
# Section Topics/Outline

- 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?
- Summary



# 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**

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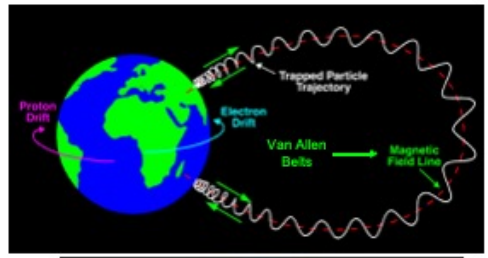
The Earth has both internal and external magnetic fields that make up its magnetosphere. The external field is the result of the solar wind. The internal field originates from within the Earth and is approximately dipolar up to altitudes of about 5 Earth radii. For the non-physics people like me, dipolar refers the separation of positive and negative charges or magnetic poles. This can be described as having one side of an object or system with a positive charge and the other side with a negative charge.

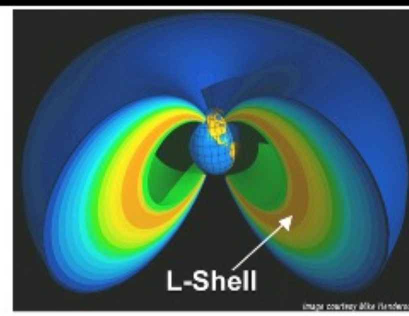
This dipole field is tilted about 11° from the Earth's north-south axis and displaced by more than 500 km from the Earth's geocenter. This tilt of dipole creates an anomaly that I'll talk about soon.

Finally trapped particles are mapped according to this dipole coordinate system. Next

# 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**

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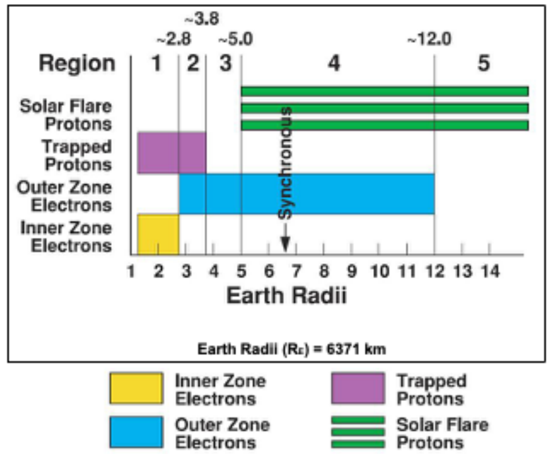
Protons and electrons trapped in these magnetic field lines – which are called the Van Allen Belts – drift around the Earth and spiral along these field lines forming so-called "drift shells" or L-shells. An L-shell equates to

Increased field strength in polar region causes particle spiral to tighten and eventually reverse direction along magnetic field line at "mirror point"

# 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**

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The figure on the right shows charged particle distribution throughout the L-shells. Two things to point out:

The L-shells contain a subset of trapped particles moving throughout the shell and are generally lumped into two distinct regions, an Inner belt and an Outer belt. The inner belt contains both protons and electrons.

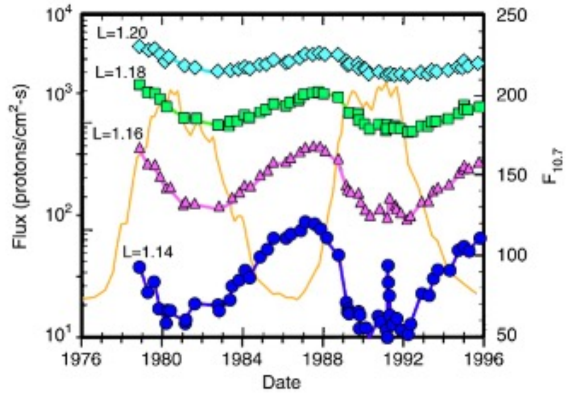
The outer belt consists primarily of electrons but does also see protons from solar flares.

As you can see each L-shell has a unique environment, with unique particles that have different effects, so you have to account for this is system design accordingly. Next

Region = L-Shell? 6.5 Sync = GEO?

# 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**

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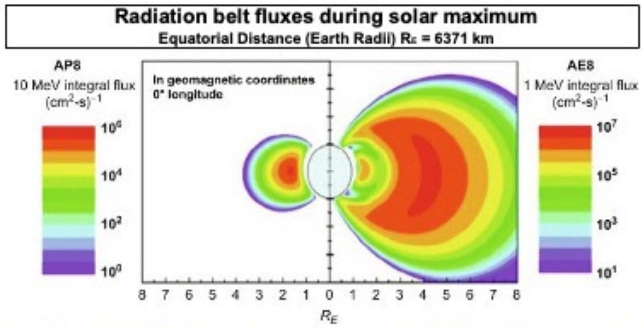
Once more, I want to emphasize that the Sun acts as a modulator. You can see this on the graph on the right which shows the trapped proton environment in the light blue, green, pink, and dark blue colors superimposed on the solar cycle which is in that yellowish/orange color. Unfortunately I'm introducing a term here, flux, that is going to be explained in greater detail in Steve and Daniel's talk later on today and tomorrow but in brief, Flux = number of particles passing through a surface per second…or another way to think of it is particle intensity.

So as solar activity increases, you can see that the proton flux in the trapped environment decreases. Also take note of the variation in flux within the inner proton belt. Also remember that as solar activity increases, you're going to see GCRs influence decrease. The takeaway is that the trapped environment is not static or uniform and requires modeling to determine the specific environment you are designing your mission to live in. Next. When designing space craft for trapped environment, this is why we model at Solar Min.

# Trapped Proton and Electron Properties

**Protons**

- Single trapped proton region for "quiet" conditions
- Earth's atmosphere limits belt to altitudes above ~200 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.

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***Presenter Notes***

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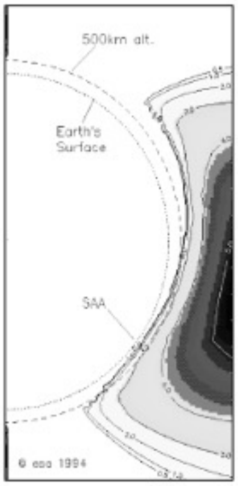
Before I talk about this chart, I do want to point out that unfortunately I did not catch a pretty big copy and paste error, so the information under Electrons is not correct. I decided to leave this chart in the deck though because I wanted you to have a visual of what the trapped environment really looks like rather than a bar graph that I showed previously.

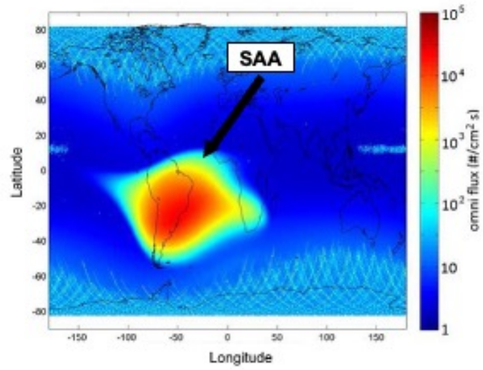
You can clearly see an inner trapped proton belt. The inner belt protons have energies up to about a Giga-electronvolt but you'll note that this graph is plotted for protons only up to 10 Mega-electronvolts (MeV). When I've asked about this value in the past, I have been told that above 10 MeV is where devices typically become susceptible to single event effects -> below 10 MeV particles typically doesn't penetrate packages on devices. 10 MeV protons are found between roughly L-shell 1.8 to 4. Moving on to the electron belts. Trapped electrons have energies up to 10 MeV and exist in two L-shell regions, an inner and outer belt. The inner belt is between L-shell 1 and 2.8 and the outer belt is between L-shell 2.8 and about 10. Note that electron belts are being plotted for 1 MeV electrons. This is because the equivalent dose damage (associated with Total Ionizing Dose effects…more to come this afternoon) occurs at 1 MeV electrons.

Finally, I want to draw your attention to the bottom of both the proton and electron inner belts. Notice how the belts appear to get closer to Earth near the bottom. Next

# 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

***Presenter Notes***
*2025-06-03 15:00:22*
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This is due to a phenomenon called the South Atlantic Anomaly. The 11.5 degree tilt and offset that I talked about earlier causes this. The SAA is most pronounced in the vicinity of South America and generally dominates the radiation environment for altitudes less than 1000 km. Next. Switch off satellites as they cross the SAA

Flux = High number of particles / particle intensity

# 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

***Presenter Notes***

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There are several models that have been developed to model the trapped environment: AP8/AE8, AP9/AE9/IRENE. There are several key differences but the main difference between the is more and newer data used to anchor the A9/IRENE models. Justin will be walking you through how to model the environment with a tool called SPENVIS after this module and will touch on why he is using one model versus the others. Next.

# 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)**

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*2025-06-03 15:00:24*
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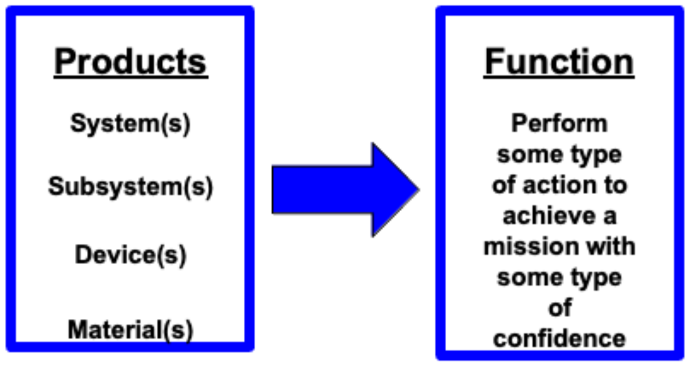
Engineers build products of varying levels. For instance, one engineer may build a rocket  which would be a system made up of many subsystems such as  a Flight Computer which is made up of many devices such as a memory which is made up of different materials. Next

# Why do environments matter?

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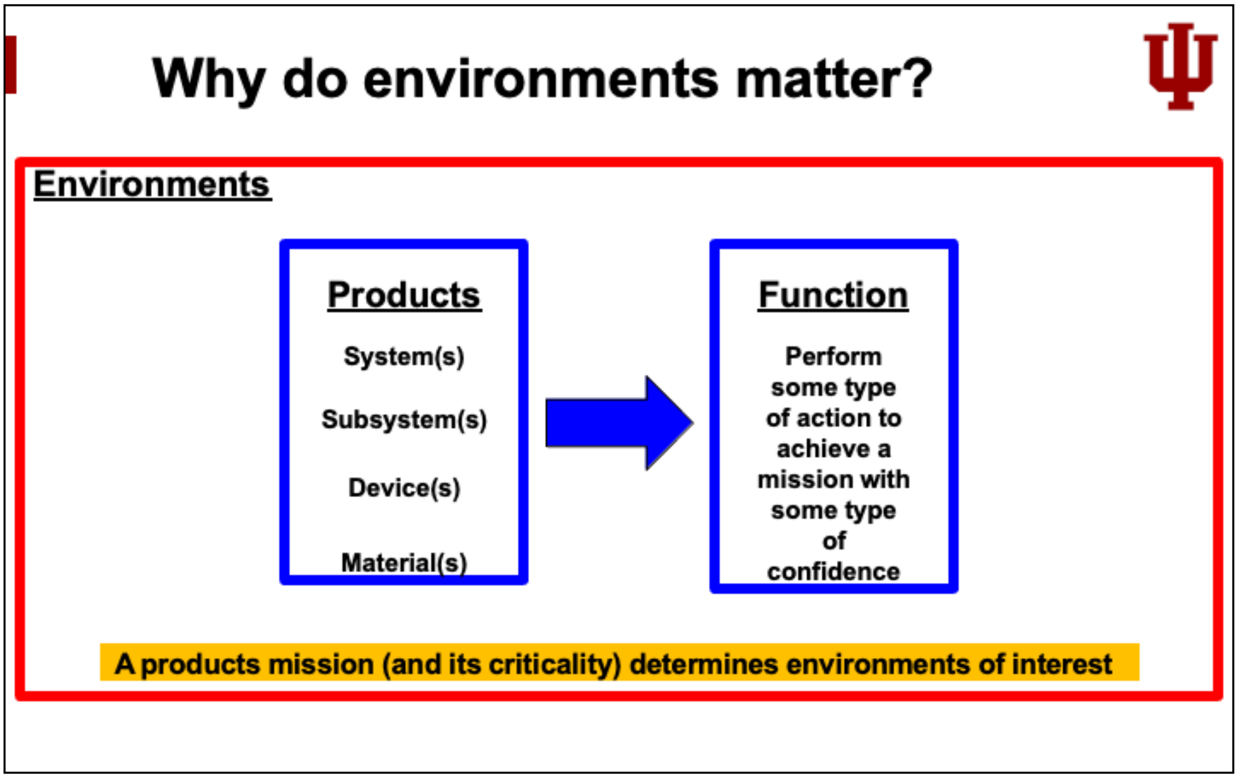
These products perform some type of function which I'm defining as performing some type of action to achieve a mission with some type of confidence. Next

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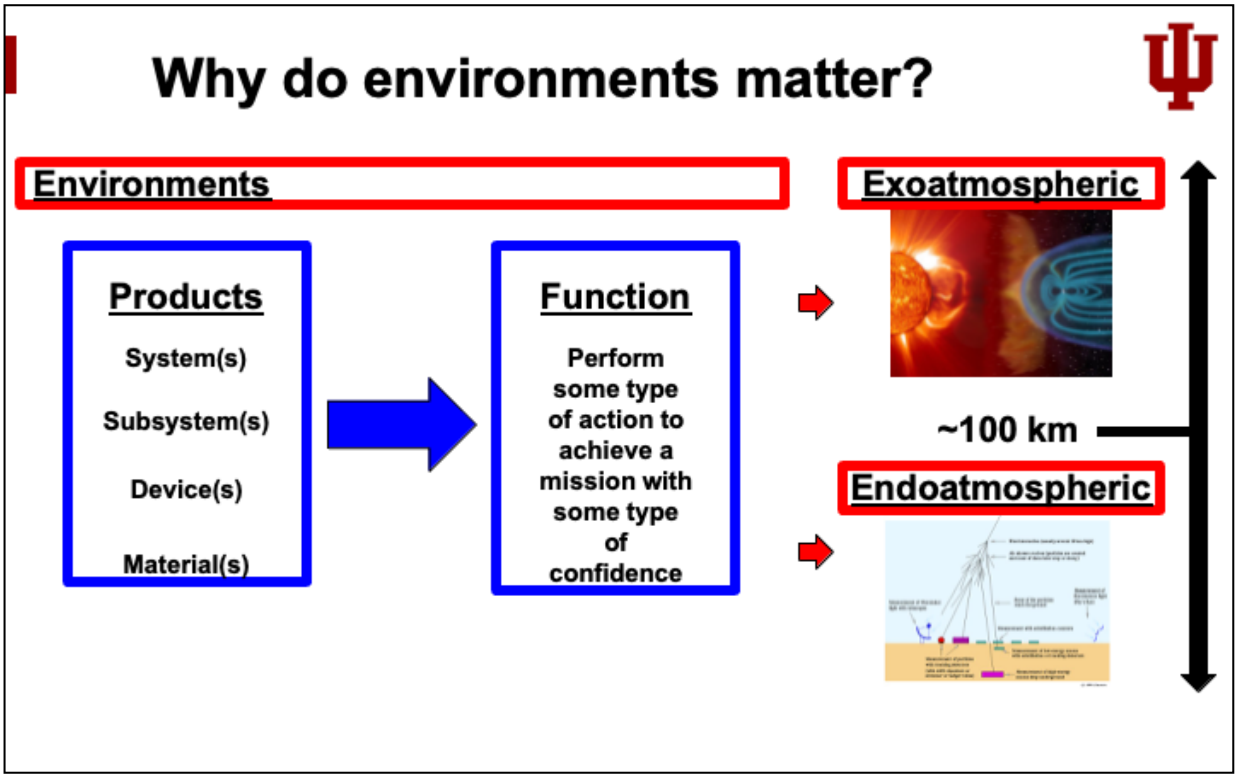
Products do not funtion in vacuums, they operate in environments.

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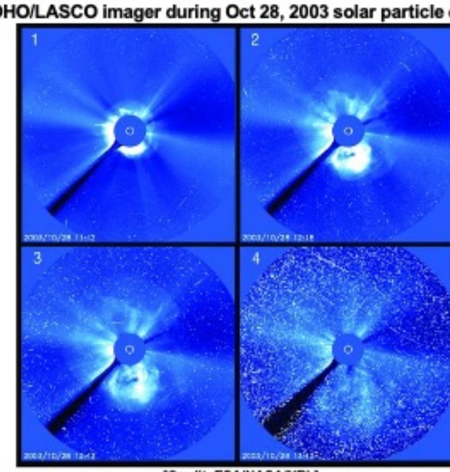
Environments can span from the surface of the earth to space. In context of the space radiation environment, altitudes above 100 km are considered exoatmospheric, which once more is where the focus of this workshop is going to be. Next

# 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?**

***Presenter Notes***
*2025-06-03 15:00:26*
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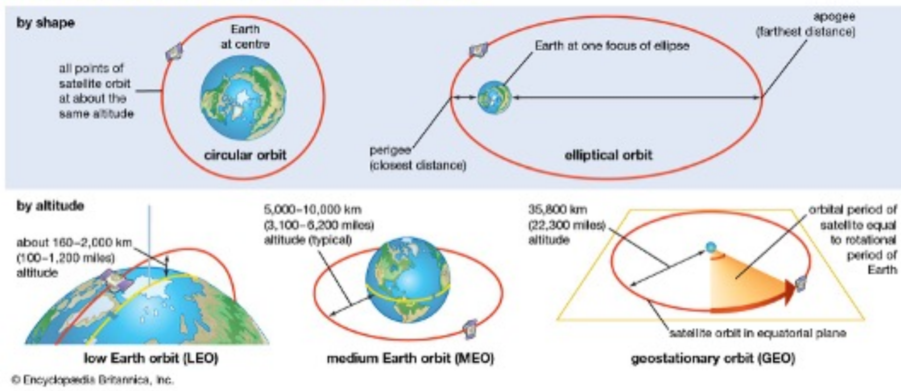
The video and images displayed are of a sensor called the Solar and Heliospheric Observatory/Solar and Heliospheric Observatory  sensor. The SOHO is focused on observing the Sun, particularly its corona and solar wind. The video on the left shows a Solar Particle Event which you can see causes great distortions in the pixels.

Environments produce effects on products that can cause malfunctions. Depending on  what malfunctions, this can be catastrophic to your mission. Justin will be talking more on mission success in his presentation tomorrow. Bottom line, if you're operating in space, you're going to encounter  varying radiation environments and need to plan accordingly. Next.

# 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




***Presenter Notes***
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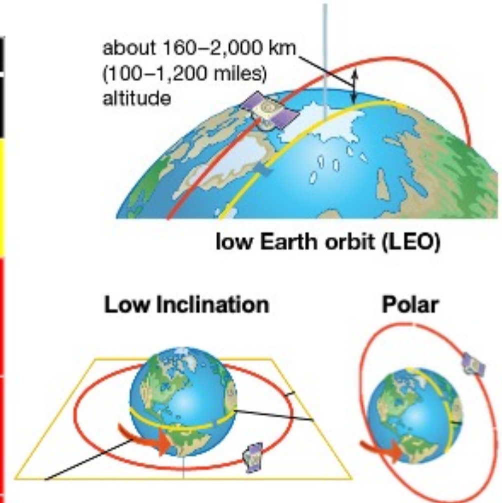
Finally, I'd like to finish out discussion on the natural space environment by looking at common orbit regimes and the specific radiation environments they'll encounter. Spoiler alert, not all orbit regimes are the same and require different environmental assessments to determine their effect on your mission. Before we move forward, I'm going to be talking about orbital inclination which is the angle between the plane of an orbit and the equator. So an orbital inclination of 0° is directly above the equator, where an orbital inclination of 90° crosses right above the pole.

One final note. What I'm about to show you are qualitative generalities concerning environments of interest. Modeling and simulation is required to really quantify the specific impact your system is going to experience in these orbits. Next

# 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**

***Presenter Notes***
*2025-06-03 15:00:27*
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Low Earth Orbits (LEO) are generally those less than 3,000 km. I've listed two LEO orbits, a low inclination (equatorial) and a polar inclination (or 90 degree) orbit.

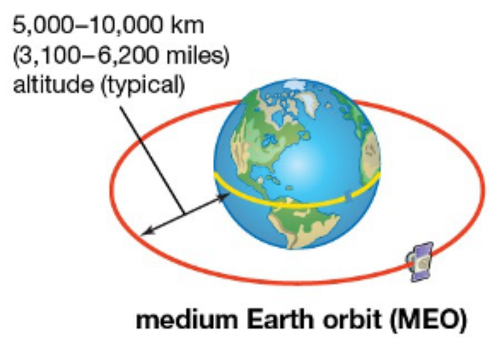
Systems traversing a Low Inc LEO orbit are close to the equator. So lets walk through are various environments. With this orbit you're going to be well within the Van Allen Belts which will be providing protection from Solar Particles as well as minimal exposure to GCRs. The environment that is really dominating this regime is your trapped protons, in particular from the South Atlantic Anomaly. Now let's look at Polar. We're still going to see roughly the same trapped environment but notice how Solar Particles and Galactic Cosmic Rays are now playing a greater factor. This is because this orbit will move across the poles where there Van Allen Belts come to a point. So systems are going to be exposed to solar protons and GCRs over the poles.

Finally to drive this home, notice that these environments are changing depending on the solar activity. Next.

# 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**

***Presenter Notes***
*2025-06-03 15:00:28*
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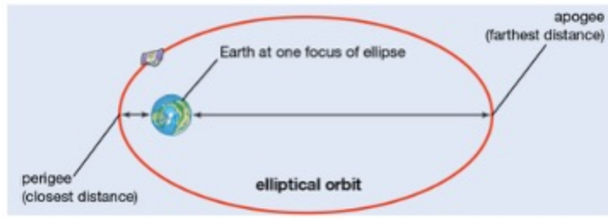
Medium Earth Orbits (or MEO) range between roughly 3,000 to ~35 km.

Systems traversing a MEO orbit should expect to see a severe hazard from trapped radiation  and are going to see more impacts as well from both solar particles and GCRs. Once more which environments are most dominate will also depend on where you are in the solar cycle.

# 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**

***Presenter Notes***

*2025-06-03 15:00:29*

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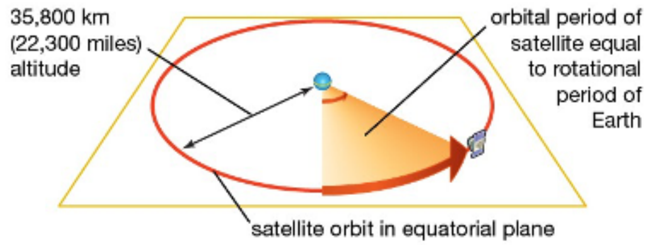
As the name suggests Highly Elliptical Orbits (or HEO) are orbits that are elliptical in shape rather than circular and off center of earth.

Systems traversing a HEO orbit should expect to see a severe hazards from all environments but truly this is going to depend on the furthest distance the system is from Earth (or apogee) and the closest distance the system is to earth (or also called perigee). Generally speaking though, one would expect a HEO system to pass through the inner belt near perigee, and be exposed to solar particle events and GCRs at apogee.

Next

# 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 |




**geostationary orbit (GEO)**

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

***Presenter Notes***
*2025-06-03 15:00:30*
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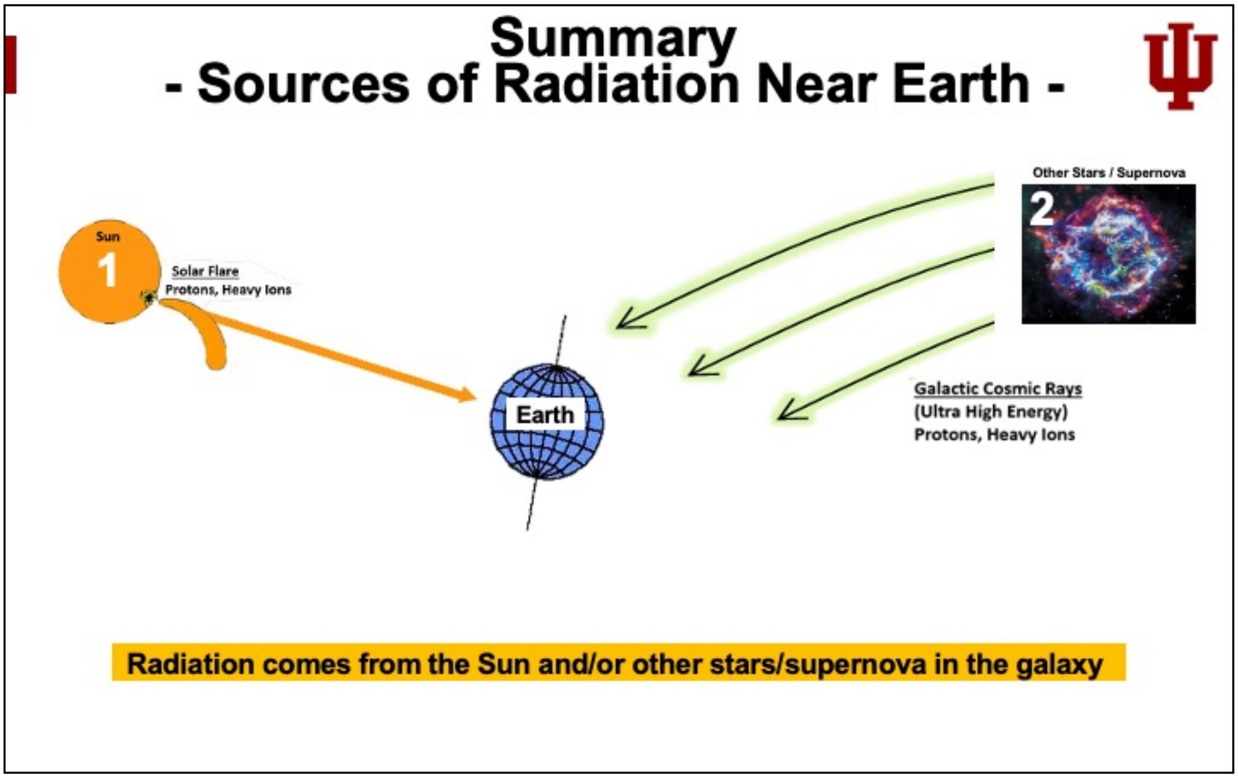
Geosynchronous Orbits (or GEO) are at an altitude of 35,856 km.

Systems traversing a GEO orbit will not see a trapped proton environment but will see a severe trapped electron environment and once more be exposed to solar particle events and galactic cosmic rays. Once more which environments are most dominate will also depend on where you are in the solar cycle.

# 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




***Presenter Notes***
*2025-06-03 15:00:31*

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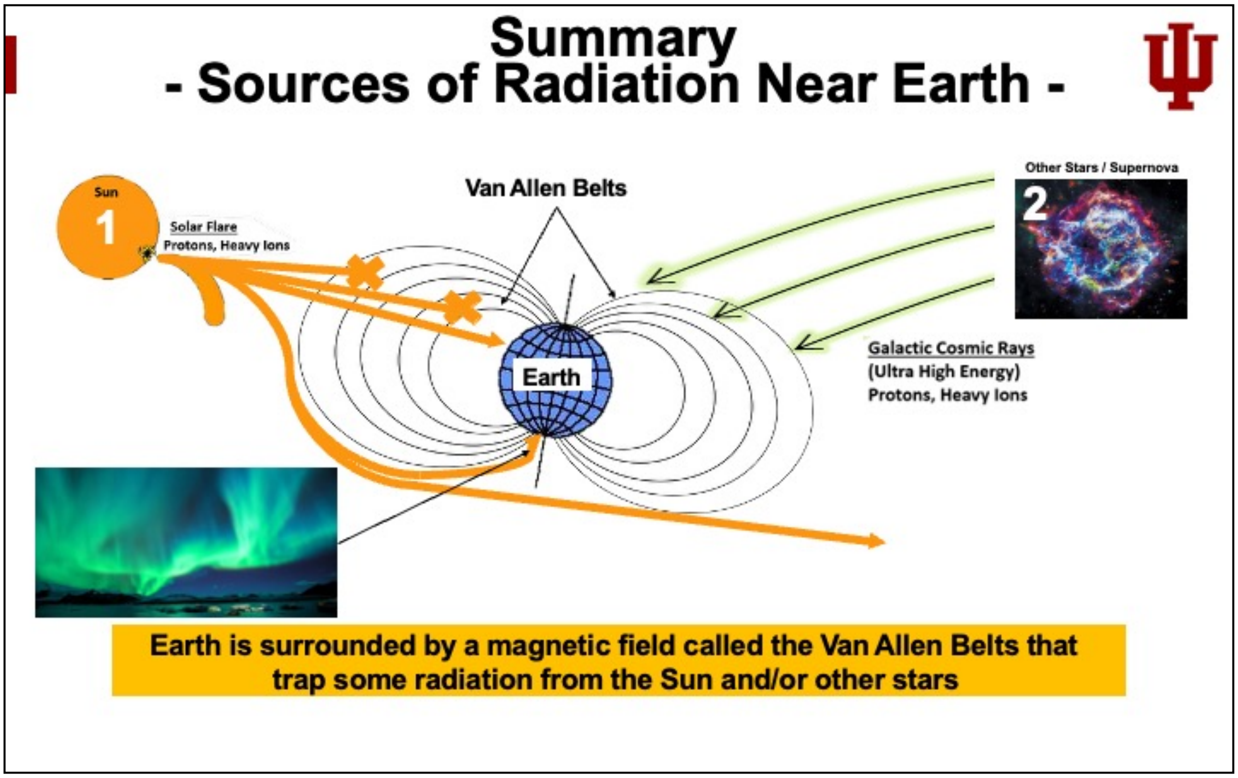
Earth sits in the natural space environment. The natural space environment is comprised of radiation. Next
The sun acts as 1 direct source of the radiation environment, producing solar particle events, to include solar flares and coronal mass ejections, that produce solar energetic particles, such as electrons, protons, and heavy ions. Next The other direct source of the radiation environment are supernova/other stars which are producing Galactic Cosmic rays which produce similar particles as the sun. Next




***Presenter Notes***

*2025-06-03 15:00:33*

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But the Earth is not simply being bombarded from these two sources.

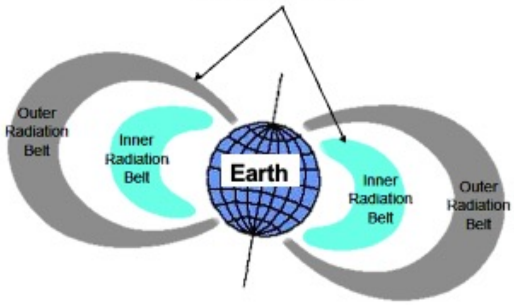
The Earth has a magnetic field around it, called the Van Allen Belts. Some particles will reach Earth still, but…Next Others will go around…Next

Others will enter at the poles, which is why we the Auroa Boreallis or Northern Lights are most prominent at the poles. Next And finally some particles will become trapped in the Van Allen Belts. Next

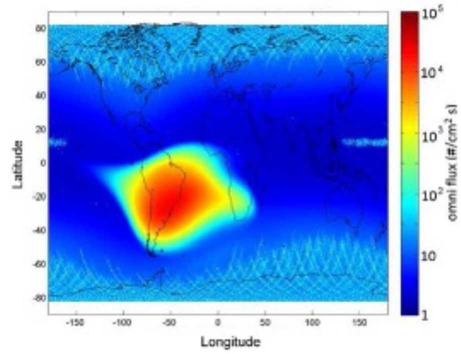
# Summary
# - Sources of Radiation Near Earth -

**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**

***Presenter Notes***
*2025-06-03 15:00:33*
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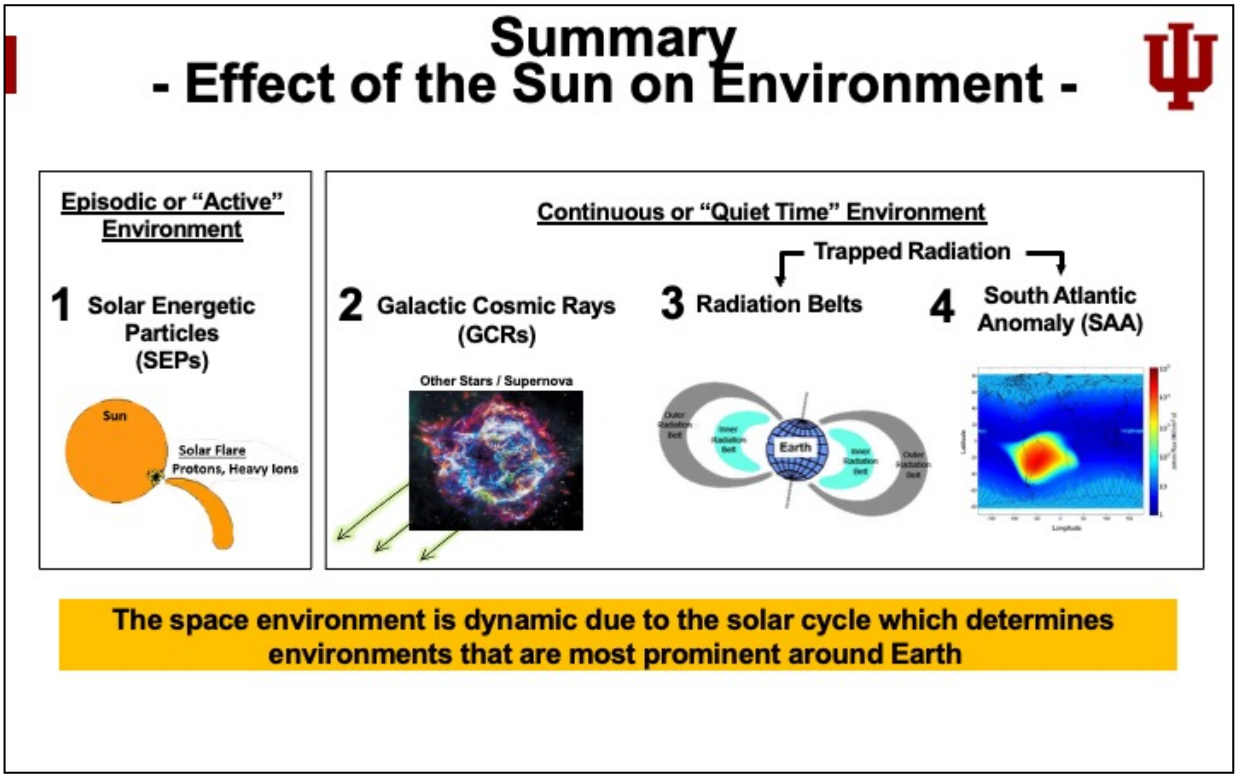
This trapped environment becomes the third source of the natural space radiation environment albeit an indirect source. The trapped environment does not produce radiation, it just collects it. Next Particles in the trapped environment mainly fall within an outer belt and an inner belt, which also includes the south Atlantic anomaly. Next




***Presenter Notes***

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The sun not only acts as a source of radiation but also acts as a modulator of the other sources of radiation environments. Next

The suns activity or solar cycle is 11 years long and includes about 7 years of active times where the sun is more active and 4 years where the sun is less active. When the sun is most active, Next, we call this the Active Environment which is when the sun contributes most to the space environment.

When the sun is less active, this is called the Quiet environment in which GCRs and the trapped environment are more pronounced.

The space environment is very dynamic due to the solar cycle and determines which environments are most prominent around Earth. Next

# 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 |

**Questions?**

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

***Presenter Notes***
*2025-06-03 15:00:36*
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All spacecraft trajectories include some portion of the space radiation environment and should be assessed to determine how to design your system to function in them. Justin will be digging into this subject deeper tomorrow when he introduces an acronym called MEAL. The E stands for Environment and is only one aspect of designing your system for the natural space environment. Thank you for your attention, I'll now be taking questions. I'd like to first start with the virtual participants and then take questions from Luddy. If you're on site in Luddy and have a question please head to the nearest microphone so that the audience can hear the question.

# 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]**

***Presenter Notes***
*2025-06-03 15:00:37*
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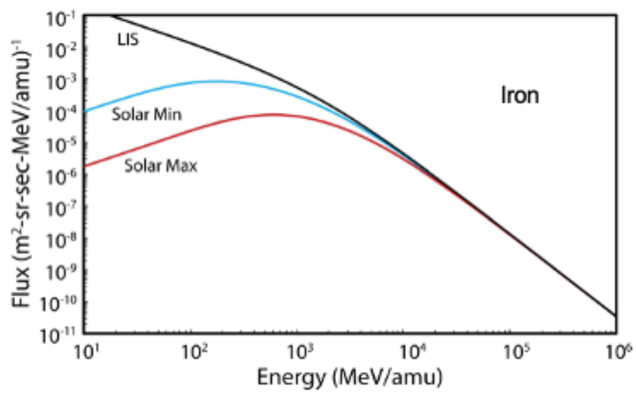
In February 2022, SpaceX witnessed the destructive power of the sun when a geomagnetic storm destroyed up to 40 Starlink satellites worth over $50 million shortly after deployment.

Starlink satellites (and other low-Earth orbit satellites) are particularly vulnerable to geomagnetic storms because they are released into very low-altitude orbits (between 60 and 120 miles (100 to 200 km), and they rely on onboard engines to overcome the force of drag, raising themselves to a final altitude of about 350 miles (550 km).

During a geomagnetic storm, Earth's atmosphere absorbs energy from the storms, heats up and expands upwards, leading to a significantly denser thermosphere that extends from about 50 miles (80 km) to approximately 600 miles (1,000 km) above the Earth's surface. A denser thermosphere means more drag which can be an issue for satellites. This is what happened in February when the batch of recently released Starlink satellites failed to overcome the increased drag caused by the geomagnetic storm and began to fall back to Earth, eventually burning up in the atmosphere.

## 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

***Presenter Notes***
*2025-06-03 15:00:40*
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On the graph, the black line is called the Local Interstellar Spectra which is what the energy spectra would look like outside of our solar system. When the Solar activity is low, Galactic Cosmic Rays influence the space environment around earth more.

When the Solar activity is high, the Sun influences the environment around earth more.

This is one reason why GCRs are considered a part of the "Quiet" Environment due to less Solar activity. If iron energies have high energies. Stronger solar max is attenuating the iron from the GCR