Radiation Environments

Dr. Heather Quinn

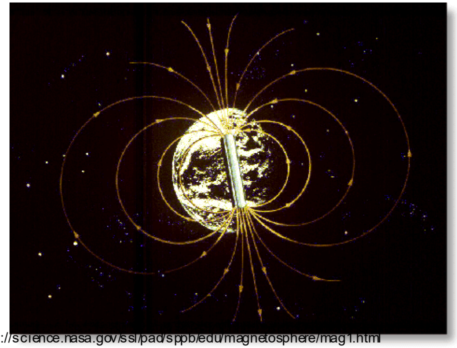
Overview

- Space and Terrestrial Environments
- Accelerator Environments

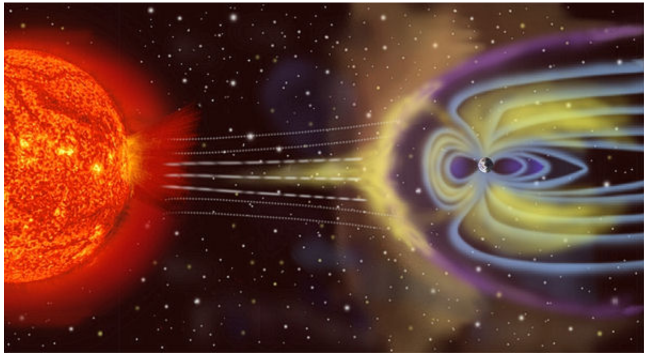
The Near-Earth Environment

The Natural Radiation Environment

- Our initial understanding of cosmic rays predates our concepts of sub-atomic particles
  - Scientists knew charged particles were coming from the atmosphere 30 years before the neutrons were discovered
  - Original definitions were "particles that rain down from the sky but do not make me wet"
- Galactic flux:
  - "Debatable Origins"
  - Very energetic (1023 eV), very dense flux (100,000/m2-s)
- Solar flux:
  - Not energetic
  - Affected by solar winds



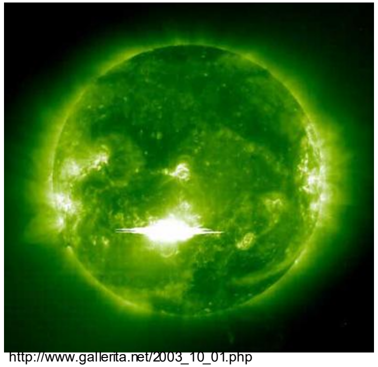
http://science.nasa.gov/ssl/pad/sppb/edu/magnetosphere/mag1.html



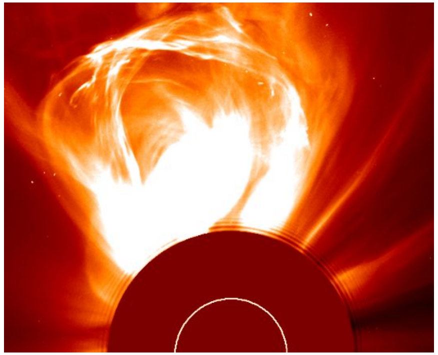
http://www.eskimo.com/~nancok/science/2007_07_01_archive.html

Solar Flares and Coronal Mass Ejections

- Coronal mass ejections (CME) release solar atmosphere
  - Often in conjunction with solar flares, but not necessarily
  - X-Ray, gamma-rays, electrons, protons, and heavy ions released at near speed of light
- CME/solar flares can filter to earth for a few hours after the event
  - Auroras
  - X-Ray-induced communication problems
  - Increased soft errors
- Every solar cycle seems to have one unusually large CME



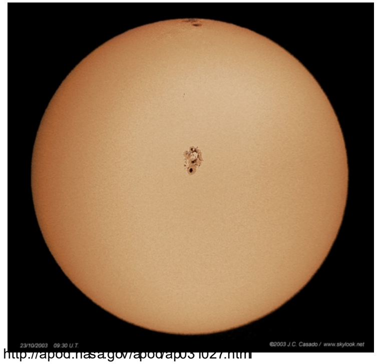
http://www.gallerita.net/2003_10_01.php



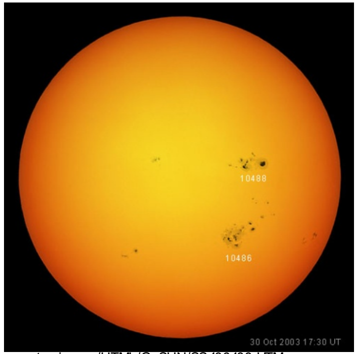
http://www.arm.ac.uk/climate/images/febcme_sohoc2_big.gif

The Halloween 2003 Coronal Mass Ejections

- Three active solar spot groups (10484, 10486, 10488):
  - All three were “remarkable in size and magnetic complexity”
  - One sun spot group (10486) was on over 13 times the size of the Earth and was the largest sun spot group observed since Nov 1990
- 17 CME ejections from mid-October to early November
  - 12 events from 10486 alone
  - Three major events: the X17 on Oct 28, X10 on Oct 29, X28e on Nov 4
  - X28e event occurred while the GOES detector saturated and was likely an X40 event



http://apod.nasa.gov/apod/ap031027.html

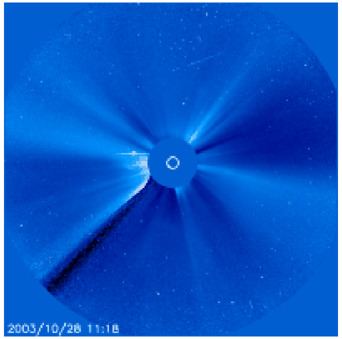


http://www.astropix.com/HTML/G_SUN/SS486488.HTM

T, Gombosi. “Comprehensive Solar-Terrestrial Environment Model for Space Weather Predictions. DoD MURI Project Report 2001-2004

Effects from The Halloween 2003 Coronal Mass Ejection

- Auroras seen as low as CO, CA, NM, AZ
- Damage caused by the Halloween storms:
  - 28 satellites (overt) damaged, 2 unrecoverably damaged
  - Diverted airplanes
  - Power failure in Sweden
- …and two supercomputers came up in late October hoping to get onto the yearly Supercomputing list on Nov 10th
  - At Los Alamos, the “Q” cluster had 26.1 errors a week and one unfortunate cluster topology
  - At Virginia Tech, System X architect joked they “felt like [they] had not only built the world's third fastest supercomputer, but also one of the world's best cosmic ray detectors.”
    - VT processed at night while in the magnetosphere tail
    - VT replaced all of their processors within the next 6 months



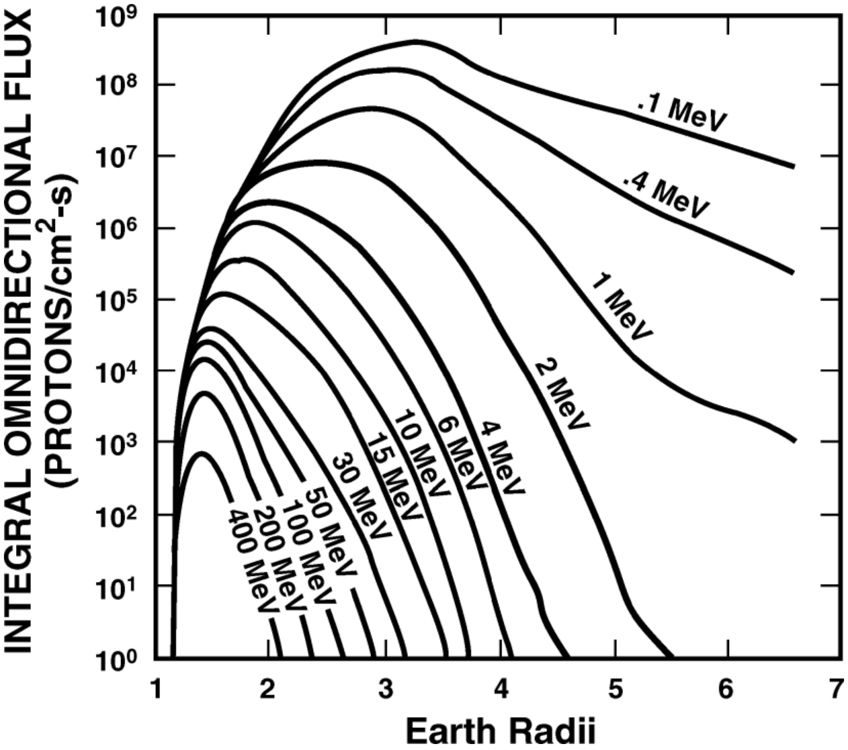
http://apod.nasa.gov/apod/ap031029.html

http://apod.nasa.gov/apod/image/0310/aurora031029b_westlake_full.jpg

T, Gombosi. “Comprehensive Solar-Terrestrial Environment Model for Space Weather Predictions. DoD MURI Project Report 2001-2004

Location Matters

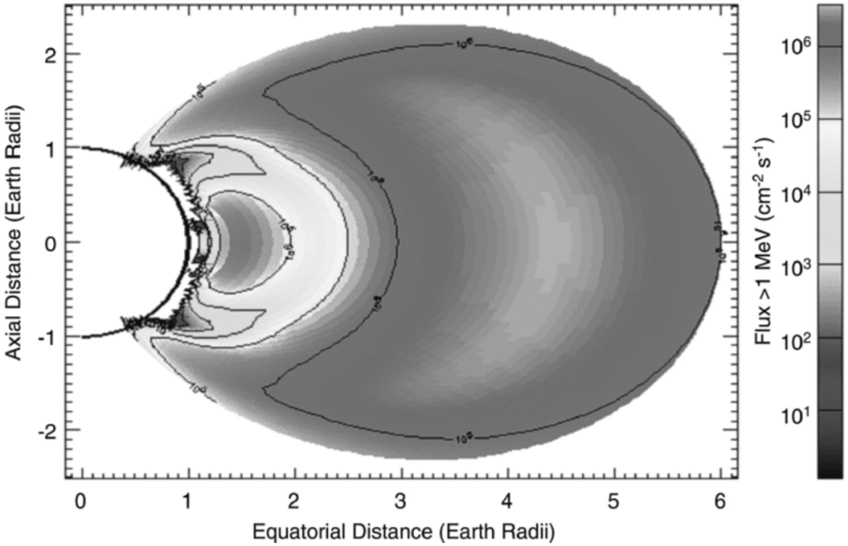
- The sun creates a dynamic environment, which the magnetosphere then moderates and changes
- Lower energy particles are more likely, but there are still a fair bit of high energy particles



J. R. Schwank, M. R. Shaneyfelt and P. E. Dodd, "Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Radiation Environments, Physical Mechanisms, and Foundations for Hardness Assurance," in *IEEE Transactions on Nuclear Science*, vol. 60, no. 3, pp. 2074-2100, June 2013.

Locations inside of the magnetosphere

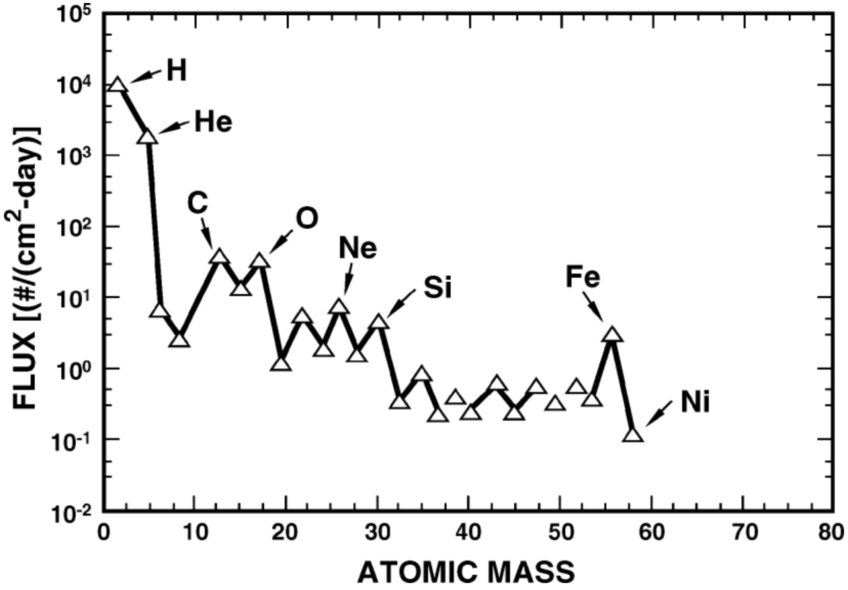
- The two trapped belts are different
- The electron environment is more dynamic than the proton environment
- Even within the trapped belts the flux changes by several orders of magnitude
- The slot region can be populated or unpopulated



J. R. Schwank, M. R. Shaneyfelt and P. E. Dodd, "Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Radiation Environments, Physical Mechanisms, and Foundations for Hardness Assurance," in *IEEE Transactions on Nuclear Science*, vol. 60, no. 3, pp. 2074-2100, June 2013.

Particles

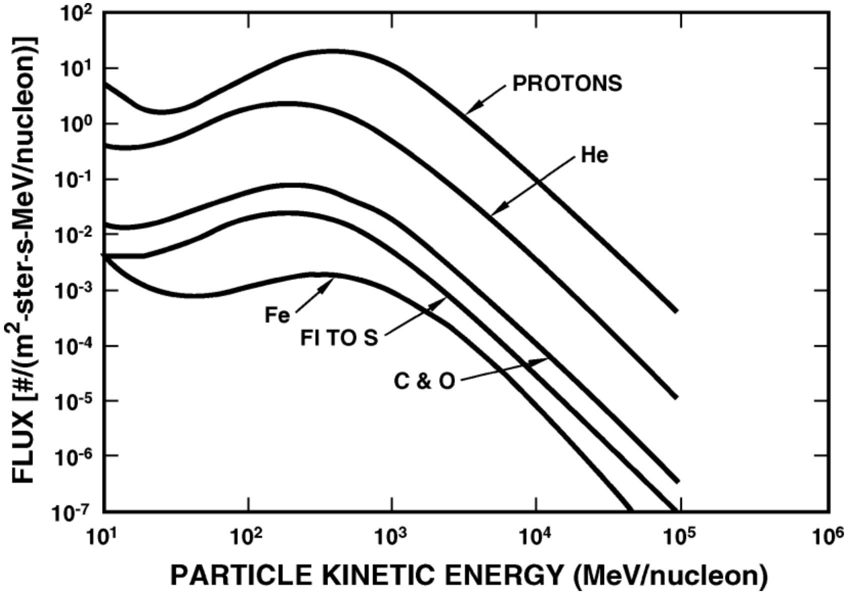
- Outside of the trapped belts, we see district ions
- The flux varies widely
  - Some of these are once in a century types of ions



J. R. Schwank, M. R. Shaneyfelt and P. E. Dodd, "Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Radiation Environments, Physical Mechanisms, and Foundations for Hardness Assurance," in *IEEE Transactions on Nuclear Science*, vol. 60, no. 3, pp. 2074-2100, June 2013.

Back to KE

- The only KE that we can make terrestrially from this graph is the protons
- Brookhaven gets closer on the ions, but is still not as high as the KE in space
- To be discussed later:
  - We cannot actually work with KE units very easily
  - Everything is converted to linear energy transfer (LET) or effective LET for non-normal incidence

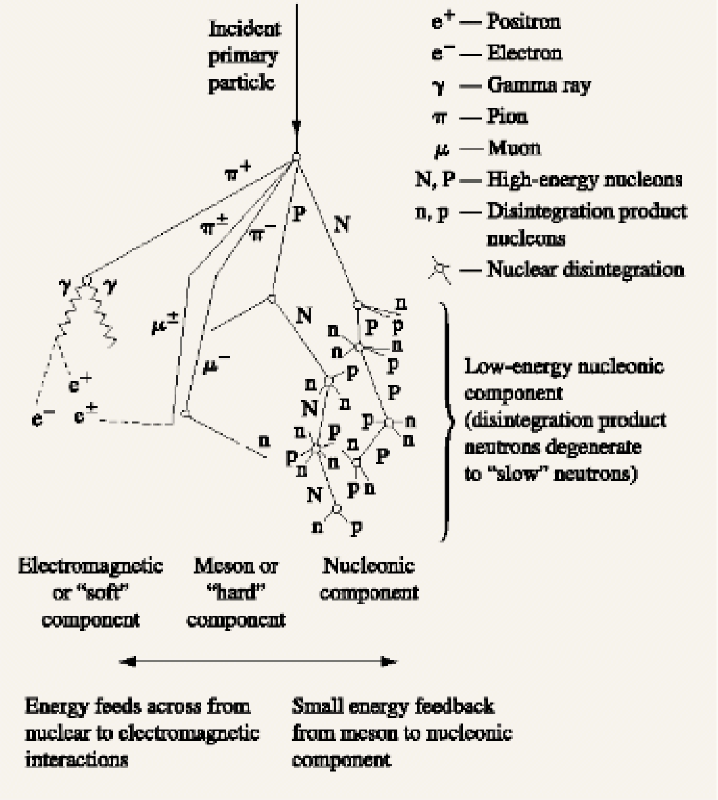


J. R. Schwank, M. R. Shaneyfelt and P. E. Dodd, "Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Radiation Environments, Physical Mechanisms, and Foundations for Hardness Assurance," in *IEEE Transactions on Nuclear Science*, vol. 60, no. 3, pp. 2074-2100, June 2013.

The Terrestrial Environment

Cosmic Rays and the Atmosphere

- Cosmic rays that make it through the magnetosphere to the atmosphere cause a cascade of particles
  - Neutrons, protons, pions, and muons



J. F. Ziegler, "Terrestrial Cosmic Ray Intesities," IBM Journal of Research and Development, Vol 42 (1), 1998

The Terrestrial Environment

- It is a bit more complex than the space environment, due to the interaction with the atmosphere:
  - Primary cosmic rays scatter on nitrogen and oxygen in the atmosphere
  - Starts a cascade of pions, muons, protons and neutrons through the atmosphere
  - The protons and neutrons at the top of the atmosphere are higher energy than at the bottom
  - Pions do not make it past the “hadron cutoff” at 40K’
- Besides that, it is greatly affected by surroundings:
  - Anything with hydrogen can moderate it: jet fuel, concrete in building materials
  - Some materials make it worse: granite in buildings on the east coast
  - Arguments amongst physicist: does the temperature of the room affect the energy of the neutrons? Maybe Jeff can explain that one to us, because I surely do not get it

Muons and Pions

- Pions:
  - Unstable particles
  - Lifetime of ~26 ns
  - Very low flux at sea level (~450 pions/cm2-year), more common at 50,000 ft
  - Rarely interact with Silicon, except for rare pion capture events
  - Cause 0.0003 fails/chip-year, considered minimum error rate possible for radiation-induced failures
- Muons:
  - Relativistic particles
  - Lifetime of ~2 μs
  - 100x more muons at sea level then any other sub-atomic particle
  - Very rarely interact with Silicon, except for muon capture events
  - Cause 0.0006 fails/chip-year
  - Muon-induced transient effects could be possible in the newest generations of electronics

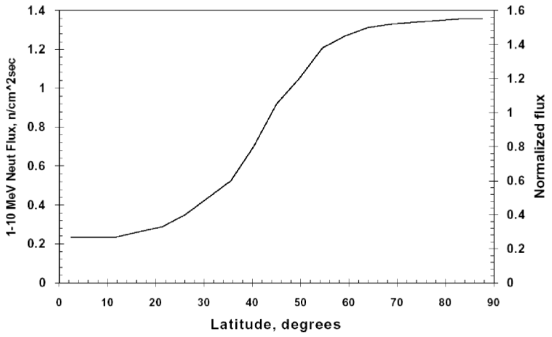
J. F. Ziegler. “SER – History, Trends, and Challenges: A Guide for Designing with Memory ICS”, Cypress Press, 2004

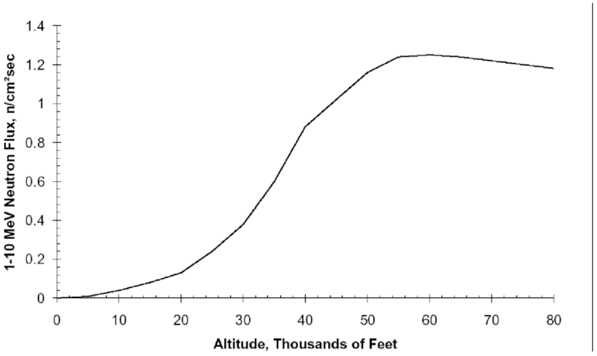
The effect of scattering on directionality on flux

- Unlike space, fast neutrons are directional
  - Primary cosmic rays are roughly perpendicular to the ground on entry
  - Resulting flux only changes direction by scattering
- Scattering causes neutrons to change directions, but only by small angles
  - Fast neutron flux might only scatter a few times, so still mostly perpendicular
  - Thermal flux has scattered 20-30 times and is considered omnidirectional
- What does this mean?
- It is actually confusing for testing: we need to align the systems in the beam as it is in the deployed system
  - Do we even know that?
  - If you do, test accordingly
  - If you don’t, test at a normal incidence
- Does angle of neutron testing matter? Likely yes, but there is so little data that it remains an open question

Neutrons

- Lifetime of 11-12 minutes
- Nearly infinite mean free path
  - A direct strike with a Silicon atom releases a heavy ion, called "nuclear recoil reaction"
  - The heavy ion causes "soft errors"
  - Protons also cause a nuclear recoil reaction and the sensitivities to both neutrons and protons often similar
- Flux dependent on longitude, latitude, altitude, geomagnetic rigidity, solar cycles, time of day, and time of the year
  - Radiation peaks at high altitudes and near poles
  - Some reduced affects at night or in winter months
- Flux sensitive to surroundings
  - Seventh transition (thermals) happens close to the electronics: either using nearby humans or building materials
  - Ship effect can increase flux by an order of magnitude
  - Can shield with water or concrete, but will need a lot of it





J. F. Ziegler, "Terrestrial Cosmic Ray Intesities," IBM Journal of Research and Development, Vol 42 (1), 1998

Neutron Spectrum in NYC

Measured data points vs. the analytical fit

Relatively flat spectrum when viewed on a linear scale

Surroundings cause so many issues that most of the measured spectra are measured outside

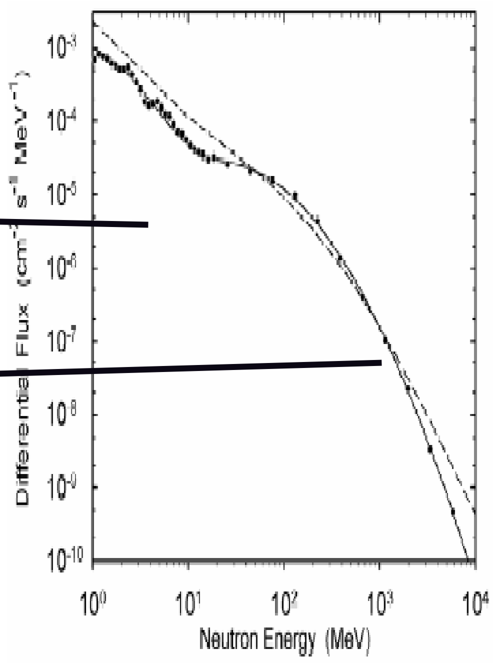


Figure A.2.1 — The differential flux of cosmic-ray-induced neutrons as a function of neutron energy under reference conditions (sea level, New York City, mid-level solar activity, outdoors). The data points are the reference spectrum, the solid curve is the analytic fit to the reference spectrum, and the dashed curve is the model from the previous version of this standard, JESD89 (2001).

Fast Neutron Spectrum in NYC

JESD89 vs. JESD89A: the original version had issues with the 0.1-10 MeV neutrons

Histogram measurements, analytical fit

There is approximately the same amount of flux from 0.1 - 10 MeV than 10-1000 MeV

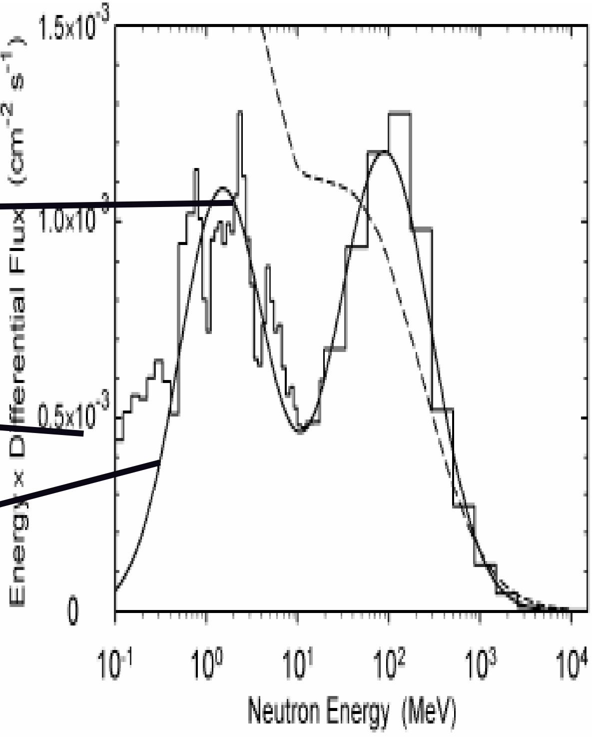
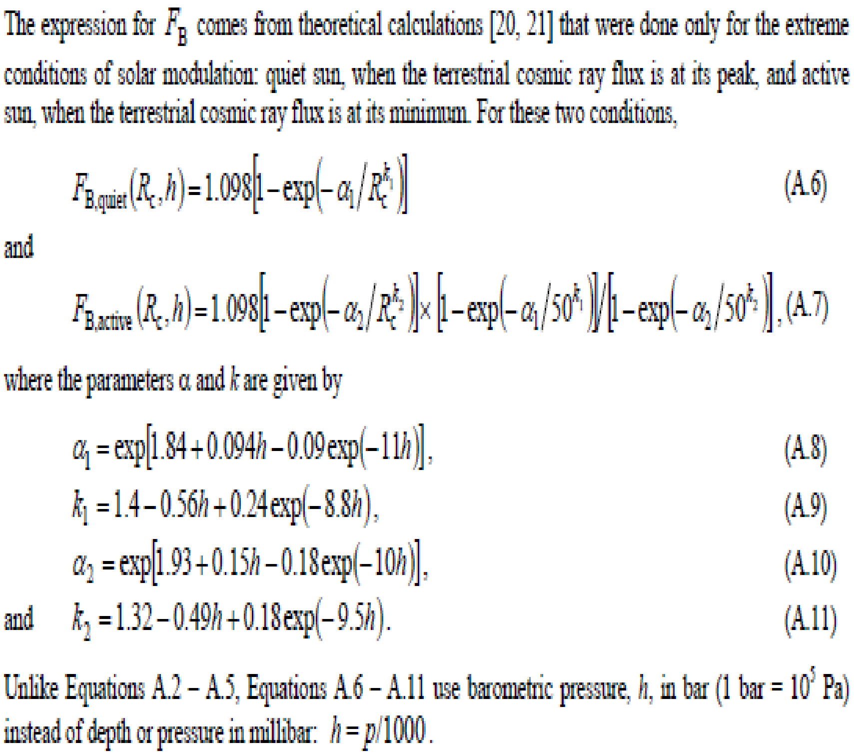


Figure A.2.2 — Reference spectrum of cosmic-ray-induced neutrons plotted as energy times differential flux as a function of neutron energy. The histogram is the reference spectrum, the solid curve is the analytic fit to the reference spectrum, and the dashed curve is the model from the previous version of this standard, JESD89 (2001).

Scaling Flux for Different Locations



The expression for F_B comes from theoretical calculations [20, 21] that were done only for the extreme conditions of solar modulation: quiet sun, when the terrestrial cosmic ray flux is at its peak, and active sun, when the terrestrial cosmic ray flux is at its minimum. For these two conditions,

$$F_{B,\text{quiet}}(R_c, h) = 1.098\left[1 - \exp\left(-\alpha_1 / R_c^{k_1}\right)\right] \qquad \text{(A.6)}$$

and

$$F_{B,\text{active}}(R_c, h) = 1.098\left[1 - \exp\left(-\alpha_2 / R_c^{k_2}\right)\right] \times \left[1 - \exp\left(-\alpha_1 / 50^{k_1}\right)\right] / \left[1 - \exp\left(-\alpha_2 / 50^{k_2}\right)\right], \text{(A.7)}$$

where the parameters α and k are given by

$$\alpha_1 = \exp\left[1.84 + 0.094h - 0.09\exp(-11h)\right], \qquad \text{(A.8)}$$

$$k_1 = 1.4 - 0.56h + 0.24\exp(-8.8h), \qquad \text{(A.9)}$$

$$\alpha_2 = \exp\left[1.93 + 0.15h - 0.18\exp(-10h)\right], \qquad \text{(A.10)}$$

and $$k_2 = 1.32 - 0.49h + 0.18\exp(-9.5h). \qquad \text{(A.11)}$$

Unlike Equations A.2 – A.5, Equations A.6 – A.11 use barometric pressure, h, in bar (1 bar = 10^5 Pa) instead of depth or pressure in millibar: $h = p/1000$.

Or use seutest.com

Several measurements of different locations

Fast neutron flux is pretty stable, when corrected for location.
NOTE: All on ground

Epithermals and thermals have some location variation, which is not understood

Thermal flux is roughly the same as 0.1-10 MeV and 10-10000 MeV flux. There can be a lot of thermals even outside. Building materials only make more, too.

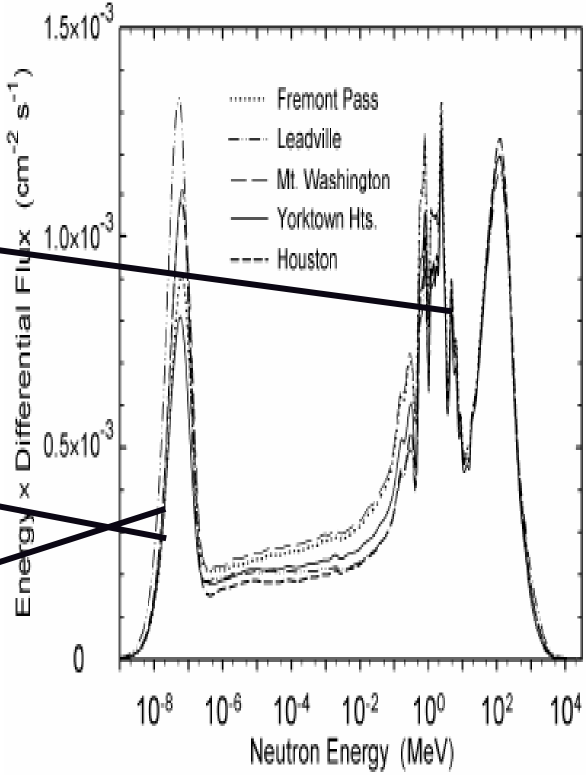


Figure A.4.1 — Spectra of cosmic-ray-induced neutrons measured at five locations. Each spectrum has been scaled to sea level and the cutoff of New York City and plotted as energy times differential flux as a function of neutron energy.

Thermals are very sensitive to location and water

Thunderstorms matter but water doesn't?

4x variation in thermal flux in roughly the same location

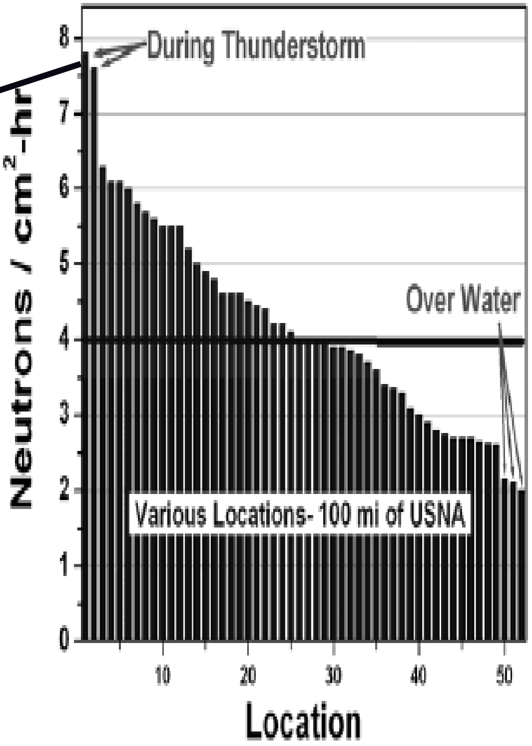
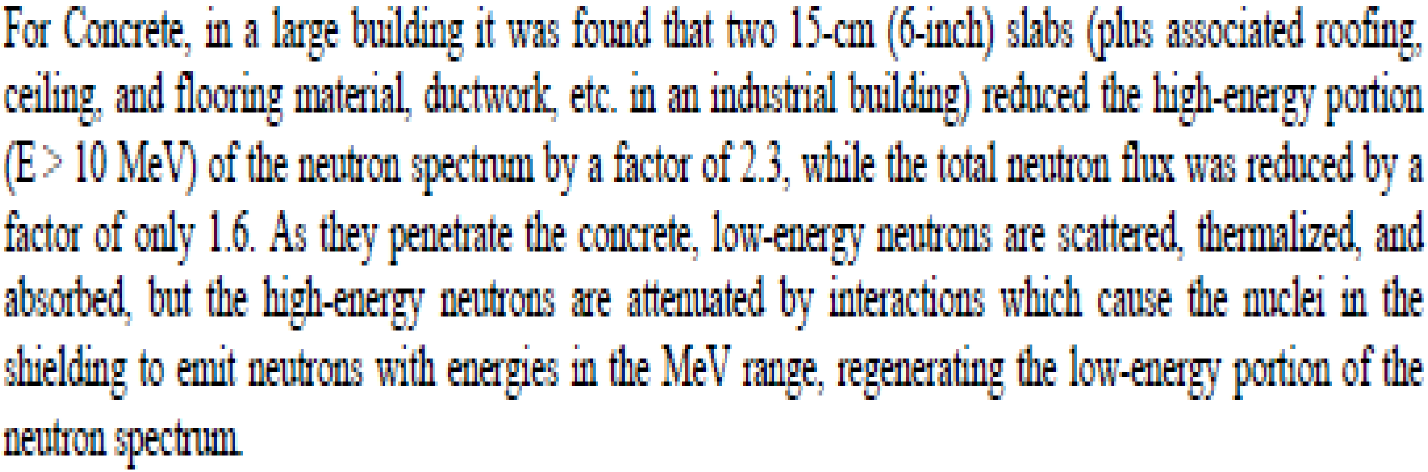


Figure A.4.2 — Thermal neutron flux measured at 52 sites near sea level within 160 km (100 miles) of the U.S Naval Academy in Annapolis, MD (39.0° N, 76.5° W) [18]. The fluxes shown have not been adjusted to the reference conditions.

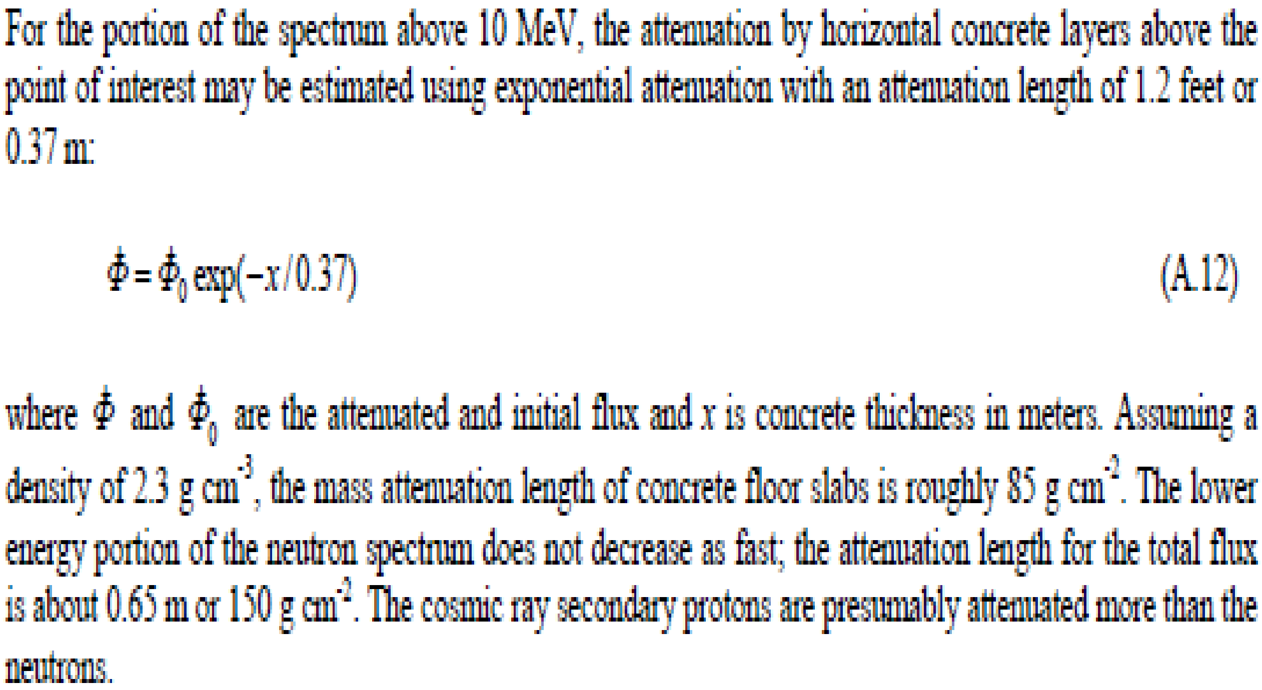
The Effect of Building Materials



For Concrete, in a large building it was found that two 15-cm (6-inch) slabs (plus associated roofing, ceiling, and flooring material, ductwork, etc. in an industrial building) reduced the high-energy portion ($E > 10$ MeV) of the neutron spectrum by a factor of 2.3, while the total neutron flux was reduced by a factor of only 1.6. As they penetrate the concrete, low-energy neutrons are scattered, thermalized, and absorbed, but the high-energy neutrons are attenuated by interactions which cause the nuclei in the shielding to emit neutrons with energies in the MeV range, regenerating the low-energy portion of the neutron spectrum.

This is often called "replacement theory." Shielding causes the spectrum to shift down in energy, but maintain the same basic shape

More on concrete



For the portion of the spectrum above 10 MeV, the attenuation by horizontal concrete layers above the point of interest may be estimated using exponential attenuation with an attenuation length of 1.2 feet or 0.37 m:

$$\Phi = \Phi_0 \exp(-x/0.37) \qquad \text{(A.12)}$$

where Φ and Φ_0 are the attenuated and initial flux and x is concrete thickness in meters. Assuming a density of 2.3 g cm^{-3}, the mass attenuation length of concrete floor slabs is roughly 85 g cm^{-2}. The lower energy portion of the neutron spectrum does not decrease as fast; the attenuation length for the total flux is about 0.65 m or 150 g cm^{-2}. The cosmic ray secondary protons are presumably attenuated more than the neutrons.

Protons

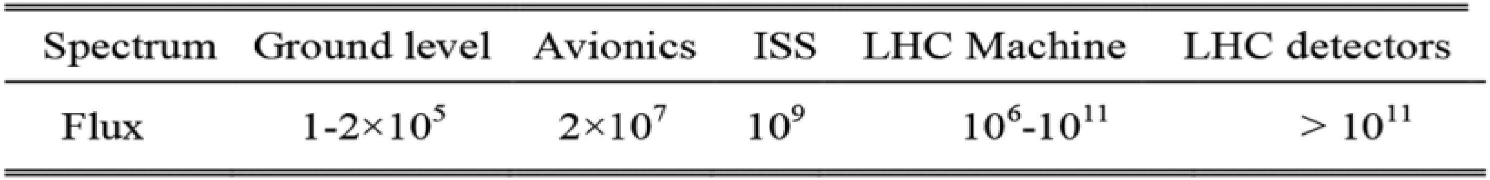
- Extremely stable outside of the nucleus – theoretically could exist for thousands of years
- Interacts with CMOS technology in a variety of ways:
  - Accumulated dose effects
  - Transient effects from both direct and indirect ionization
- While the terrestrial proton environment is very low at sea level, higher concentrations are found in space and high-altitude environments
  - One third of the fast neutron environment in high-altitude airplane environments
  - Lower Van Allen Belt in low earth orbit has a significant trapped proton region, which can affect electronics

Accelerator Environments

Accelerator Electronics

- Already you might have an intuition around radiation effects in electronics:
  - The specific environment matters in terms of the radiation, the energy, the directionality, the total fluence, and the ability to shield

- Each accelerator environment is different
  - The pointy end of the beam is always worse than the natural environments
  - But even around the machine could be worse than the natural environments
  - I have personally lost more electronics around proton accelerators than in the beam

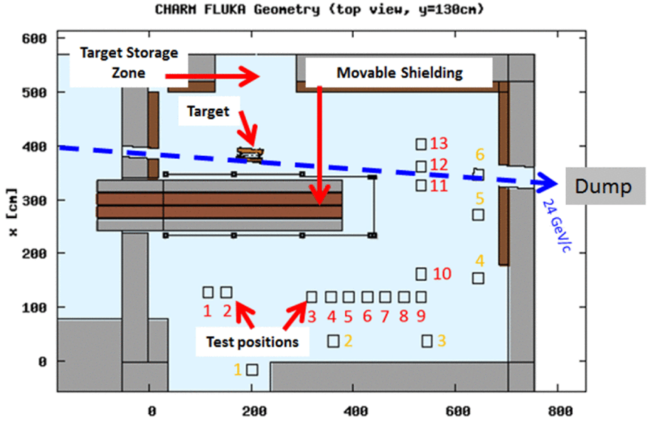


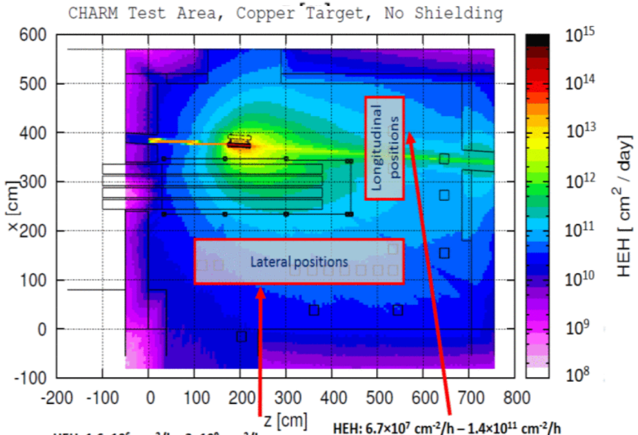
Spectrum	Ground level	Avionics	ISS	LHC Machine	LHC detectors
Flux	$1\text{-}2\times10^5$	2×10^7	10^9	$10^6\text{-}10^{11}$	$> 10^{11}$

J. Mekki, M. Brugger, R. G. Alia, A. Thornton, N. C. D. S. Mota and S. Danzeca, "CHARM: A Mixed Field Facility at CERN for Radiation Tests in Ground, Atmospheric, Space and Accelerator Representative Environments," in *IEEE Transactions on Nuclear Science*, vol. 63, no. 4, pp. 2106-2114, Aug. 2016.

Figuring Out the Accelerator Radiation Environment

- One method would be to measure it, but that might not be simple
- Most researchers are using some combination of modeling tools:
  - MCNP
  - Fluka
  - TRAD
- Determining this environment early on is important: it is one of the source terms
  - We will use the CHARM environment this week





HEH: 1.6×10^{6} cm^{-2}/h - 3×10^{9} cm^{-2}/h ;
TID: 0.7 mGy/h - 1.5 Gy/h

HEH: 6.7×10^{7} cm^{-2}/h – 1.4×10^{11} cm^{-2}/h
TID: 75 mGy/h - 45 Gy/h

J. Mekki, M. Brugger, R. G. Alia, A. Thornton, N. C. D. S. Mota and S. Danzeca, "CHARM: A Mixed Field Facility at CERN for Radiation Tests in Ground, Atmospheric, Space and Accelerator Representative Environments," in *IEEE Transactions on Nuclear Science*, vol. 63, no. 4, pp. 2106-2114, Aug. 2016.

E_0 and E_max: do we need to do something about this?

- All of the have different E_0 and E_max
- LANL has been studying whether E_0 needed to be changed in the JESD89
  - Many but not all electronics have onsets below 10 MeV, so the fluence is under counted
  - All of the facilities have too many 1-10 MeV neutrons, so we might overcount fluence if we lower E_0
  - We did not change it for JESD89B, because the information was contradictory
- Open Questions:
  - Can we make simplifications of the Weibull parameters based on feature size and/or effect?
  - Can we fix the accelerator spectrum?
  - Could something like a sensor response function help us out?
  - Can we predict the error in broad spectrum testing without doing 1-10 MeV mono-energetic neutron testing
  - Why does 1-10 MeV neutron sensitivities not look like 1-10 MeV proton sensitivities? What to do about the fit?