Lecture 5: Space Weather, Galactic Cosmic Rays, and the Atmospheric Spallation Source

CBE 30235: Introduction to Nuclear Engineering — D. T. Leighton

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1 Introduction: The Earth as a Nuclear Target

In our study of nuclear engineering thus far, we have largely focused on **closed systems**: a fuel pellet, a reactor core, or a lead-shielded source. In these environments, we control the flux and the geometry. However, from a geochemical and geophysical perspective, the Earth itself is a giant, unshielded target in a high-energy radiation field.

1.1 The "Open System" Perspective

Most standard textbooks, including Lamarsh, treat the Earth as an isolated system where radionuclides are either "primordial" (left over from the Earth's formation, like ^{238}U) or "anthropogenic" (man-made, like ^{137}Cs).

This perspective ignores a third, vital category: **Cosmogenic Radionuclides**. These are isotopes constantly being "manufactured" in the atmosphere by the interaction of cosmic rays with stable gas molecules. Without this external nuclear "rain," tools like Carbon-14 dating would not exist, as the primordial inventory of Carbon-14 would have decayed away billions of years ago.

1.2 Defining "Space Weather"

In a nuclear context, **Space Weather** is the study of the varying fluxes of particles and electromagnetic radiation originating from the Sun and the Galaxy. For a Nuclear Engineer, Space Weather represents the "Source Term" for the atmospheric reactor.

- **Kinetic Space Weather:** High-velocity particles (protons, alphas) that trigger nuclear transmutations. This is the driver for ^{14}C production.
- **Electromagnetic Space Weather:** X-rays and solar flares that impact the ionosphere and can induce massive currents in the power grid (e.g., the Carrington Event).

1.3 The Atmospheric Shield

We often think of the atmosphere only as something we breathe, but in nuclear terms, it is a **biological shield**.

- The atmosphere has an "areal density" of approximately $1030\,\text{g/cm}^2$ (the mass of the air column above a square centimeter at sea level).
- In terms of radiation protection, this is equivalent to roughly **10 meters (33 feet) of water** or **3 feet of steel**.

1.4 Engineering Context: Why this matters

Understanding the Earth as a target is no longer just for geologists. Modern engineers must account for this "target" behavior in several fields:

1. **Aerospace Engineering:** Pilots and frequent flyers receive a measurable increase in dose because they are "higher up" in the shield.
2. **Microelectronics:** As transistors get smaller, a single secondary neutron from a cosmic ray can flip a bit in a memory chip, causing a "Single Event Upset" (SEU).
3. **Environmental Monitoring:** To accurately measure man-made leaks from a reactor, we must first subtract the "background" created by the atmospheric spallation we will discuss today.

> *Core Concept:* The Carbon-14 clock is not a closed system; it is a **steady-state inventory** where the production rate (P) from space weather exactly balances the decay rate (λN) of the global inventory.

1.5 Reference for Further Reading

- **UNSCEAR (2000) Report:** Annex B: Exposures from Natural Radiation Sources. This document provides a rigorous breakdown of cosmic radiation flux, altitude effects, and the global production rates of cosmogenic radionuclides.

2 The Sun: Our Local Plasma Source

The Sun is the most prominent feature of our local radiation environment, but from a nuclear transmutation perspective, it is surprisingly "quiet." To understand why, we must look at the kinematics of the Solar Wind.

2.1 The Solar Wind: Composition and Velocity

The Solar Wind is a plasma consisting primarily of ionized hydrogen (protons) and electrons, with a small fraction of alpha particles. This plasma is not "radiated" like light; it is physically ejected from the solar corona and flows outward throughout the solar system.

- **Velocity:** Typically ranges from 300 to 800 km/s (often categorized as "slow" or "fast" solar wind).
- **Energy Profile:** While these speeds are immense by terrestrial standards, the *kinetic energy* of a proton moving at 500 km/s is only about **1.3 keV**. Even the most energetic particles in a standard solar stream rarely exceed **10 keV**.

2.2 The Earth's First Line of Defense: The Magnetosphere

Because the Solar Wind consists of charged particles, it is subject to the Lorentz force ($\mathbf{F} = q\mathbf{v} \times \mathbf{B}$). The Earth's intrinsic magnetic field creates a "bubble" known as the **Magnetosphere**.

- **Deflection:** The vast majority of solar protons are deflected around the Earth at the **Bow Shock**, similar to water flowing around the prow of a ship.

- **The Aurora:** Some particles are captured and funneled along magnetic field lines toward the North and South poles. When these keV-range protons collide with Nitrogen and Oxygen in the upper atmosphere, they excite the electrons in those atoms. The resulting "de-excitation" releases the visible light we recognize as the **Aurora**.

2.3 The Nuclear "Dead End"

For a Nuclear Engineer, the most important takeaway is the **Coulomb Barrier**.

- To trigger a nuclear reaction (like spallation or capture), a proton must get close enough to a nucleus for the Strong Force to take over. This requires overcoming the electrostatic repulsion of the target nucleus.
- The Coulomb barrier for a Nitrogen nucleus is approximately **2–3 MeV**.
- **Conclusion:** Solar wind protons ($\sim$1 keV) are three orders of magnitude too weak to cause nuclear transmutations. They cause *atomic* excitations (light) and *electronic* disruptions, but they cannot create Carbon-14.

Reference for Further Reading

- **NASA Space Physics:** The Solar Wind Tutorial. This provides the specific flux and density data for solar plasma at 1 AU.
- **Kallenrode, M. B. (2004):***Space Physics: An Introduction to Plasmas and Particles in the Heliosphere and Magnetospheres*. Springer. (A standard textbook reference for the energy-dependent behavior of solar vs. galactic particles).

3 The Carrington Event: EM vs. Kinetic Energy

While we have established that solar particles generally lack the kinetic energy to trigger nuclear transmutations, the Sun is capable of massive electromagnetic (EM) outbursts. In nuclear engineering, we must distinguish between "Hard Radiation" (particles) and "Inductive Effects" (fields).

3.1 Coronal Mass Ejections (CMEs)

A CME is a massive burst of solar wind and magnetic fields rising above the solar corona or being released into space. Unlike the steady-state solar wind, a CME is a coherent "slug" of plasma that carries an immense frozen-in magnetic field.

3.2 The 1859 Carrington Event

The most famous example occurred in September 1859, observed by British astronomer Richard Carrington.

- **The Observation:** A "white-light flare" was seen on the solar disk, followed approximately 17 hours later by a massive geomagnetic storm.
- **The Impact:** The Earth's magnetosphere was severely compressed. Auroras were visible as far south as the Caribbean.

- **Engineering Consequence:** The rapidly changing magnetic field ($\frac{d\mathbf{B}}{dt}$) induced massive currents in long-wire telegraph systems. Operators reported sparks leaping from their equipment, and in some cases, the lines continued to send signals even after the batteries were disconnected.

3.3 The Engineering Lesson: Ionizing vs. Inductive

For the Nuclear Engineer, this distinction is critical for system design:

1. **Ionizing Radiation:** Requires high kinetic energy (MeV/GeV) to penetrate shielding or flip bits in microchips. This is largely a **Galactic** problem.

2. **Geomagnetically Induced Currents (GIC):** Requires a massive, moving magnetic field. This is a **Solar** problem. A modern "Carrington-level" event would likely destroy high-voltage power transformers across the globe, not through radiation damage, but through thermal failure due to induced DC currents saturating the magnetic cores.

Reference for Further Reading

- **Space.com:** The Carrington Event: History's greatest solar storm. A historical and technical review of the Carrington observations with lots of additional references.

4 Crossing the Border: The Heliopause

To understand where the Carbon-14 "fuel" actually comes from, we have to look far beyond the Earth, past the orbit of Pluto, to the edge of the Sun's physical influence.

4.1 The Heliosphere: Our Magnetic Bubble

The solar wind we discussed in Section 2 doesn't just stop at the planets; it flows outward in all directions, creating a giant "bubble" in the interstellar medium known as the **Heliosphere**.

- Inside this bubble, the environment is dominated by solar plasma and the Sun's magnetic field.

- Outside this bubble lies the "Interstellar Medium" (ISM)—the debris, gas, and high-energy radiation of the Milky Way galaxy.

4.2 The Heliopause: The Pressure Balance

The **Heliopause** is the theoretical boundary where the outward "dynamic pressure" of the solar wind ($P = \frac{1}{2}\rho v^2$) exactly balances the inward pressure of the interstellar gas.

4.3 The Voyager Discovery (The "In-Situ" Experiment)

For decades, our understanding of the Heliopause was purely mathematical. That changed with the Voyager 1 and 2 missions.

- **The Crossing:** In August 2012, Voyager 1 became the first human-made object to cross the Heliopause.

- **The Data:** Scientists observed a dramatic, sudden drop in solar particles and a simultaneous, massive **surge in high-energy Galactic Cosmic Rays (GCRs)**.
- **The "Shield" Confirmed:** This measurement proved that the Sun's magnetic wind acts as a giant "shield" (via magnetic scattering and diffusion), blocking approximately **90%** of the galaxy's lower-energy cosmic rays from ever reaching the inner solar system.

4.4 Implications for the C-14 Clock

This discovery is critical for the "Nuts and Bolts" of Carbon-14 dating:

1. **The Source Baseline:** We now know the "unmodulated" flux of the galaxy.
2. **The Modulation Effect:** Because the solar wind strength varies with the 11-year solar cycle, the "thickness" of this shield changes. This causes the production rate of Carbon-14 on Earth to fluctuate slightly over time—one of the primary reasons we must "calibrate" the Carbon-14 clock against known-age samples like tree rings.

Reference for Further Reading

- **NASA Jet Propulsion Laboratory (JPL):** Voyager: The Interstellar Mission. This is the official mission page detailing the transition into interstellar space and the specific instruments used to measure the cosmic ray surge.
- **Technical summary of recent Voyager results:** Galactic Cosmic Rays Throughout the Heliosphere and in the Very Local Interstellar Medium.

5 The Galactic "Violent" Source (GCRs)

Now that we have moved outside the protective "bubble" of the Sun, we encounter the true source of our atmospheric nuclear reactions: **Galactic Cosmic Rays (GCRs)**.

5.1 What are GCRs?

Despite the name "rays," these are not electromagnetic radiation (like X-rays or Gamma rays). They are high-mass, relativistic charged particles.

- **Composition:** Approximately 89% protons (H^+), 10% alpha particles (He^{++}), and 1% heavier nuclei (up to Iron).
- **The Origin:** Accelerated to near-light speeds by the massive shockwaves of **Supernovae** occurring across our galaxy.

5.2 Energy: The GeV Scale

While we measure Solar Wind in keV, GCRs are measured in **GeV (Giga-electron volts)** and even **TeV**.

- A typical GCR proton has a kinetic energy of 1 GeV to 10 GeV.
- **The Engineering Comparison:** The protons in the Large Hadron Collider (LHC) are accelerated to 6.5 TeV. Nature is hitting the top of our atmosphere with particles of comparable—and sometimes much higher—energies.

5.3 Penetration: Punching through the Magnetosphere

In Section 2, we saw that the Earth's magnetic field easily deflects the 1 keV solar wind. However, for a 10 GeV GCR proton, the Earth's field is essentially "transparent."

- **Magnetic Rigidity:** This is a measure of a particle's resistance to being deflected by a magnetic field. Because GCRs have such high momentum, their *gyroradius* is often larger than the Earth's magnetosphere itself.
- **Impact:** These particles do not get funneled to the poles like the solar wind; they strike the atmosphere at all latitudes (though there is a slight "latitude effect" where the field is weaker at the poles).

5.4 The Biological/Engineering Shield (Revisited)

Because GCRs are so energetic, they represent the primary radiation hazard for deep-space travel (e.g., a mission to Mars).

- **Secondary Radiation:** When a GCR hits a metal spacecraft wall, it creates a shower of secondary neutrons and pions—ironically making the radiation environment *inside* a poorly designed ship worse than the one outside.
- **Earth's Advantage:** We are protected not by a magnetic field, but by the **mass** of our atmosphere. The GCRs must pass through $\sim$1000 g/cm^2 of air, which acts as a "spallation target" that absorbs their energy.

Reference for Further Reading

- **NASA Goddard Space Flight Center:** Cosmic Rays. A clear breakdown of GCR composition and the "Extra-Solar" origin.
- **The Voyager Interstellar Mission:** Voyager 1 & 2 Mission Profile.

6 The Atmospheric Spallation Source

In a standard nuclear reactor, we rely on **fission** (splitting heavy nuclei with low-energy neutrons). In the upper atmosphere, we see **spallation**: the "shattering" of light nuclei by ultra-high-energy particles.

6.1 The Physics of Spallation

When a GeV-scale GCR proton strikes a nucleus (primarily ^{14}N or ^{16}O), the wavelength of the projectile is much smaller than the dimensions of the nucleus.

- **The Intranuclear Cascade:** The proton doesn't "bounce off"; it plow through, colliding with individual nucleons. This "cue ball" effect ejects a spray of secondary particles.
- **Evaporation:** The remaining "heated" nucleus sheds its excess energy by "boiling off" additional neutrons and protons.

6.2 The Secondary "Debris" Flux

A single primary GCR proton can generate a "shower" of thousands of secondary particles. For our purposes, the most important are:

- **Neutrons (n):** These are the "parent" particles for ^{14}C.
- **Muons ($\mu^{\pm}$):** Highly penetrating particles that reach the Earth's surface. (Fun fact: about 10,000 muons pass through your body every minute).
- **Pions (π):** Short-lived mesons that decay into the muons and gammas we detect at sea level.

6.3 Engineering Tie-in: The SNS (Oak Ridge)

This is not just "space physics"—it is a major tool in material science.

- At the **Spallation Neutron Source (SNS)** in Oak Ridge, TN, engineers use a linear accelerator to fire 1 GeV protons at a liquid Mercury target.
- **The Advantage:** Unlike a reactor, which provides a steady (DC) flux of thermal neutrons, a spallation source provides an extremely intense, **pulsed** (AC) flux of high-energy neutrons.
- The Earth's upper atmosphere is essentially a "Natural SNS," where the "target" is the Nitrogen gas.

Reference for Further Reading

- **Oak Ridge National Laboratory:** Virtual Tour. A virtual tour of the SNS facility, with links to other resources.
- **Wikipedia:** Cosmogenic Nuclides. A useful discussion of all the nuclides formed from cosmic ray bombardment.

7 The Production of Carbon-14

Once the spallation process in the upper atmosphere has liberated a "sea" of neutrons, the final nuclear synthesis of ^{14}C can begin. This requires two distinct steps: Moderation and Capture.

7.1 Neutron Moderation: Slowing Down

The neutrons produced by spallation are "fast" (carrying MeV of energy). However, Nitrogen-14 has a much higher capture cross-section for "thermal" neutrons (energy ≈ 0.025 eV).

- **The Moderator:** The atmosphere itself (primarily N_2 and O_2 molecules) acts as the moderator.
- **Elastic Scattering:** Through repeated collisions with these nuclei, the neutrons lose kinetic energy until they reach thermal equilibrium with the surrounding gas.

7.2 The (n, p) Reaction

The primary channel for ^{14}C production is an **exothermic** (n, p) **reaction** with the most abundant isotope in our atmosphere, Nitrogen-14.

$$^{14}_{7}\text{N} + {}^{1}_{0}n \longrightarrow {}^{14}_{6}\text{C} + {}^{1}_{1}H + 0.626\,\text{MeV} \tag{1}$$

- **The Mechanics:** The thermal neutron is absorbed by the ^{14}N nucleus, forming an excited intermediate state which then ejects a proton to reach the relatively stable (but radioactive) ^{14}C state.
- **Energy Balance:** The reaction is exothermic, releasing about 626 keV of energy, which is carried away by the kinetic energy of the ejected proton and the recoiling ^{14}C nucleus.

7.3 Chemical Fate: From Nucleus to CO_2

As a Nuclear Engineer, you must ask: "What happens to the atom after the reaction?"

1. The nascent ^{14}C atom is highly reactive (a "hot atom").
2. It quickly reacts with atmospheric Oxygen to form ^{14}**CO (Carbon Monoxide)** and eventually ^{14}**CO$_2$ (Carbon Dioxide)**.
3. This $^{14}CO_2$ is chemically identical to standard $^{12}CO_2$, allowing it to enter the global carbon cycle through photosynthesis.

7.4 Other Cosmogenic "Debris"

While ^{14}C is the most famous, other capture and spallation channels produce a suite of radionuclides:

- **Tritium (^{3}H):** Produced via $^{14}\text{N} + n \longrightarrow {}^{12}\text{C} + {}^{3}\text{H}$.
- **Beryllium-7 and 10:** Produced by the direct spallation (fragmentation) of Nitrogen and Oxygen.

Reference for Further Reading

- **Wikipedia:** Carbon-14. (A reliable summary of the (n, p) reaction and the discovery of the isotope by Kamen and Ruben in 1940).

8 Space Engineering Implications

The high-energy environment that creates our "Atmospheric Nuclear Reactor" poses significant challenges for modern engineering, particularly as we move beyond the protective "shield" of Earth's atmosphere and magnetosphere.

8.1 Deep Space Travel: The Shielding Paradox

One of the most significant hurdles for a manned mission to Mars is not the Sun, but the Galactic Cosmic Rays (GCRs) we discussed in Section 5.

- **Transient vs. Continuous:** Solar flares (Solar Particle Events) are intense but transient; astronauts can retreat to a "storm shelter" made of hydrogen-rich material (like water or polyethylene) for a few hours.
- **The GCR Constant:** GCRs are a continuous, omnidirectional "background" of GeV-scale particles. Because they are so energetic, they are nearly impossible to stop with conventional shielding.
- **Secondary Spallation:** When a GeV proton strikes a heavy metal shield (like lead or aluminum), it triggers spallation *within the shield itself*, creating a shower of secondary neutrons and X-rays. This can actually increase the biological dose to the crew—a phenomenon known as the "shielding paradox."

8.2 Electronics Hardening: Single Event Upsets (SEUs)

As we shrink the size of transistors on silicon chips to the nanometer scale, the amount of charge required to represent a "1" or a "0" (the critical charge) becomes tiny.

- **Bit Flipping:** When a secondary neutron or a heavy cosmic ray ion passes through a semiconductor, it leaves a trail of ionization. This can deposit enough charge to flip a bit in memory or a logic gate.
- **SEUs:** This is known as a **Single Event Upset**. While usually not destructive to the hardware, it causes software "glitches" that can be catastrophic for flight control systems.
- **Rad-Hardening:** Spacecraft engineers must use "Rad-Hard" components, which often involve redundant logic (e.g., Triple Modular Redundancy, where three chips "vote" on every calculation) or specialized manufacturing processes like Silicon-on-Insulator (SOI).

Reference for Further Reading

- **NASA Goddard:** Space Radiation is Risky Business. A high-level overview of the biological and engineering risks of GCRs.
- **IEEE Spectrum:** How to Kill a Supercomputer. A fascinating look at how cosmic rays cause errors even in terrestrial computers at high altitudes or in large data centers.

9 Conclusion: From Cosmic Rays to Global Tracers

We have seen that the Earth is not a closed system, but a target in a high-energy galactic laboratory. The constant "rain" of cosmic rays creates a steady-state inventory of isotopes that would not otherwise exist on our planet.

- **The Steady State:** On a global scale, the production rate (P) of ^{14}C in the upper atmosphere is balanced by its radioactive decay (λN) and its sequestration in the oceans and biosphere.

- **The Engineering Challenge:** While these particles are a "nuisance" for spacecraft designers and chip manufacturers, they provide geochemists with a unique set of tools.

Looking Ahead: In the next lecture, we will move from the physics of the "Atmospheric Reactor" to the application of its products. We will explore the "Nuts and Bolts" of ^{14}C dating, and see how human activities—from the Industrial Revolution to the Cold War "Bomb Pulse"—have perturbed this natural clock, allowing us to track everything from the age of King Tut to the deep-sea circulation of the Atlantic Ocean.

Technical Note: Thermodynamics of (n, p) Reactions
From Atmospheric Chemistry to Biological Hazard

1 Introduction: The General Rule vs. The Exception

In nuclear reactor analysis, we generally categorize neutron-proton reactions, denoted as (n, p), as **Threshold Reactions**. This means they typically require high-energy "fast" neutrons ($E_n > 1$ MeV) to occur.

However, the absorption of neutrons by Nitrogen-14 is a notable exception. It occurs readily with **thermal** neutrons ($E_n \approx 0.025$ eV). This mechanism is critical not only for radiocarbon dating but also for understanding the biological risks of neutron radiation in space environments.

2 Case 1: The Nitrogen Anomaly (^{14}N)

2.1 The Reaction

We consider the reaction responsible for Carbon-14 production:

$$^1_0n + ^{14}_7\text{N} \longrightarrow ^{14}_6\text{C} + ^1_1p + Q \tag{2}$$

2.2 Thermodynamic Analysis (Q-Value)

The Q-value is defined as the mass difference between reactants and products (converted to energy).

$$Q = \left[(m_n + M(^{14}\text{N})) - (M(^{14}\text{C}) + M(^1\text{H}))\right] c^2$$

Using standard atomic masses (in AMU):

- Mass of Reactants: $1.008665 + 14.003074 = 15.011739$ u
- Mass of Products: $14.003241 + 1.007825 = 15.011066$ u

$$\begin{aligned}\Delta m &= 15.011739 - 15.011066 = +0.000673 \text{ u}\\ Q &= 0.000673 \text{ u} \times 931.5 \text{ MeV/u}\\ \mathbf{Q} &\approx \mathbf{+0.626} \text{ MeV}\end{aligned}$$

2.3 Physics Interpretation

Because $Q > 0$, the reaction is **Exothermic**.

1. **No Kinetic Energy Required:** The system releases energy upon reaction. Therefore, the incident neutron does not need to bring kinetic energy to "pay" for the mass difference.
2. **Nuclear Structure:** ^{14}N is an "Odd-Odd" nucleus (7p, 7n). Converting it to ^{14}C ("Even-Even", 6p, 8n) increases the nuclear binding energy. Nature prefers this configuration.

Result: The cross-section follows the $1/v$ law for thermal neutrons, reaching a significant $\sigma_{th} \approx 1.83$ barns.

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3 Biological Implications: The Thermal Neutron Hazard

In the context of Space Weather and radiation protection, the $^{14}\text{N}(n,p)$ reaction presents a unique hazard. While the bulk of the human body is Oxygen and Hydrogen, Nitrogen constitutes roughly 3% by weight (found in DNA and amino acids).

3.1 The Hazard is the Proton, Not the Carbon

A common misconception is that the danger comes from the creation of radioactive Carbon-14. While ^{14}C is indeed radioactive, it has a half-life of 5,730 years; its decay rate is negligible in the context of acute dose.

The immediate danger arises from the **emitted proton**.

3.2 Kinetic Energy Partition

The reaction releases $Q = 0.626$ MeV of kinetic energy. Due to Conservation of Momentum, this energy is split between the heavy ^{14}C recoil nucleus and the light proton.

$$E_p \approx Q \left(\frac{M_{^{14}\text{C}}}{M_{^{14}\text{C}} + m_p} \right) \approx 0.626 \text{ MeV} \left(\frac{14}{15} \right) \tag{3}$$

$$\mathbf{E_p} \approx \mathbf{0.584} \text{ MeV} \quad \text{(Proton Energy)} \tag{4}$$

3.3 Linear Energy Transfer (LET) and Cell Damage

Why is a 0.584 MeV proton worse than a gamma ray?

1. **High LET:** The proton is a heavy, charged particle. It interacts strongly with electrons in the tissue, creating a dense trail of ionization.

2. **Short Range:** A 0.6 MeV proton travels approximately **10 μm** in water/tissue. This is roughly the diameter of a single human cell.

3. **Localized Dose:** Unlike a Gamma ray (which often passes through the body without interacting) or the 2.2 MeV Gamma from Hydrogen capture ($^{1}\text{H}(n,\gamma)$), the proton dumps 100% of its energy *inside the cell where the neutron was captured.*

This results in a high **Relative Biological Effectiveness (RBE)**. In dosimetry calculations, protons from this reaction are often assigned a Quality Factor (w_R) of 20, meaning they are considered 20 times more damaging per unit energy than gamma rays.

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4 Transport and Competition: The Depth of the Hazard

If a thermal neutron flux strikes a human body, how far does it penetrate, and which nucleus actually absorbs it?

4.1 Penetration Depth (The Diffusion Length)

Thermal neutrons do not travel in straight lines through tissue. Because the body is mostly water, neutrons undergo frequent elastic scattering collisions with Hydrogen atoms (Mean Free Path $\lambda_s \approx 0.3$ cm).

The neutron effectively performs a "Random Walk." The net distance traveled before absorption is characterized by the **Diffusion Length** (L):

$$L_{tissue} \approx 2.8 \text{ cm} \tag{5}$$

Because the flux attenuates exponentially ($e^{-x/L}$), thermal neutrons are primarily a **surface hazard** (skin, lens of the eye). By a depth of 10 cm, the thermal flux is reduced by over 95%.

4.2 The Competition: Hydrogen vs. Nitrogen

Once the neutron is thermalized, two reactions compete for the capture:

1. **Hydrogen Capture:** $^1\text{H}(n,\gamma)^2\text{H}$ ($\sigma \approx 0.33$ b). The body is $\sim$ 10% Hydrogen by mass (60% by atom count).

2. **Nitrogen Absorption:** $^{14}\text{N}(n,p)^{14}\text{C}$ ($\sigma \approx 1.83$ b). The body is $\sim$ 3% Nitrogen by mass.

Despite the lower cross-section, Hydrogen is so abundant that it wins the "capture race" roughly 85% of the time. However, the 15% of captures that occur in Nitrogen contribute nearly **half the biological dose equivalent** due to the high Quality Factor of the emitted proton.

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5 Case 2: The Oxygen Standard (^{16}O)

For contrast, we examine Oxygen-16.

$${}^1_0n + {}^{16}_8\text{O} \longrightarrow {}^{16}_7\text{N} + {}^1_1p + Q \tag{6}$$

5.1 Thermodynamic Analysis

$$Q = \left[(m_n + M(^{16}\text{O})) - (M(^{16}\text{N}) + M(^1\text{H}))\right] c^2 \approx \mathbf{-9.64} \text{ MeV}$$

Because $Q < 0$, the reaction is **Endothermic**. The incident neutron must provide enough kinetic energy to create the extra mass.

$$E_{th} \approx |Q| \left(1 + \frac{m_n}{M_{target}}\right) \approx \mathbf{10.2} \text{ MeV} \tag{7}$$

Result: A thermal neutron (0.025 eV) has insufficient energy. The cross-section is exactly zero.

6 Summary Comparison

Parameter	**Nitrogen-14**	**Oxygen-16**
Reaction	^{14}N$(n,p)^{14}$C	^{16}O$(n,p)^{16}$N
Q-Value	$+$**0.626** MeV	$-$**9.64** MeV
Biological Hazard	**High** (High-LET Proton)	**None** (Stable ^{17}O via capture)
Threshold Energy	None (0 eV)	$\approx$ 10.2 MeV
σ(0.025 eV)	**1.83 barns**	**0 barns**

Table 1: Comparison of atmospheric/biological nuclei. Nitrogen acts as a "proton mine" for thermal neutrons, while Oxygen is essentially transparent to this reaction channel.

Technical Note: The Earth's Antimatter Halo

Abstract

Summary: The Earth is the brightest gamma-ray source in the sky in the 0.511 MeV band. This lecture explains the origin of this "Antimatter Glow" (Pair Production), its energy threshold, how it serves as a calibration tool for satellites, and why it acts as "noise" for interstellar astronomy. We also explore its inverse correlation with the Solar Cycle.

1 1. The Mechanism: How the Earth Generates Antimatter

Why does the Earth glow at exactly **0.511 MeV**? It is not primarily due to radioactive decay (like ^{13}N), but rather a high-energy conversion process.

1.1 The Source: The Electromagnetic Cascade

When Galactic Cosmic Rays (GCRs) strike the upper atmosphere, they initiate a particle shower.

1. **Pion Production:** $p_{GCR} + N_{air} \longrightarrow p + N + \pi^0 + \ldots$
2. **Pion Decay:** The neutral pion decays instantly (10^{-16} s) into high-energy photons:

$$\pi^0 \longrightarrow \gamma + \gamma \quad (E_\gamma \approx 70 \text{ MeV})$$

3. **Pair Production:** These high-energy photons interact with atmospheric nuclei:

$$\gamma \longrightarrow e^- + e^+$$

1.2 The Threshold Energy Calculation

To create this matter/antimatter pair, the incident photon must possess enough energy to create the rest mass of two electrons.

$$E_{th} = 2 \times m_e c^2$$
$$E_{th} = 2 \times 0.511 \text{ MeV}$$
$$E_{th} = \mathbf{1.022} \text{ MeV}$$

The Energy Gap: Since the incident photons from pion decay have energies > 50 MeV, they exceed this threshold by a factor of 50. This is why the upper atmosphere is flooded with positrons.

2 2. The Signal: Annihilation

The positrons do not survive long. They thermalize (slow down) and find an electron.

$$e^+ + e^- \longrightarrow \gamma_1 + \gamma_2 \tag{8}$$

Conservation of momentum requires two photons emitted back-to-back (180°). Conservation of energy requires:

$$E_\gamma = m_e c^2 = \mathbf{0.511} \text{ MeV}$$

This creates a sharp spectral "line" at 0.511 MeV, often called the *Annihilation Line.*

3 3. Temporal Variation: The Solar Inverse

The intensity of Earth's antimatter glow is **not constant**. It breathes with the Sun.

3.1 The Anti-Correlation Mechanism

The raw fuel for this process is Galactic Cosmic Rays (GCRs).

- **Solar Minimum:** The Sun's magnetic field is weak. GCRs penetrate easily.
- **Solar Maximum:** The Sun's magnetic field is turbulent and strong. It "blows away" the lower energy GCRs.

Result: The Earth glows *brightest* when the Sun is quiet.

> *Observation:* Data from the SMM satellite (1980s) showed the 0.511 MeV flux dropping by $\sim 20\%$ during Solar Max compared to Solar Min.

4 4. Satellites and the "Light Bulb" Problem

For gamma-ray astronomers, the Earth is a nuisance. It is a massive, bright "light bulb" that blinds sensitive detectors.

4.1 The Satellites

- **CGRO (Compton Gamma Ray Observatory):** Its OSSE instrument mapped the Earth's "albedo" to understand atmospheric physics.
- **Fermi Gamma-ray Space Telescope:** The GBM instrument uses the Earth's 0.511 MeV line as a constant **calibration source** to ensure its detectors are tuned correctly.
- **INTEGRAL (ESA):** A master of "background subtraction." It looks for 0.511 MeV signals from the center of the galaxy and must rigorously filter out the Earth's glow.

4.2 Detection Issues: "Occultation"

Satellites in Low Earth Orbit (LEO) cannot look "down." Roughly 40% of their field of view is blocked by the Earth (the "Earth Occultation").

- **The Issue:** Not only is the view blocked, but the "Earth Albedo" enters the detector from the back/sides, raising the noise floor.
- **The Workaround:** Heavy lead shielding is placed behind detectors to block the Earth's glow, but at 0.511 MeV, shielding is heavy and expensive.

5 5. Correlations with Interstellar Events?

You asked if the Earth's glow correlates with interstellar events (like Supernovae).

5.1 The "Steady State" Reality

Generally, **No.** The flux of GCRs is an average over millions of years of galactic history. A single supernova occurring today (unless it was very close, $<$ 30 light years) would not significantly change the GCR flux hitting Earth immediately.

5.2 The Exception: Forbush Decreases

While we don't see "spikes" from interstellar events, we do see "dips" caused by solar events.

- When a massive Coronal Mass Ejection (CME) hits Earth, it acts as a magnetic shield, temporarily sweeping away GCRs.
- **Effect:** The Earth's 0.511 MeV glow **diminishes** sharply for a few days. This is called a *Forbush Decrease*.

5.3 The "Galactic Center Excess"

There is a major astrophysical mystery called the **511 keV Galactic Center Excess**.

- **The Mystery:** The center of the Milky Way glows in 0.511 MeV light far more brightly than known supernova rates can explain.
- **Relevance:** We use satellites like INTEGRAL to study this. The main challenge? *Distinguishing the Galaxy's glow from the Earth's glow.* We have to point the satellite away from Earth and carefully subtract the "atmospheric noise" to see the "galactic signal."

6 References and Further Reading

1. **NASA Fermi Mission:** Fermi Gamma-ray Space Telescope. (Search for "GBM Calibration").
2. **ESA INTEGRAL Mission:** *Mission Accomplished*. (Retrospective on INTEGRAL Science Operations).
3. **SMM Data Analysis:** Harris, M. J, et al. (2003). "Spatial and temporal variability of the gamma radiation from Earth's atmosphere during a solar cycle" *Journal of Geophysical Research.*
4. **Physics Overview:** Grieder, P. K. (2001). *Cosmic Rays at Earth*. Elsevier Science. (Comprehensive text on air showers).

Lecture 5 Addendum: Engineering Implications of Space Weather

1 Introduction: The Three Zones of Hazard

When designing for radiation survivability—whether for biological organisms or silicon transistors—the "Space Environment" is not a monolith. It varies drastically depending on the spacecraft's position relative to Earth's magnetosphere.

We categorize the hazards into three distinct orbital regimes:

1. **LEO (Low Earth Orbit):** Protected by the magnetosphere and atmosphere.
2. **GEO (Geostationary Orbit):** Inside the trapping region (Outer Van Allen Belt).
3. **Interplanetary (Translunar):** Unshielded deep space environment.

2 Zone 1: Low Earth Orbit (LEO)

Altitude: ~ 400 km (ISS) to $2,000$ km.
The Shield: 400 km of atmosphere and strong magnetic field lines.

2.1 The Anomaly: SAA (South Atlantic Anomaly)

While LEO is generally safe, the Earth's magnetic dipole is offset from the planetary center by approximately 500 km and tilted by 11°. This causes the inner Van Allen proton belt to "dip" into the atmosphere over Brazil/South Atlantic.

- **Biological Hazard:** Astronauts on the ISS receive the majority of their daily dose during the few minutes they pass through the SAA. EVAs (spacewalks) are scheduled to avoid these passes.
- **Electronic Hazard (SEU):** The SAA is a "Proton Trap." High-energy protons cause **Single Event Upsets (SEUs)**—non-destructive bit flips in memory.

  Example: Standard laptops on the ISS frequently "blue screen" or reboot when passing over the South Atlantic due to memory corruption.

2.2 Atmospheric Drag and Solar Max

During high solar activity (Solar Max), UV radiation heats the upper atmosphere, causing it to expand (puff up). This increases the drag on LEO satellites by increasing the (very small) gas density at LEO orbit altitudes.

> *Case Study:* In February 2022, a mild geomagnetic storm caused the atmosphere to warm, increasing drag by 50%. This effectively destroyed 40 newly launched SpaceX Starlink satellites, which burned up upon reentry.

3 Zone 2: Geostationary Orbit (GEO)

Altitude: $35,786$ km.
The Trap: The heart of the Outer Van Allen Belt.

3.1 The Electron Hazard

GEO is dominated by high-energy electrons (often called "Killer Electrons").

3.1.1 Electronics: Dielectric Charging

The primary failure mode in GEO is not bit-flips, but **Deep Dielectric Charging**.

- High-energy electrons (> 1 MeV) penetrate the spacecraft skin.
- They embed themselves inside circuit board insulation or coaxial cable sheathing.
- Charge builds up over days until it exceeds the breakdown voltage of the material.
- **Result:** A massive electrostatic discharge (ESD) occurs inside the satellite, frying components.

3.1.2 Biological Hazard: Bremsstrahlung

If humans were to inhabit a GEO station, the hull shielding would present a paradox.

- As high-energy electrons strike an aluminum hull, they decelerate rapidly.
- This deceleration produces intense **Bremsstrahlung** (X-rays).
- *Engineering Solution:* Shielding must be graded—a low-Z material (like polyethylene) on the outside to slow electrons gently, followed by high-Z (lead/tungsten) to stop residual X-rays.

4 Zone 3: Translunar / Deep Space

Altitude: $> 60,000$ km (Outside Magnetosphere).
The Void: Exposure to the raw Interplanetary Magnetic Field (IMF).

4.1 Hazard A: Solar Particle Events (SPE)

These are "Acute" events. A Coronal Mass Ejection (CME) accelerates protons to relativistic speeds.

- **Flux:** Can increase by factors of $10,000\times$ in less than an hour.
- **Biological Consequence:** Without shelter, an astronaut could receive a lethal dose (Acute Radiation Syndrome) in hours. Lunar bases require a "Storm Shelter" (e.g., walls of water or buried regolith habitats).

4.2 Hazard B: Galactic Cosmic Rays (GCR)

These are "Chronic" background events.

- **Composition:** High-Z, High-Energy (HZE) particles (Iron, Silicon nuclei) stripped of electrons, moving at $0.99c$.
- **Electronics (SEL):** GCRs deposit massive charge tracks. This can trigger a **Single Event Latch-up (SEL)**. A parasitic short-circuit forms in the silicon, drawing massive current until the device burns out physically.

- **Biological Consequence:** These heavy ions tear through DNA like a bullet, causing complex Double-Strand Breaks. This is the primary limiting factor for a Mars mission due to increased lifetime cancer risk and potential cognitive degradation.

5 Summary

Orbit	Primary Shield	Dominant Particle	Key Engineering Risk
LEO	Magnetosphere	Trapped Protons (SAA)	**SEUs** (Bit flips) & Drag
GEO	None (Trapped)	Trapped Electrons	**Dielectric Charging** (ESD)
Lunar	None	Heavy Ions (GCR) + Solar Protons	**Latch-ups** (Hardware Death) & Bio-Dose

Table 2: Comparison of Radiation Hazards by Orbital Regime.

References and Further Reading

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3. NASA. (2014).*Space Faring: The Radiation Challenge*. NASA EP-2014-10-025-JSC.

4. Dyson, P. (2022). "SpaceX loses 40 satellites to geomagnetic storm." *BBC News*. [Atmospheric Drag Case Study].