All KC events will be approved for public using NASA Form 1676.

This synopsis provides information about the Knowledge Capture event below.

Topic: Space Radiation Environments

Date: June 29, 2017   **Time:** 11:30 a.m. to 1:00 p.m.   **Location:** JSC/B5S/R3102

DAA 1676 Form #: 40023

This is a link to all lecture material and video \\js-ea-fs-03\pd01\EC\Knowledge-Capture\FY17 Knowledge Capture\20170629 Koontz_Space Radiation Environments\1676 Review

*A copy of the video will be provided to the NESC Academy Online, NASA Technical Library and STI Program's YouTube, EA Engineering Academy, Spacesuit Knowledge Capture, and JSC History Office domains when the DAA 1676 review is complete.

Assessment of Export Control Applicability:

This Knowledge Capture event has been reviewed by the EC5 Spacesuit Knowledge Capture manager in collaboration with the author and is assessed to not contain any technical content that is export controlled. It is requested to be publicly released to the NESC and JSC Engineering Academy, as well as to STI for distribution through NTRS or NA&SD (public or non-public) and with video through DVD or Large File Transfer request or YouTube viewing with download of any presentation material.

* This file is also attached to this 1676 and will be used for distribution.

For 1676 review use_Synopsis_Koontz_Space Radiation Environments_6-29-2017.docx

Presenter: Dr. Steven Koontz

Synopsis: The space-flight ionizing radiation (IR) environment is dominated by very high-kinetic energy-charged particles with relatively smaller contributions from X-rays and gamma rays. The Earth's surface IR environment is not dominated by the natural radioisotope decay processes. Dr. Steven Koontz's lecture will provide a solid foundation in the basic engineering physics of space radiation environments, beginning with the space radiation environment on the International Space Station and moving outward through the Van Allen belts to cislunar space. The benefits and limitations of radiation shielding materials will also be summarized.

   Biography: Dr. Steven Koontz has worked for NASA for over 30 Years with space-flight environment effects on spacecraft materials and systems. Before working with NASA, he earned a bachelor of science in chemistry with an emphasis in nuclear chemistry from the University of California at Berkeley, and a Ph.D. in chemistry with an emphasis in analytical instrumentation from the University of Arizona at Tucson. At NASA, he specializes in spacecraft-plasma interactions, spacecraft charging and contamination, as well as space radiation effects on materials and avionics systems, and spacecraft contamination. He has applied nuclear reaction and transport codes (FLUKA, HZETRN, and CREME-96) to Single-Event Environment/Total Ionizing Dose (SEE/TID) analysis and prediction of in-flight SEE and TID

rates for the International Space Station (ISS) system level avionics safety and reliability. He has served on the NASA review panels and as a journal referee. He has been the principal investigator or co-investigator on several space flight experiments aimed at quantifying space environment effects. As ISS System manager for Space Environments, he is responsible for the ISS plasma contactor units and the floating potential measurement unit, as well as management of spacecraft charging risks for ISS. His work has resulted in receiving several significant awards including the Astronaut's Personal Achievement Award, the NASA Exceptional Service Medal, and the NASA Silver Achievement Medal.

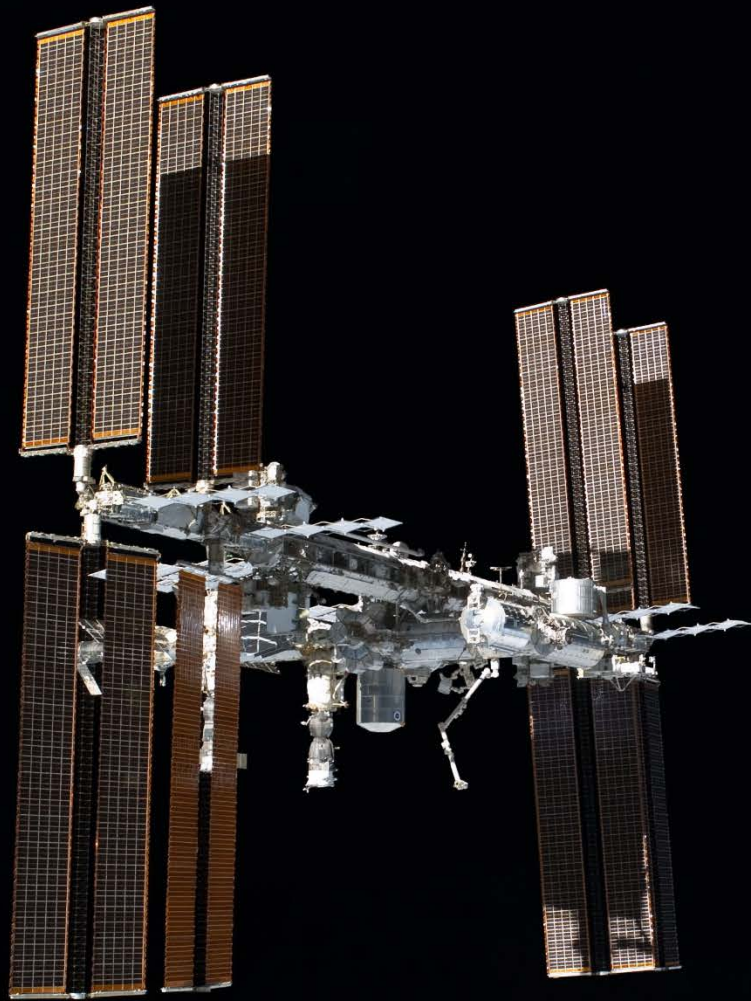**EC5 Spacesuit Knowledge Capture POCs:**

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Space Flight Ionizing Radiation Environments

ES4/Dr. Steve Koontz, ISS System Manager for Space Environments

NASA Johnson Space Center, 2101 NASA Parkway, Houston, Texas, 77058, USA, 281-483-8860
Email: steven.l.koontz@nasa.gov

June 29, 2017

Presentation Outline

- **Space Radiation Environments: What, Where, When, and How Much?**
  - Some general characteristics of space radiation environments – directionality, energy spectra, randomness
  - Energetic photons – primarily solar X-rays and extreme UV (not enough gamma rays to matter)
  - Radiation Belts – trapped protons and electrons (relatively "soft" kinetic energy spectra)
  - Solar Particle Events – mostly protons and electrons (with some heavier nuclei); "harder" energy spectra
  - Galactic Cosmic Rays (GCR) – extremely "hard" spectra and significant heavy nuclei content
- **How does space radiation interact with matter (i.e., us and our stuff)?**
  - Direct ionization/excitation (particle tracks)
  - Nuclear reactions and secondary particle showers (leading to more nuclear reactions and particle tracks)
  - Displacement Damage Dose (optoelectronics, solar cells, LEDs, photodiodes) disrupting crystal structure
- **Space Station Zero – space radiation shielding specification and performance, in perspective, with humanities oldest (and lowest cost) spacecraft**
  - Shielding mass and geomagnetic field
  - Shielding performance – surface environments
  - Shielding performance – commercial and military aircraft environments
- **International Space Station – space radiation shielding specification and performance**
  - Spacecraft shielding mass and geomagnetic field
  - Shielding performance – internal to pressurized elements
  - Shielding performance – surface materials
- **Beyond GEO – the interplanetary radiation environment – GCR and Solar Particle Event (SPE)**
  - GCR and SPE
  - Shielding mass, shielding materials, total dose and LET Spectra
  - Environments definitions for design and verification
  - Interplanetary environment, models, and spacecraft measurements
- **Some space radiation nuclear reaction and transport analysis tools**
- **Summary**
- **Back-up and References**

Space Radiation Environments: What, Where, When, and How Much
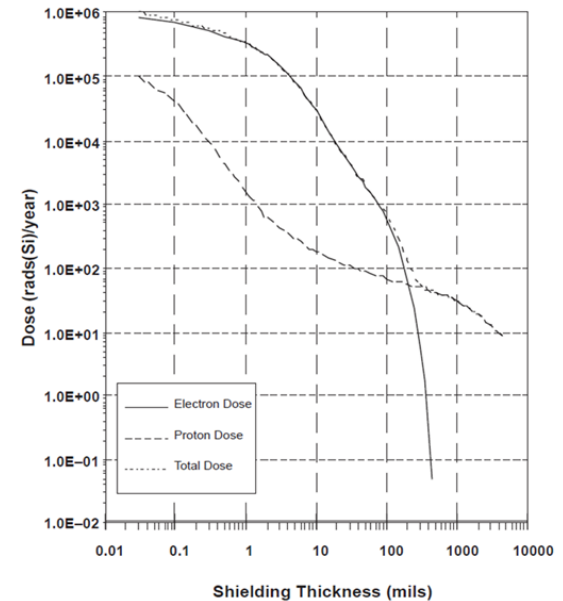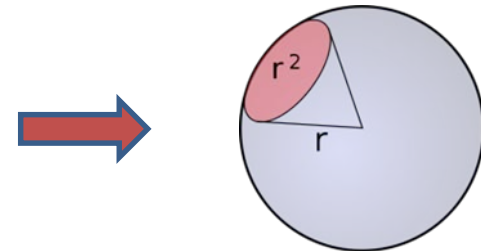
Some General Features of Space Radiation

- **Definitions and Units – Particle (ion, electron, photon) energy**
  - In physics, the electron volt (eV) is a unit of energy equal to approximately **1.602×10^{-19} joule**. By definition, it is the amount of kinetic energy gained by the charge of a single electron moving across an electric potential difference of one volt.
- **Definitions and Units – Total Ionizing Dose (TID)**
  - TID reported for a specified material; TID (H20) ≠ TID (Si)
  - Original Unit of absorbed dose – rad = 100 ergs/gram
  - SI unit of absorbed dose – grey (Gy) = 1J/kg = 100 rads, so 1 rad = 1 cGy
- **Definitions and Units – Shielding mass/path length as areal density**
  - Shielding mass thickness reported as grams/cm^2
  - Same units for particle path length through target
  - Thickness (cm) x density(g/cm^3) = g/cm^2
- **Definitions and Units – Linear Energy Transfer (LET)**
  - Quantifies energy deposition, by ionization/excitation production, along the charged particle track when high-energy charged particles move through a specific material composition; e.g., dE/dx (Si)
  - Essential for microelectronic single event environment effects assessments and crew dose evaluations
  - Energy deposition along the track can be orders of magnitude greater than the average dose for the object
  - Units – keV/μ or MeV cm^2/mg
- **Definitions and Units – Non-Ionizing Energy Loss (NIEL) and Displacement Damage Dose (DDD)**
  - DDD = $\int$ NIEL [dΦ(E)/d(E)] d(E); NIEL units keVcm^2/g or MeVcm^2/g and DDD units keV/g or MeV/g

Some General Features of Space Radiation
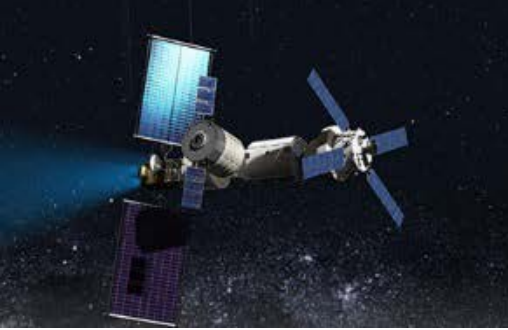
- **In free space, charged particle flux is approximately isotropic, or nearly so, in all cases, so no shadow shielding (except by planets, asteroids, moons, etc.)**
  - **Fraction of 4π <u>steradians</u> covered by shielding mass is important**
    - Any area on a sphere, totaling the square of its radius and observed from its center, subtends precisely one steradian.
- **Energetic photons are not isotropic: line-of-sight to source**
  - **Shadow shielding can work for solar X-ray flares**
- <u>**Low-energy particles/photons are much more abundant than high-energy particles/photons**</u>
  - **Penetration of active or passive shielding depends on particle energy:**
  - **high energy => greater penetration so we have,**
  - **High spacecraft skin dose – and rapidly decreasing dose as shielding mass increases**
    - **Greatest % reduction in the first 1 to 10 g/cm^2**
    - **Much lower % reduction as shielding mass increases beyond 10 g/cm^2**
- How and where the dose is distributed in a particular object (Dose/Depth for spacecraft, asteroids, moons, planetary surfaces, and atmospheres, etc.) depends on the ionizing radiation environment and how that environment interacts with that object's configuration and materials.

ISS Design Environment – electron and proton dose to the center of an aluminum sphere, of radius = shielding thickness, in mils (1 mil = 0.025 mm)

Some General Features of Space Radiation:
# Randomness, Probability, and Particle Counting Statistics

- The number of cosmic ray particles arriving in a counter or target material in some time interval, **t**, is a **random** (Poisson) process characterized by:

  - Event probability is independent of previous or subsequent events

  - An average event count, $n_{ave}= \mu$, averaged over for many (>>t) time intervals

  - The uncertainty (standard deviation) in any n_t is equal to $\sqrt{n_t}$, where n_t is a sample estimate of $n_{ave} = \mu$

  - So, the fractional uncertainty in n_t becomes smaller with increasing n_t; $(\sqrt{n_t} /n_t)$

  - Note that μ can be constant for long periods (homogeneous Poisson process) or variable in time (inhomogeneous Poisson process)

- As an example, just because you see an event at high latitude or in the SAA, the high radiation likelihood location doesn't, by itself, prove it was a radiation event.

- Similarly, you can't conclude that an event observed in a low radiation likelihood location, like the western Pacific or southeast Asia, isn't a radiation event.
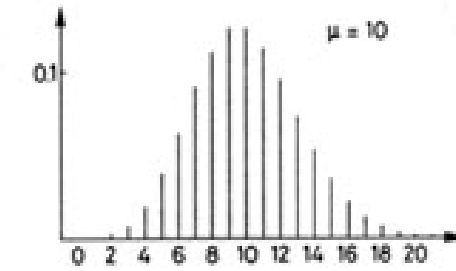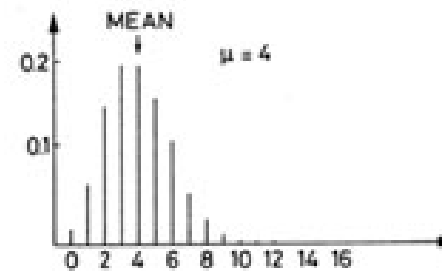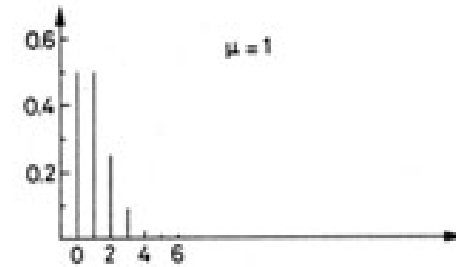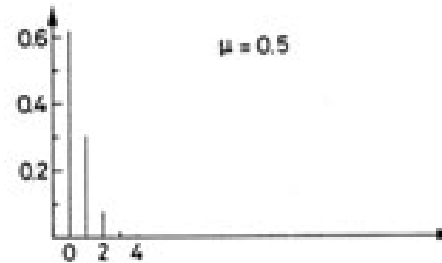
Note that the most probable count for a low likelihood event is 0

Some General Features of Space Radiation:
# Charged Particle Populations
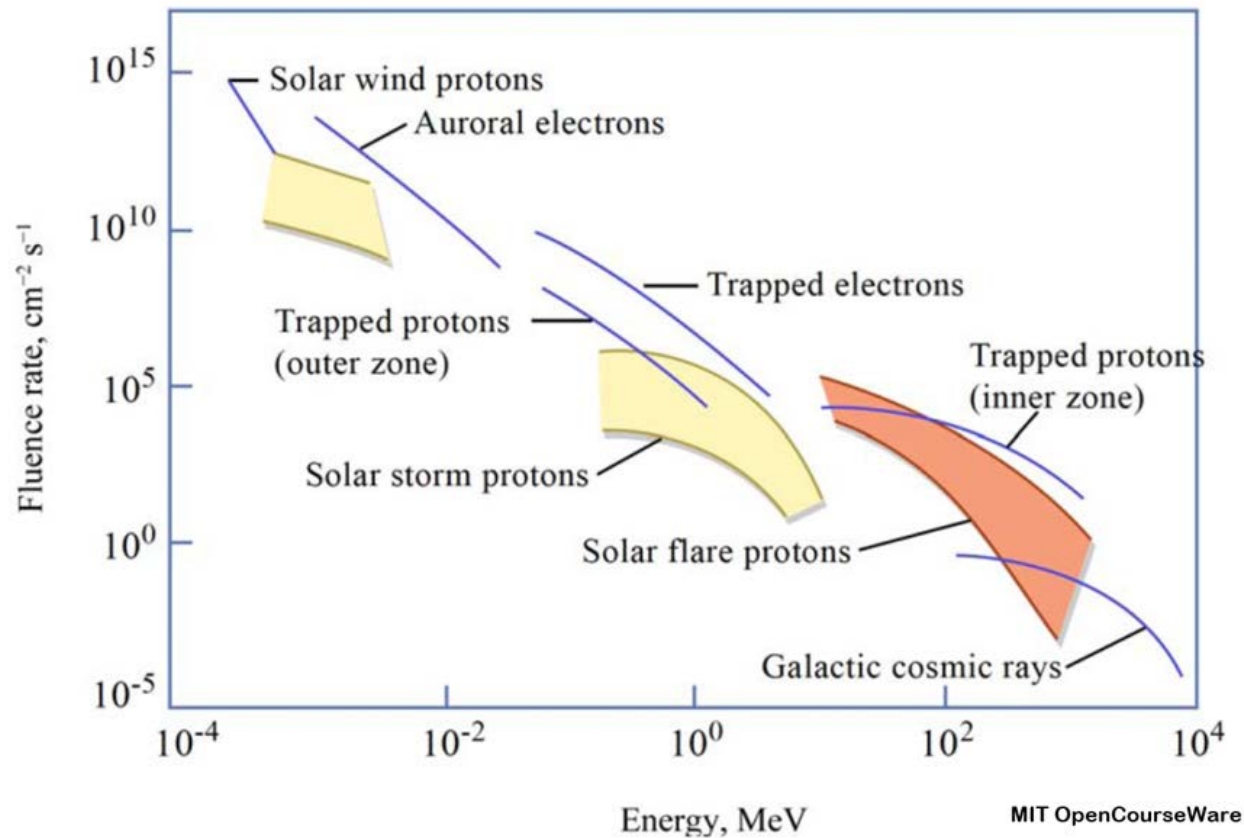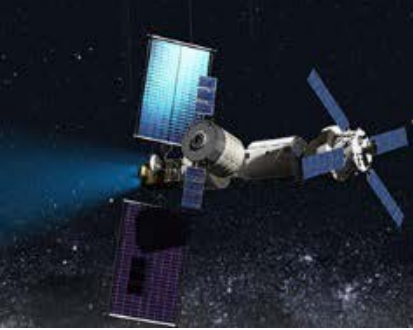
Synoptic view of integral particle fluence rate of space radiation versus upper boundary of particle energy (Wilson, J.W., 1978. Environmental geophysics and SPS shielding. Lawrence Berkeley Laboratory Report LBL-8581, pp 33-116).

Energetic Photons

- TID depends on the material mass adsorption coefficient, i.e. on how much mass the energy is deposited into – consider 1 m^2 (10^4 cm^2) of material facing the sun (yes, there is a cosine and solar exposure time factor here)

  - If 90% of the energy (10^{-4} W/m^2) is adsorbed in the top 10µ (10^{-3} cm) of a solid of density 1 then we have 1 cGy/sec

  - If 90 % of the energy (10^{-4} W/m^2) is deposited in the top 10 cm then the dose rate is 10^{-4} cGy/sec

  - **Example - solar x-rays contribute about 20% to total ISS external surface dose**

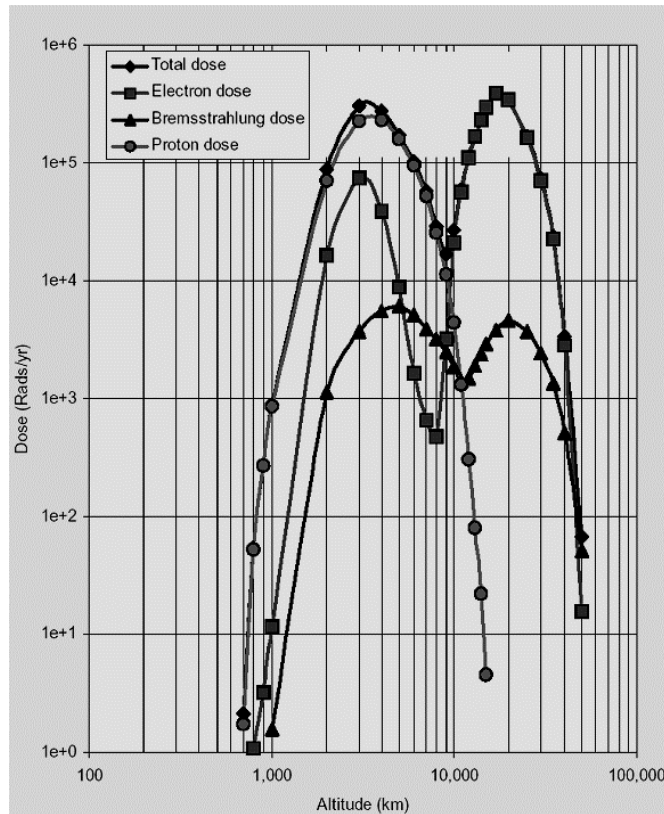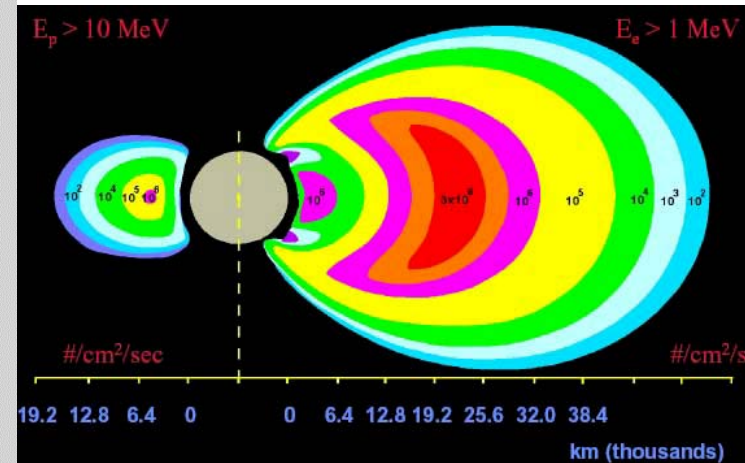 - **http://www.swpc.noaa.gov/products/goes-x-ray-flux**
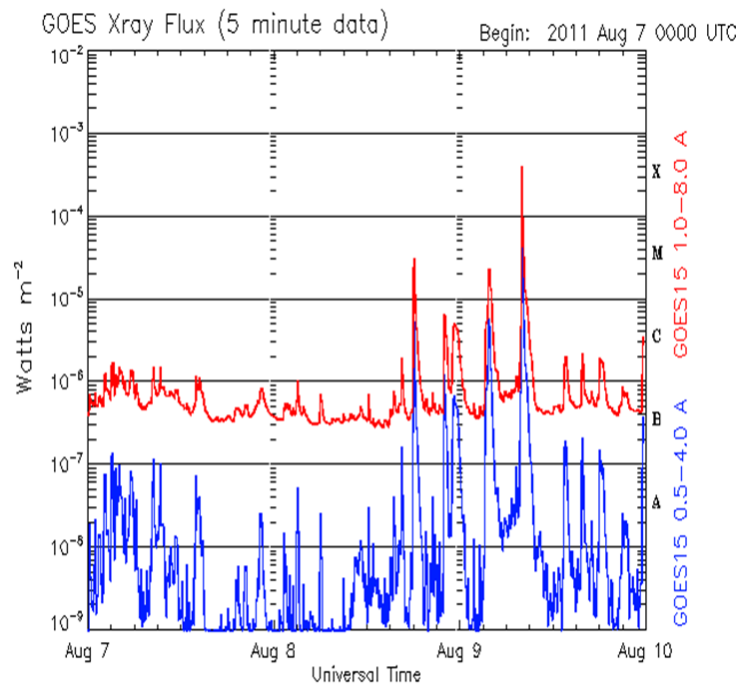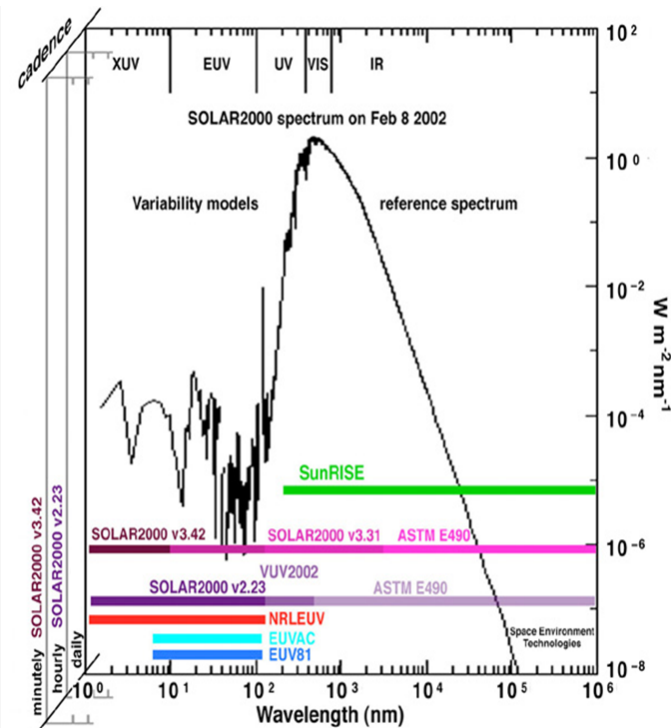
Radiation Belts

- Confined to planetary radiation belts
- Origin – uncertain at this time – some contribution from decay of neutrons produced by GCR interactions with Earth's atmosphere and some from capture of solar particle event protons and electrons
- Composition – **protons and electrons for the most part**
- Flux and fluence – **up to 10^6 to 10^8 per cm^2/sec**
- Energy and spectrum – **10 MeV to 100 MeV**

http://www.swpc.noaa.gov/products/goes-electron-flux

TID (Si) under 4 mm Al vs. altitude
ESA SPENVIS

http://propagation.ece.gatech.edu/ECE6390/project/Fall2012/Team06/Webpage%20Folder/Webpage%20Folder/riskmitigation.html
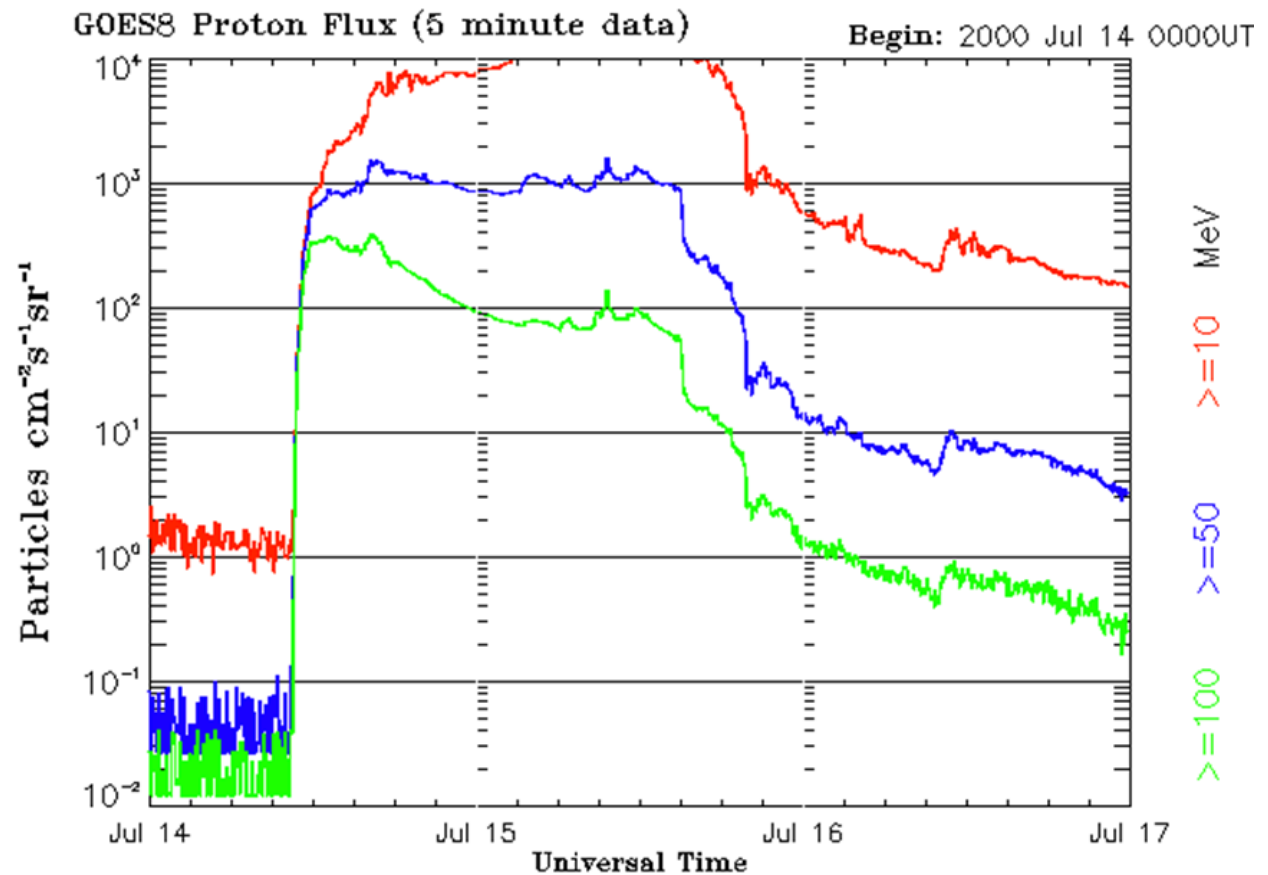
Solar Particle Events

- Origin – solar flares and coronal mass ejections
- Composition – **mostly protons/electrons with small percentage of heavier ions**
- Flux and fluence – 10^2 **to** 10^3 **protons/(cm^{2}sec)** at **E > 100MeV**
- SPEs are of short duration; 2 to 3 days typically
- Energy and spectrum – **10 MeV to > 1 GeV**
- **SPEs show a high degree of event-to-event variability**
  - **How to select a worst-case design environment?**

GOES8 Proton Flux (5 minute data)   Begin: 2000 Jul 14 0000UT
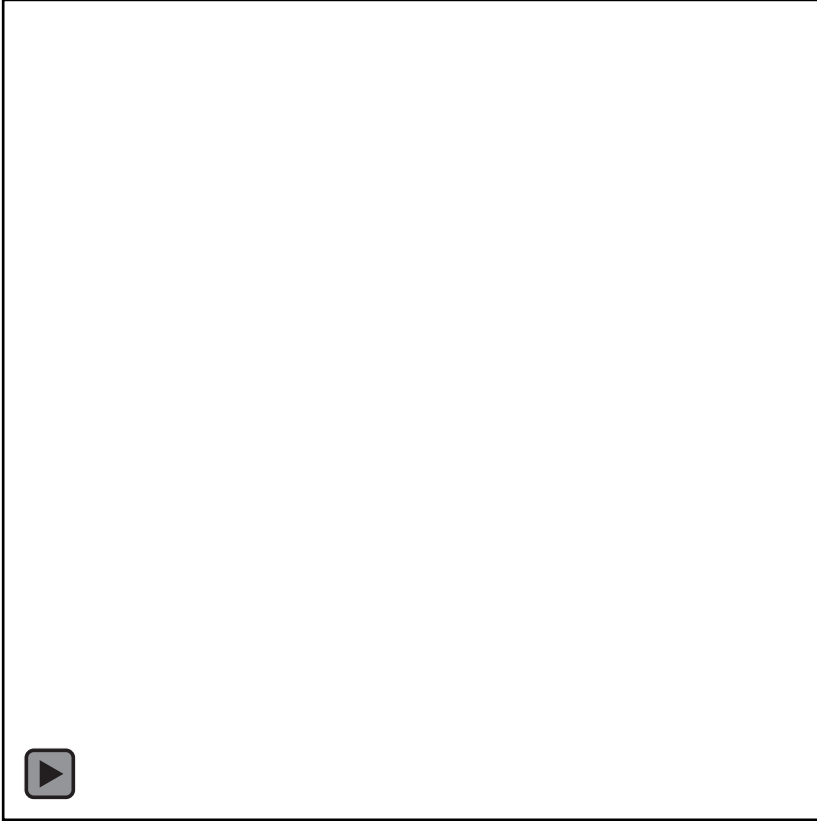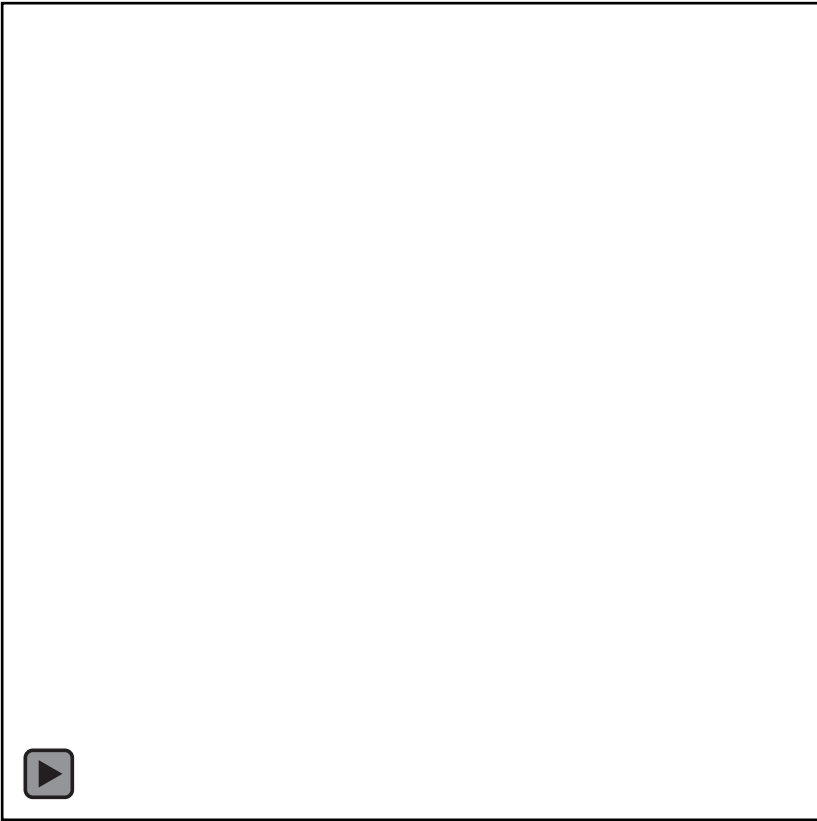
Updated 2000 Jul 16 23:56:03   NOAA/SEC Boulder, CO USA

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Solar Particle Events

NASA Image Spacecraft

ESA SOHO Spacecraft

Galactic Cosmic Rays:
1 AU Spectrum, Composition,
and Solar Cycle Modulation

- Origin – outside the solar system, but inside the Milky Way galaxy for the most part (supernovae & other extreme events)
- Composition – **atomic nuclei (and a few electrons and gamma rays) – all the elements of the periodic table are represented** – 87% protons, 12% He nuclei, 1% heavier nuclei, smaller flux of energetic gamma ray photons
- Flux and fluence (abundance) – about **$0.1/(cm^2\ sec)$** at the top of earth's atmosphere and about **$0.5/(cm^2\ sec)$** in interplanetary space (geomagnetic shielding)
- GCR flux modulated significantly by the **11-year solar cycle**
- Energy spectrum – Most energetic charged particle population – relativistic or ultra-relativistic, – Most in the energy range between **100 MeV to >> 100 GeV**
- **Little or no change of the 1 AU flux/spectrum between the orbit of Mercury and the asteroid belt**
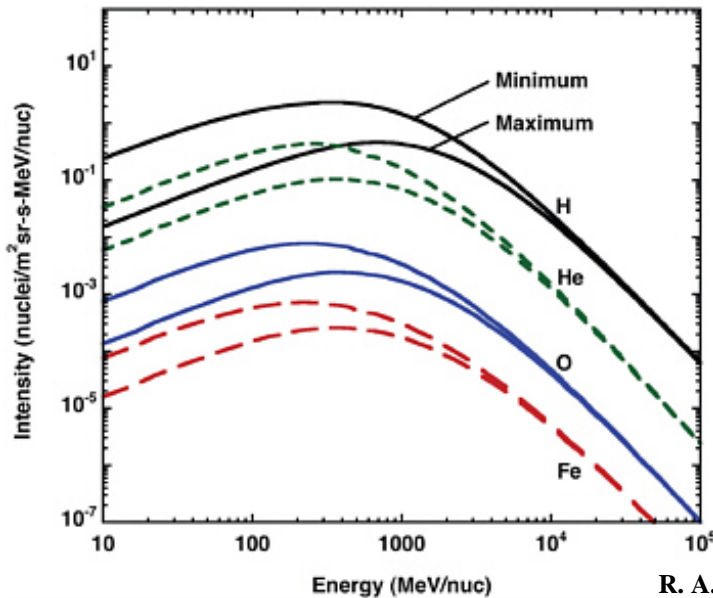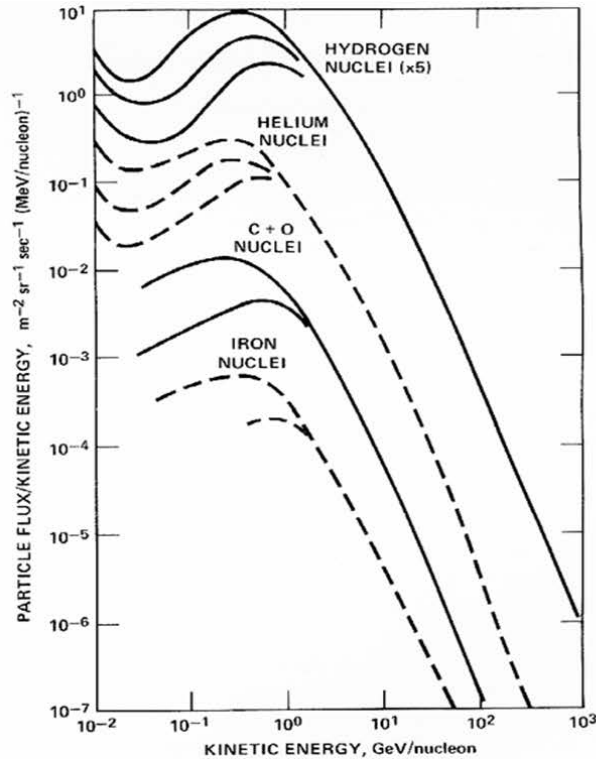

R. A. Mewaldt, Cal Tech, JPL
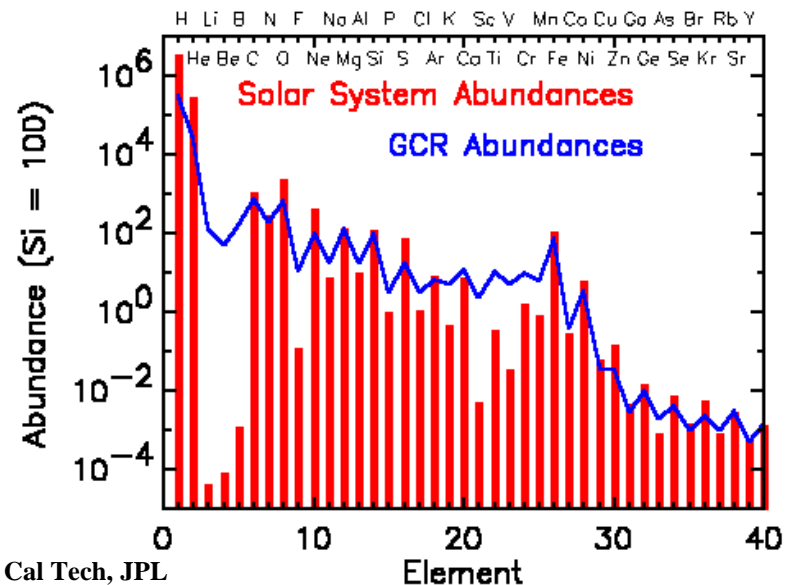
GCR Spectra


Figure 2-7.— Distribution of energies of galactic cosmic rays. This is a graph of the more abundant nuclear species in cosmic rays as measured near the Earth. Below a few GeV/nucleon these spectra are strongly influenced by the Sun. The different curves for the same species represent measurement extremes resulting from varying solar activity. (Taken from Physics Today, Oct. 1974, p. 25.)
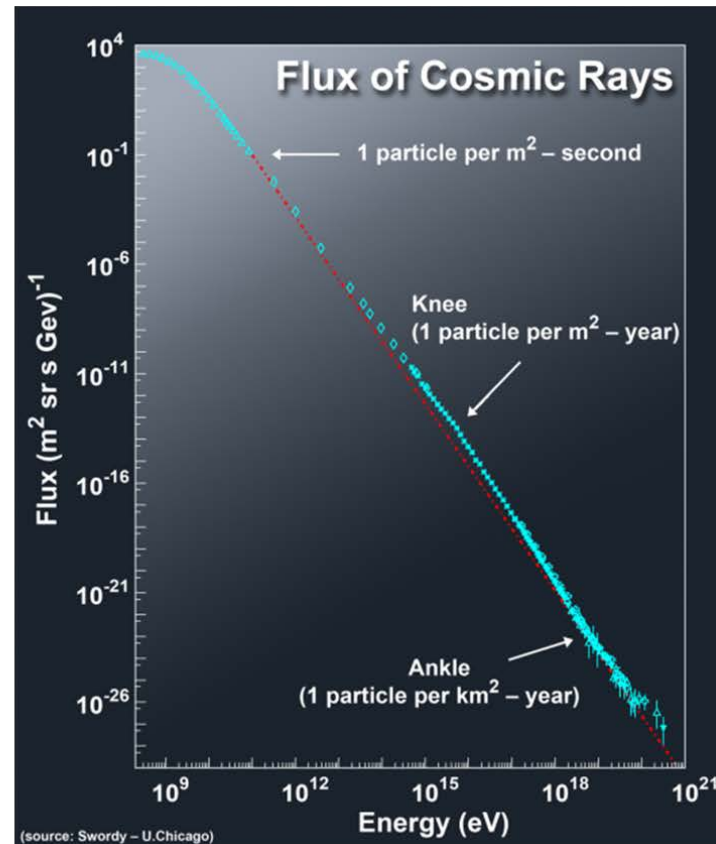
Galactic Cosmic Rays (GCR): Heliosphere modulation/shielding

https://www.nasa.gov/topics/solarsystem/features/ray_surge.html
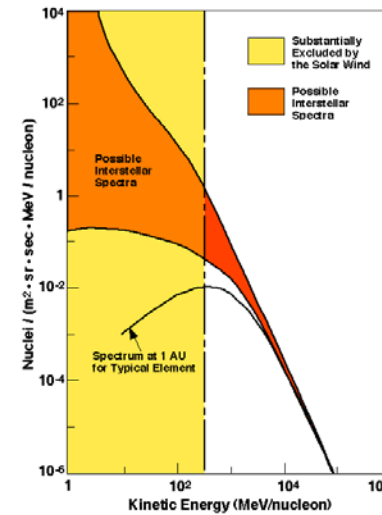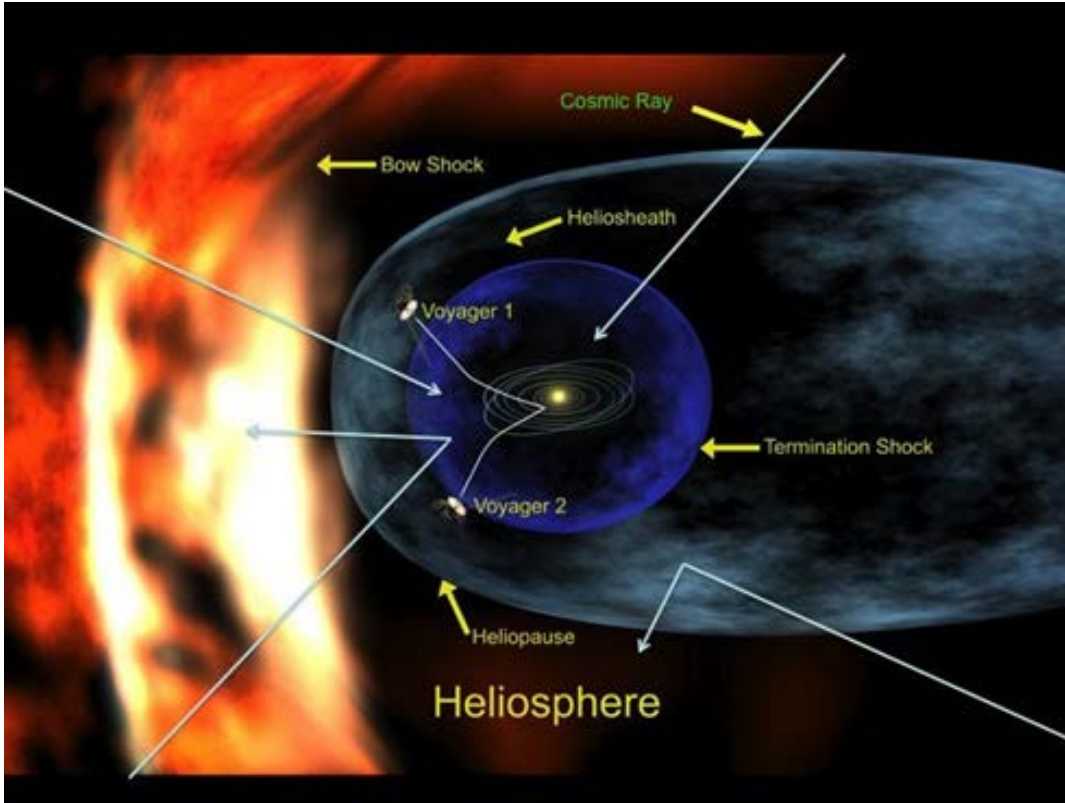
Attenuation of Interstellar GCR by the solar wind and estimated local Interstellar spectra
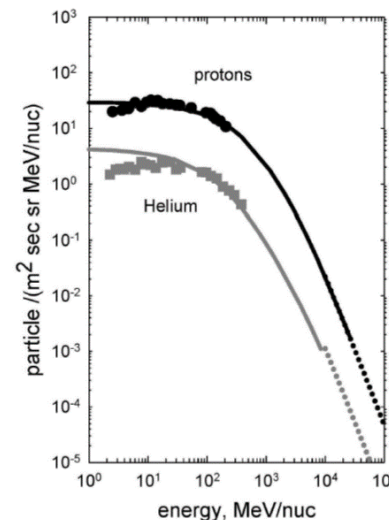
Voyager 1 (interstellar, solid circles) and Pamela (earth orbit. dots) measurements compared to GCR transport and solar wind attenuation model (solid line)

Ptuskin, V. S., Seo, E. S., Zirakashvili, V. N.; "Interpretation of Voyager 1 data on low energy cosmic rays in the galactic wind model," 24th European Cosmic Ray Symposium (ECRS2014), Journal of Physics: Conference Series 632 (2015) 012022

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How does space radiation interact with matter (i.e., us and our stuff)?

The Electromagnetic Force – Direct Ionization & Excitation (Electromagnetic Force) of Target Substance

- **High-speed charged particles decelerate by losing energy to target substance electrons during columbic collisions (with electrons) leaving an ionization/excitation damage track**
  - ◆ Nuclear collisions make little contribution to deceleration except at the lowest kinetic energies near end of track (displacement damage), but are the cause of secondary particle showers and limit the distance traveled by very high-energy primary CR particles
  - ◆ http://pdg.lbl.gov/2010/reviews/rpp2010-rev-passage-particles-matter.pdf
- **dE/dx is the rate of energy transfer: keV/micron or MeV-cm²/mg in a particular target substance**
  - ◆ Linear and nearly constant over most of the particle range – **hence the term linear energy transfer (LET)**
  - ◆ Nonlinear near end of track – most of the energy is deposited near the end of track in the "Brag Peak;" basis of accelerator hadron therapy for certain cancers
  - ◆ More info and some look-up tables
    - ◆ http://holbert.faculty.asu.edu/eee460/IonizationRange.pdf
    - ◆ http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_5/4_5_1.html
- **Quantified by the relativistic Bethe-Bloch equation**

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

Projectile (space radiation particle) dependencies

$\beta = v / c$; v = velocity of the particle; E = energy of the particle; x = distance travelled by the particle in the target; c = speed of light; z = particle charge; ε_0 = vacuum permittivity

**Target substance dependencies**

I = mean excitation potential of the target = 10eV(Z), n = electron density of the target = $(N_A Z \rho)/A M_\mu$; ρ = density of the target; Z = target atomic number; A = target atomic mass number; N_A = Avogadro number; and M_u = Molar mass constant = 1 in Si units; e = charge of the electron; m_e = rest mass of the electron

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The Electromagnetic Force – Direct Ionization & Excitation (Electromagnetic Force) of Target Substance

Powell Fowler Perkins/Science Photo Library
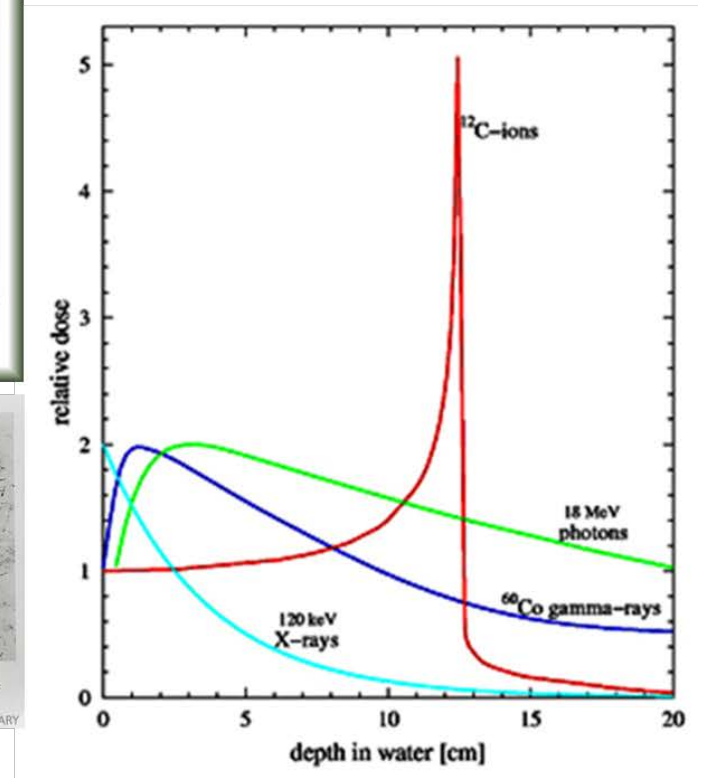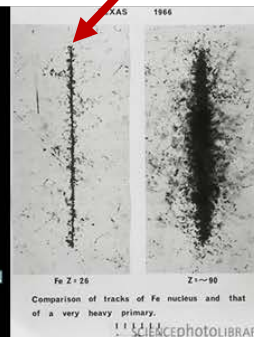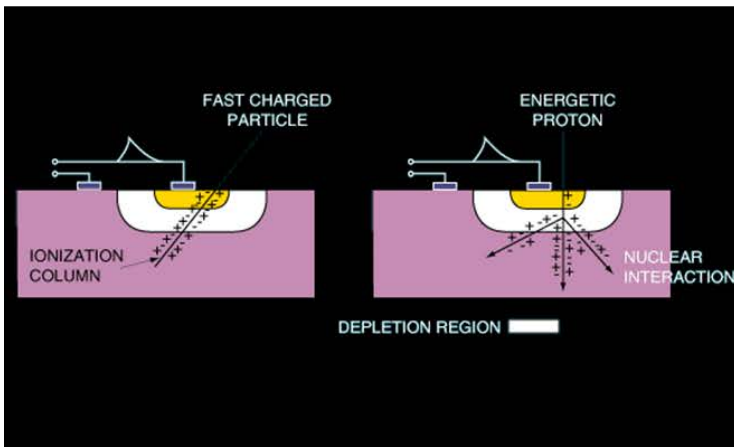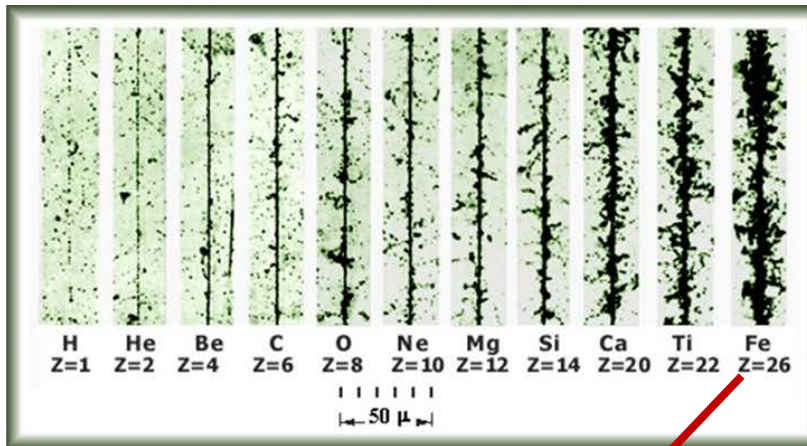
Single event upset (SEU) in a MOS/CMOS Field effect transistor. The space radiation single event environment is an important consideration for spacecraft and aircraft reliability. The figure on the right should read high energy proton or neutron

The Strong and Electroweak Forces – Nuclear Reactions and Secondary Particle Showers

- **Inelastic Nuclear collisions attenuate the primary flux exponentially and generate secondary particle showers via nuclear reactions**
  - **$N(l) = N(0) \exp(-l/\lambda)$**
    - λ = inelastic collision length (grams/cm^2)
    - l = thickness in g/cm^2
  - **http://pdg.lbl.gov/2010/reviews/rpp2010-rev-atomic-nuclear-prop.pdf**
    - **λ ranges from 42 g/cm^2 to 118 g/cm^2 for protons in various materials**
      - **λ increases with target atomic number**
    - At fixed target mass, number of collisions decreases with increasing atomic weight (i.e., fewer target nuclei per gram)
    - λ Scales as (**projectile atomic number**)$^{-0.77}$
- **$\langle n_{event} \rangle$ = average number of secondary particles per single collision event**
- **$\langle n_{event} \rangle$ is proportional to A(projectile) x A(target) x (average nuclear thickness function) and collision energy**
- **$\langle n_{shower} \rangle$ is proportional to primary projectile energy**
- *Neutrons are an important secondary particle shower products as are pions, muons, and γ rays*
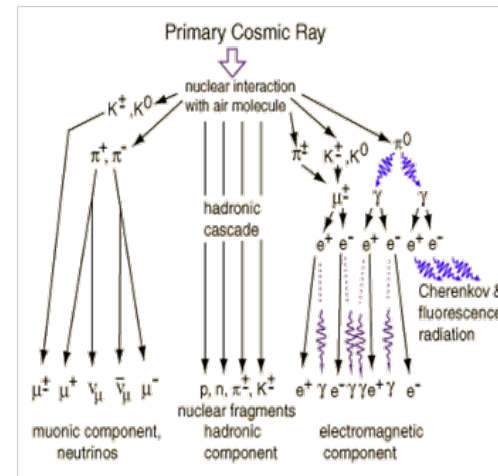
GCR secondary particle shower schematic
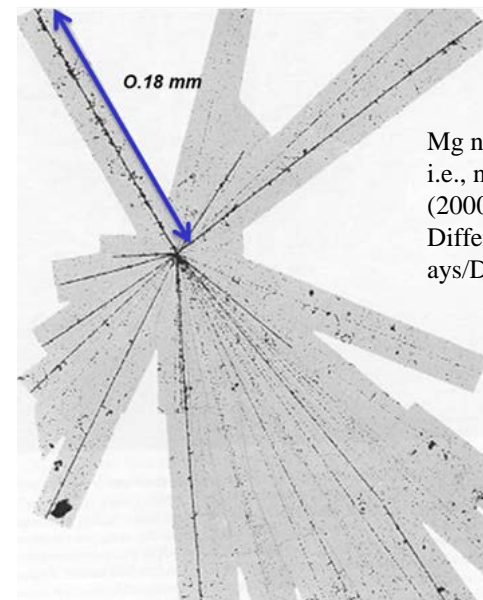
Mg nucleus cosmic ray emulsion "star," i.e., nuclear reaction event- Albert Lim (2000) http://astro.com.sg/articles/ Difference_%20btw_Gamma_n_Cosmic_R ays/DiffRays_image001.jpg

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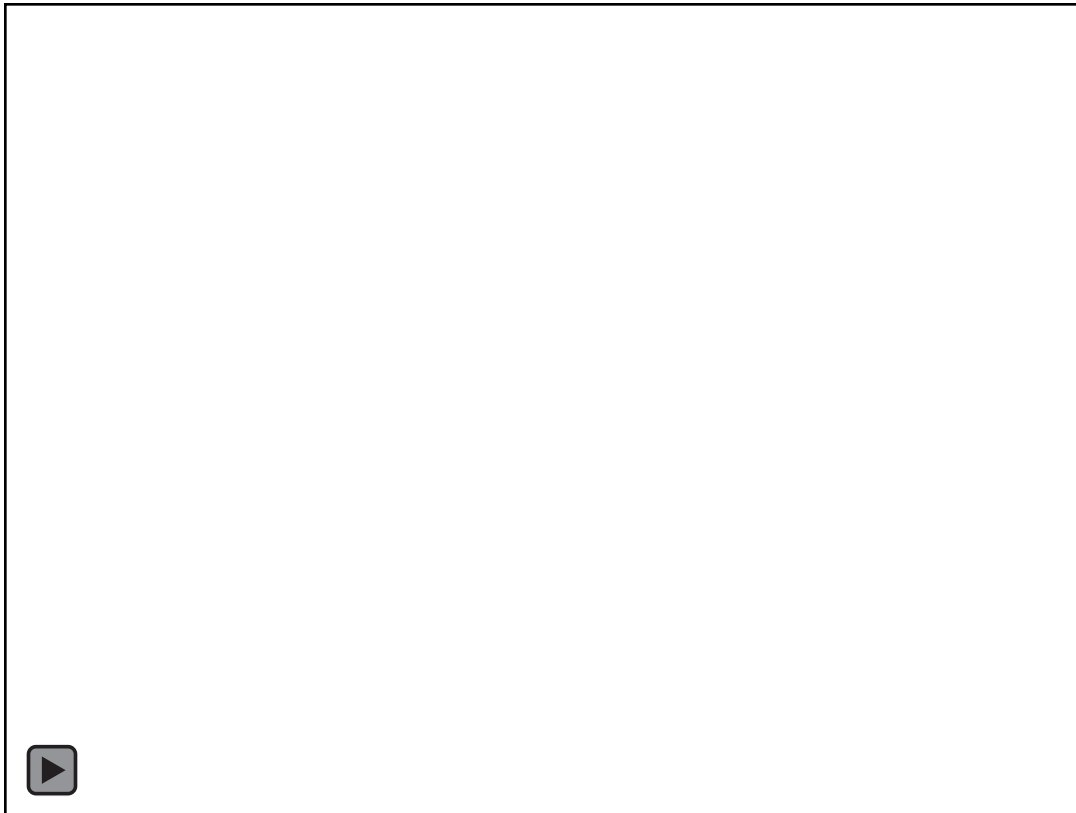
Video by Cosmus using AIRES (AIRshower Extended Simulations) to simulate what happens when a proton with 1Tev (1 trillion electron volts) of energy hits the atmosphere about 20 km above the ground. The shower is in a 20km x 5km x 5km box. Different particles are given different colors, electrons and positrons are green, muons are red and gamma rays are cyan. Source- http://http://astro.uchicago.edu/cosmus/projects/aires/
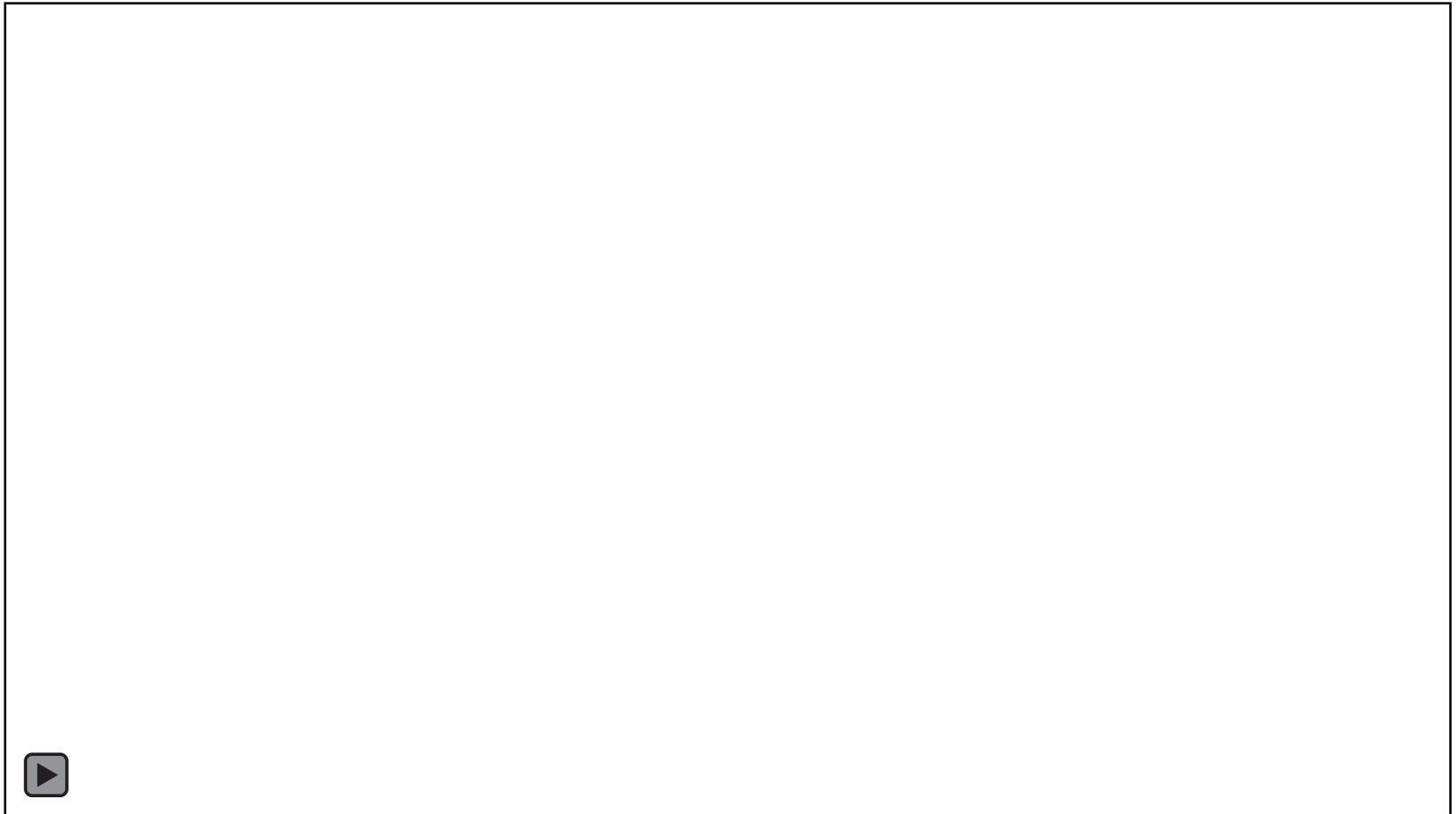
The Strong and Electroweak Forces – Nuclear Reactions and Secondary Particle Showers

And it looks like this when it hits the ground…

5 meters
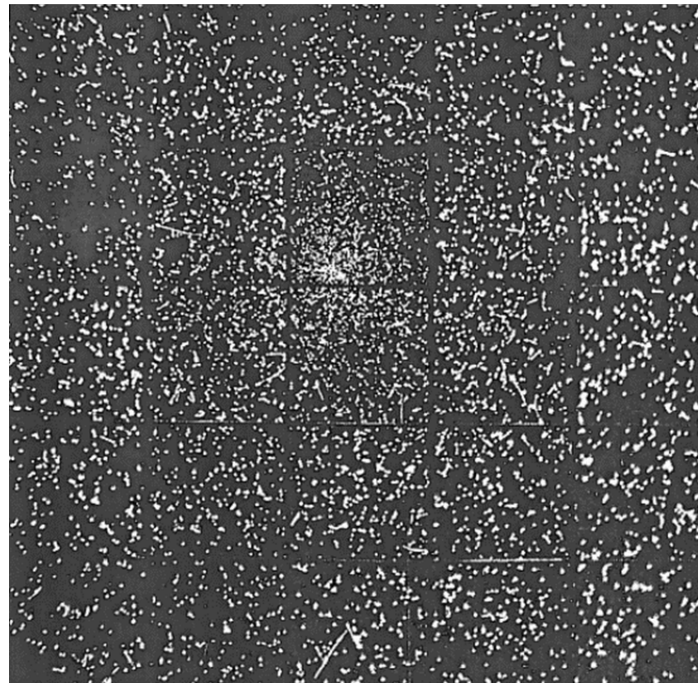
5 meters

A photograph of the central region of a small, vertically incident air shower as seen by the University of Leeds close packed horizontal array of discharge chambers (5 x 5 meters) Leslie Hodson 1990 (from Gaisser, T. K.; Cosmic Rays and Particle Physics, Cambridge University Press, Cambridge, 1990, Frontpiece)

Displacement Damage
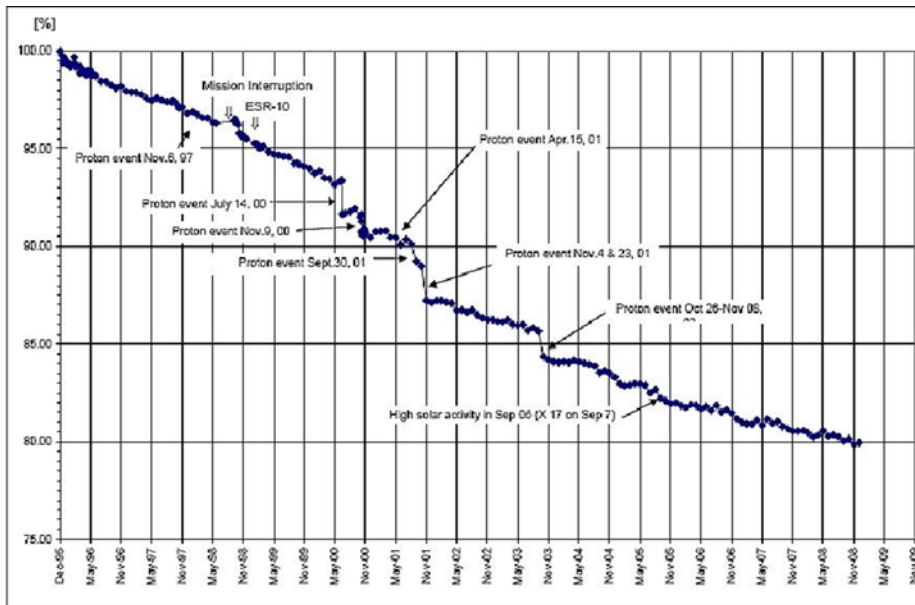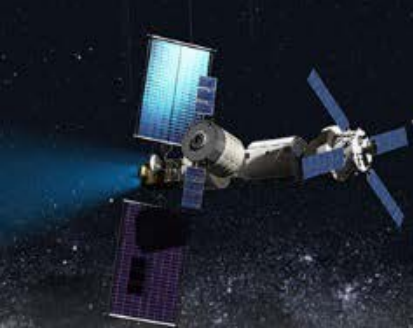
Ton van Overbeek, Jean-Philippe Olive, "SOHO, 13 years since launch and still going strong," Proceedings of the 32nd AAS Guidance and Control Conference, Breckenridge, CO, USA, Jan. 31.- Feb. 4, 2009, AAS 09-032
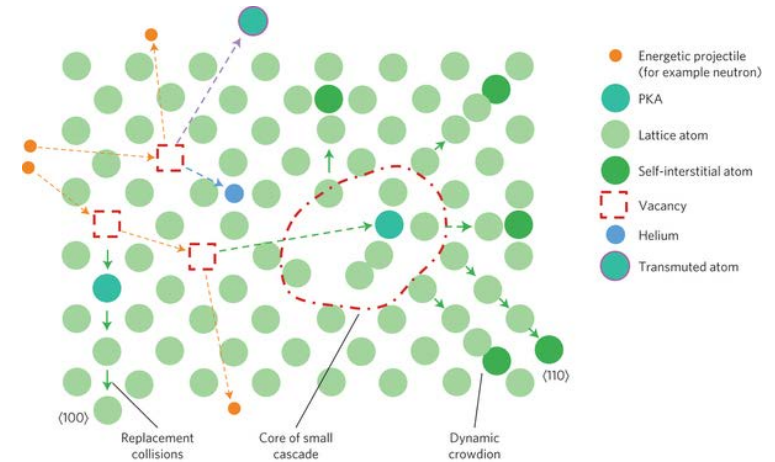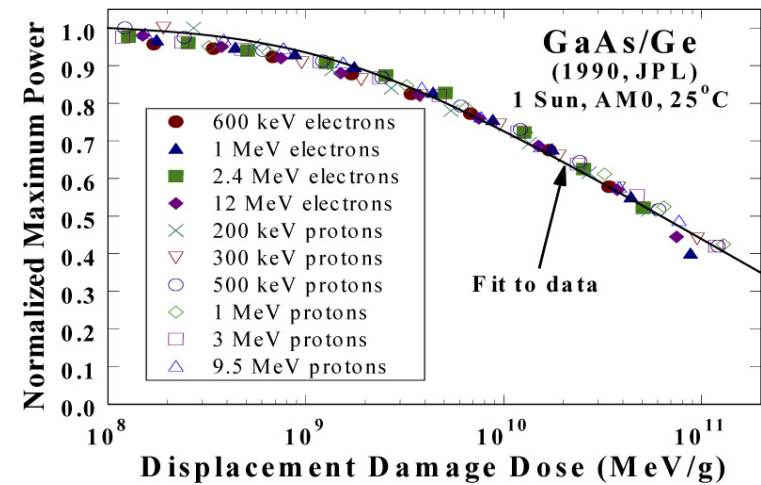
J. Knaster, A. Moeslang, T. Muroga; Nature Physics 12, 424–434 (2016)

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Space station zero – space radiation shielding specification and performance (in perspective) with humanities oldest and lowest cost spacecraft
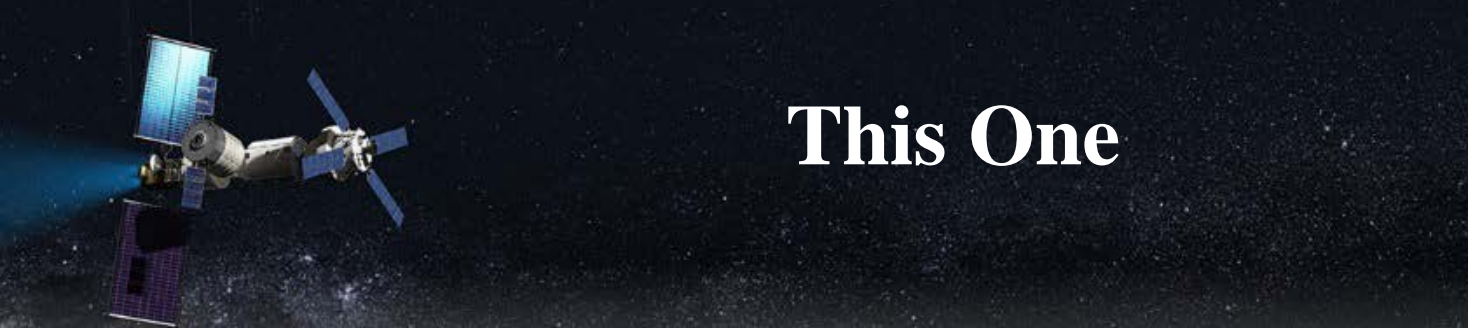
This One
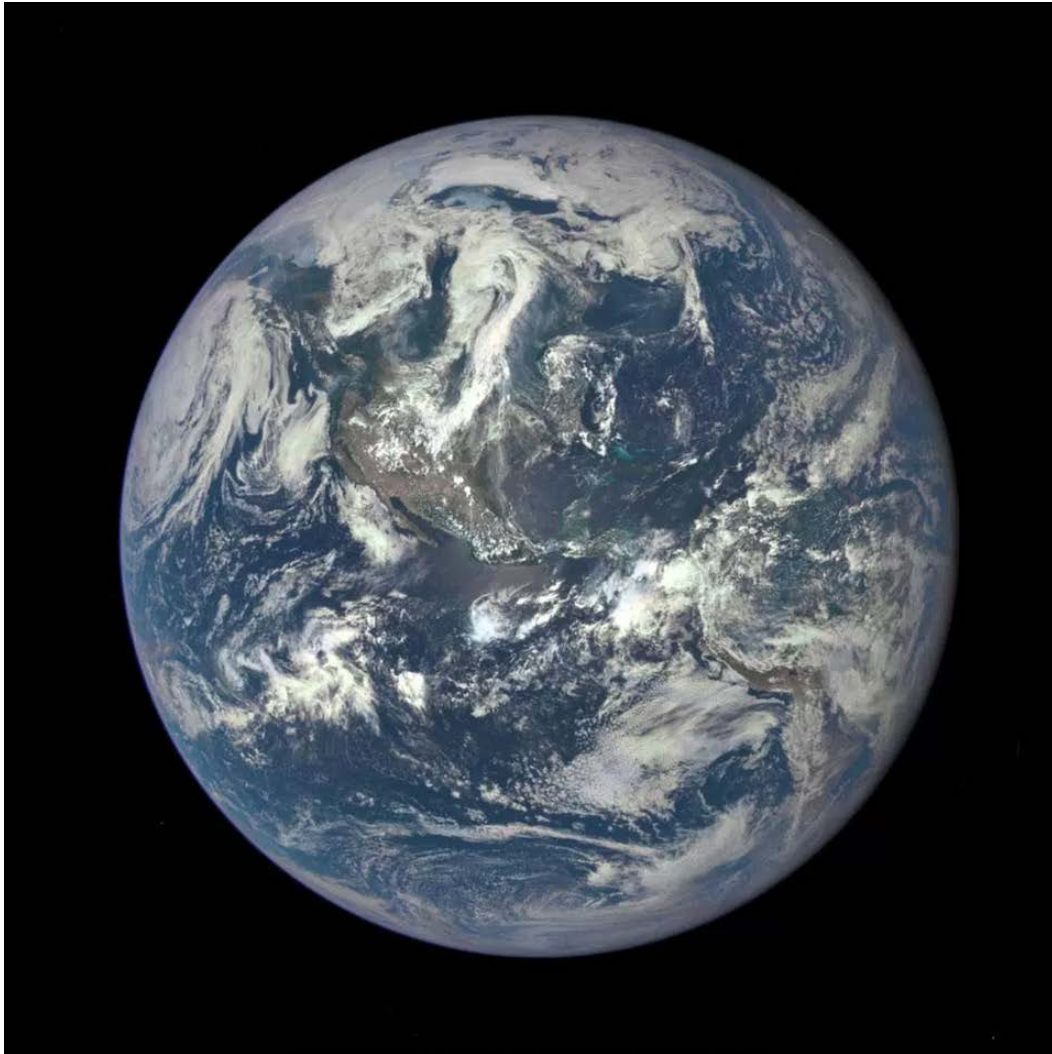
Shielding Specification and Performance Summary

- **Structural shielding mass**
- Diameter = 12,756.3 km
- Mass = 5.9736×10^{24} kg
- Composition – silicate rock with iron core (slightly radioactive from naturally occurring radioisotopes)
- At surface, blocks **all** space radiation over ~ 2π steradians (under your feet)

- **Atmospheric shielding mass**
- Thickness = ~100 km (1033 g/cm^2) measured along a radius
- Mass = 5.1480×10^{18} kg
- Composition – 77% nitrogen, 21% oxygen, with traces of argon, carbon dioxide and water (note – low Z elements)
- Accounts for most space radiation shielding effect for the remaining 2π Sr (overhead) and the production of cosmogenic radioisotopes

- **Geomagnetic field** – At the Earth's surface ranges from 25 to 65 microteslas (0.25 to 0.65 gauss). Effectively blocks solar wind. Mitigates GCR and SPE **in an altitude, latitude, and particle kinetic energy dependent manner.**
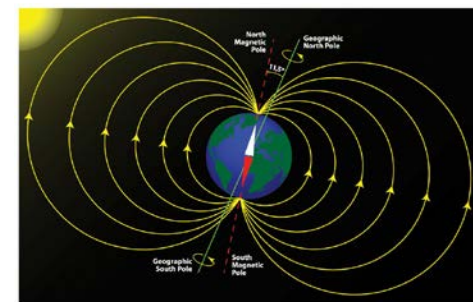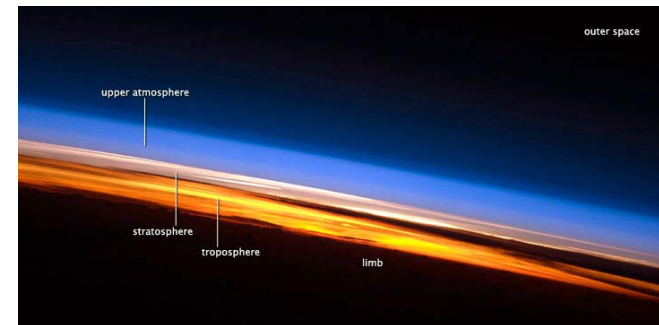
Shielding performance – Surface environments

- Earth surface ionizing radiation dose environments are dominated by natural radioisotope decay and man-made radiation source
  - Radon gas is the most important contributor
- 2 to 8 mSv (~0.2 to 0.8 rad) annual dose at the surface
- Space radiation contributions on the order of 10% of the total

AVERAGE ANNUAL DOSES FROM NATURAL RADIATION SOURCES

Legend: Cosmic rays, Gamma outdoors, Gamma indoors, Radon

Sources of Radiation Exposure in the United States

- Cosmic (Space) - 5%
- Terrestrial (Soil) - 3%
- Internal - 5%
- Radon and Thoron - 37%
- Industrial and Occupational - .1%
- Consumer Products - 2%
- Nuclear Medicine - 12%
- Medical Procedures - 36%
- Natural Sources - 50% ~310 millirem (0.31 rem)
- Manmade Sources - 50% ~310 millirem (0.31 rem)

Source: NCRP Report No.160(2009)
Full report is available on the NCRP Web site at www.NCRPpublications.org.

Sources of Radiation

- Medicine - 14%
- Nuclear Industry - 1%
- Buildings/Soil - 18%
- Cosmic - 14%
- Radon - 42%
- Food/Drink Water - 11%

Natural Radiation 85%

http://www.world-nuclear.org/info/inf05.html

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The Pfotzer Maximum: GCR + Earth's Atmosphere

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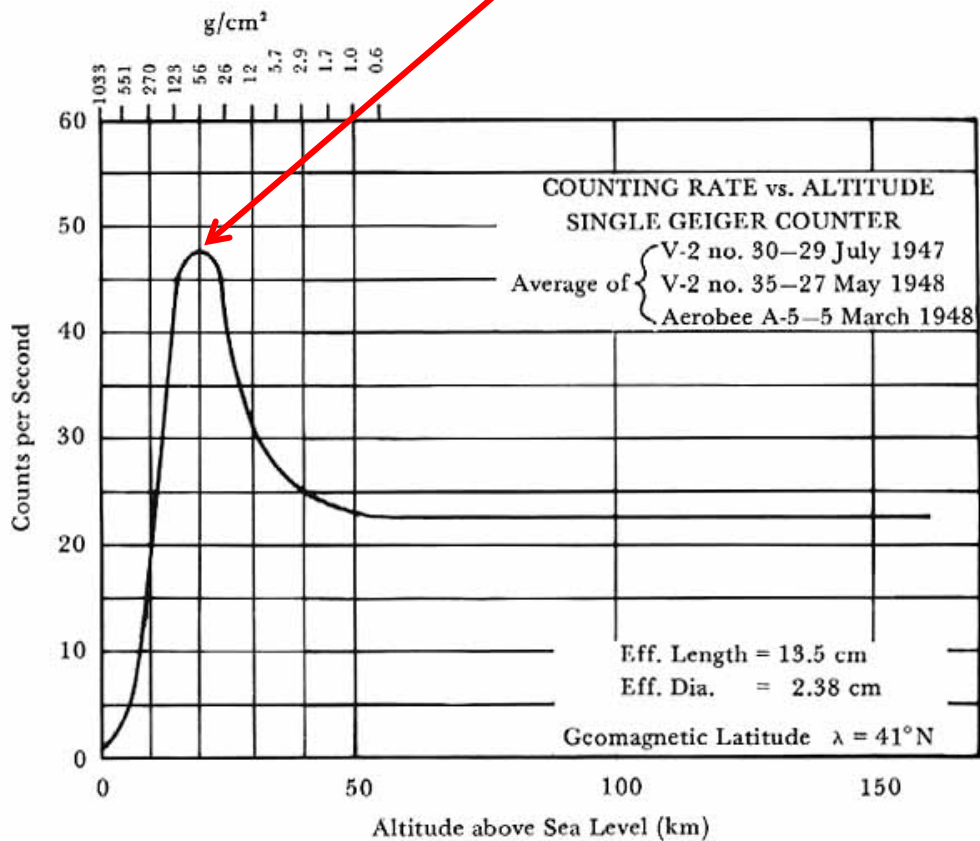
Shielding Performance – Commercial and Military Aircraft Environments

Equator (0°, 20°E)

60,000 ft; 3.98 (3.77-4.09) μSv/h
80,000 ft; 3.49 (3.32-3.60) μSv/h
40,000 ft; 2.71 (2.55-2.78)μSv/h
20,000 ft; 0.43 (0.40-0.44) μSv/h

High Latitude (70°N, 20°E)

80,000 ft; 19.2 (10.3-25.4) μSv/h
60,000 ft; 15.0 (8.97-18.9) μSv/h
40,000 ft; 7.37 (4.89-8.87) μSv/h
20,000 ft; 0.86 (0.63-0.98) μSv/h
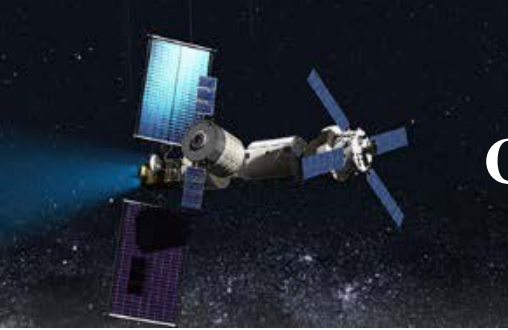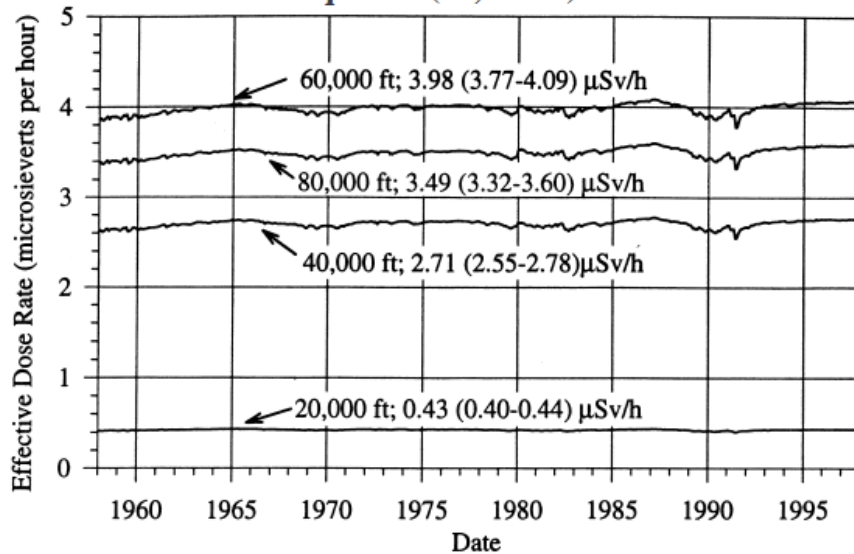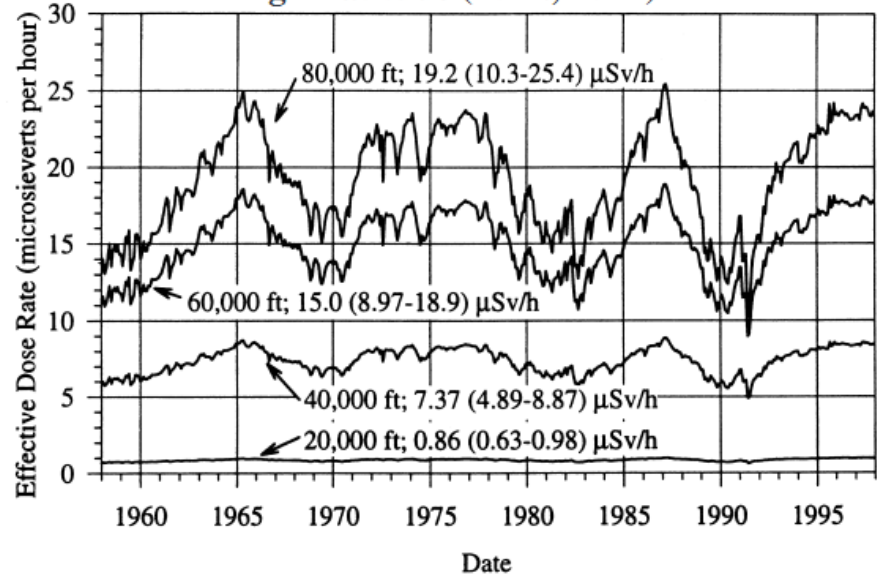
Fig. 1. Galactic radiation levels (monthly means) at various altitudes, at the equator and at a high latitude, January 1958–December 1997. Forty-year mean (minimum-maximum) effective dose rates are also shown. The effect of the 11-year solar cycle on cosmic radiation levels is apparent at high latitude.

(Source: W. Friedberg, et al. Reproduced from *Cosmic Radiation and Aircrew Exposure*, pp. 323–328, with permission from Nuclear Technology Publishing, P.O. Box 7, Ashford, Kent TN23 1YW, England.)

- **Average ISS hourly crew dose rates are on the order of 20 μSv/hr, comparable to commercial aircraft rates (polar route flights)**
- **Want to experience space radiation? Buy a plane ticket for a polar route flight**
- **Current polar route GCR/SPE dose environments can be viewed here**
  - **http://sol.spacenvironment.net/nairas/Dose_Rates.html**
- **Estimate you flight dose at the FAA CARI on-line calculator**
  - **http://jag.cami.jccbi.gov/cariprofile.asp**

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Shielding Performance – Solar Cycle Modulation of GCR Flux: Monitoring GCR Secondary Particle Shower Neutrons
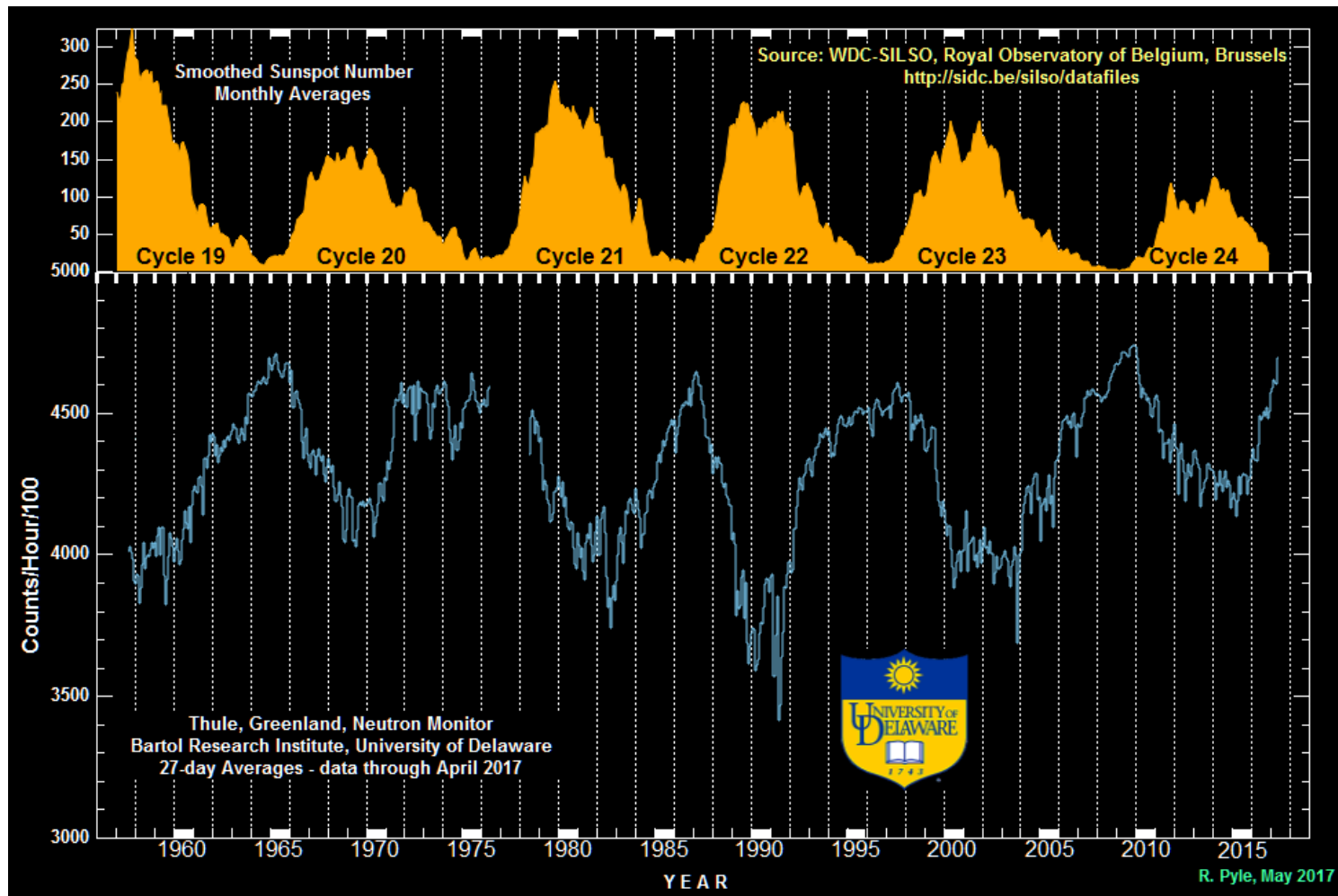
International Space Station – Space radiation shielding specification and performance

Geomagnetic Field

LA-1 MDM-16 Internal (2009:217 - 2014:190)

AMS01*TF = primaries at low orbit
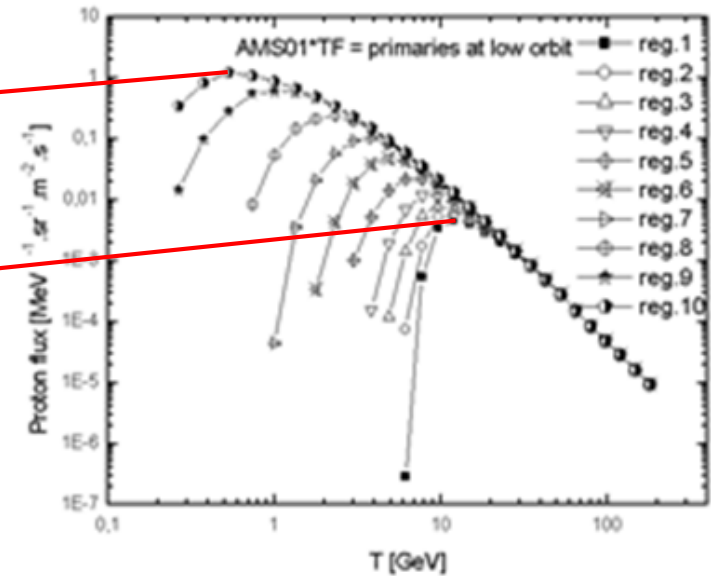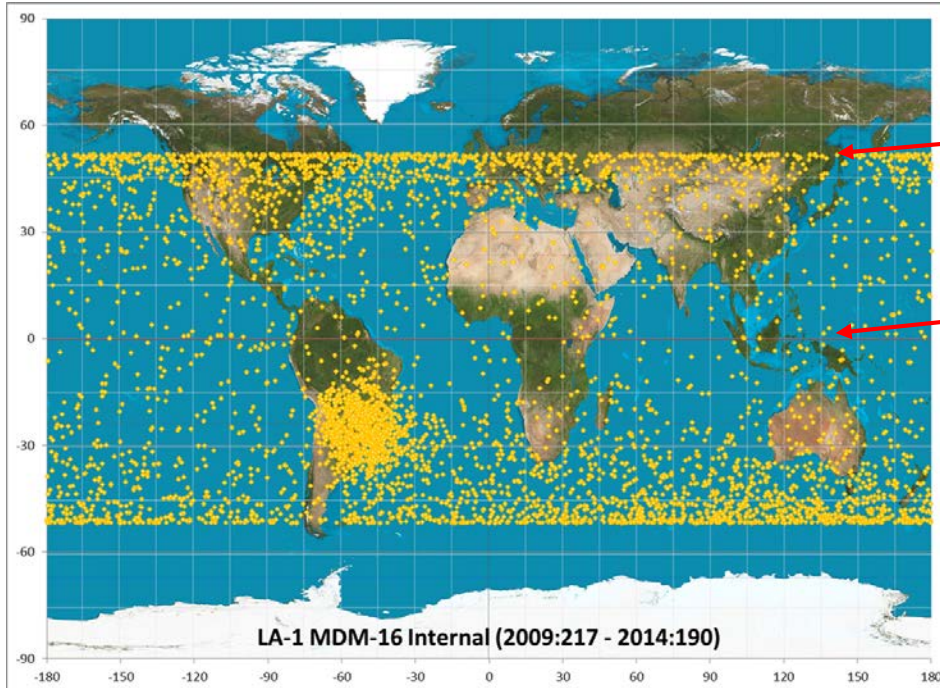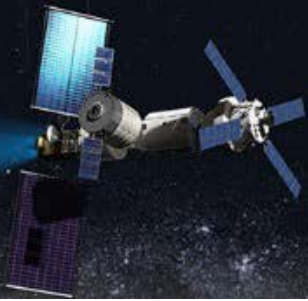
- **Latitude dependence of ISS LA-1 MDM-16 DRAM single event upset rate reported by system EDAC firmware**
- **Higher magnetic latitude => reduced geomagnetic shielding**
- **Higher magnetic latitude => greater similarity to interplanetary GCR environment**

- **Latitude dependence of GCR spectrum for ISS orbit**
- **AMS-01/STS-91**
- **Higher magnetic latitude => reduced geomagnetic shielding**
- **Higher magnetic latitude => greater similarity to interplanetary GCR environment**

Bobik, P., Boschini, M., Gervasi, M., Grandi, D., Kudela, K., Micelotta, E.; In: Solar variability as an input to the Earth's environment. International Solar Cycle Studies (ISCS) Symposium, 23 - 28 June 2003

Geomagnetic Field

- AMS-01 STS-91 He^{++} GCR fluxes:
- Low latitude region - ■
- Mid latitude region - ▲
- High latitude region - ◆
- Interplanetary at 1 AU - ●

- ISS enjoys significant geomagnetic GCR shielding at low latitude and almost none at high latitude (too bad about that SAA region)
- At high latitude, ISS is in a GCR environment very similar to the interplanetary GCR environment
- ISS can be used as a flight demonstration platform for exploration hardware with a high degree of confidence
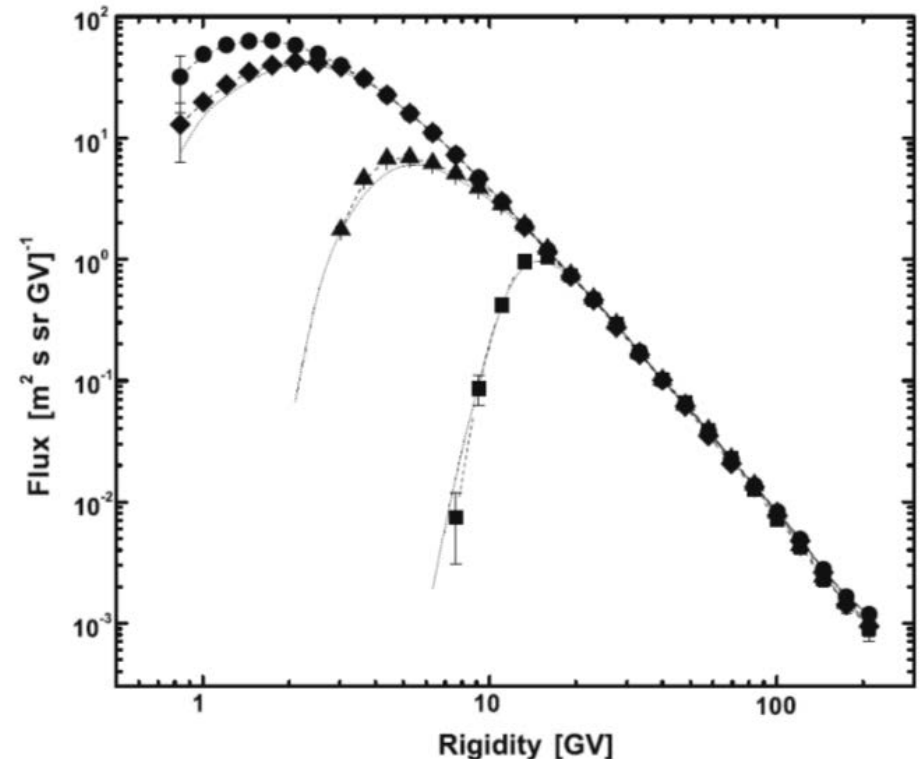
P. Bobik, G. Boella, M.J. Boschini, M. Gervasi, D. Grandi, K. Kudela, S. Pensotti, P.G. Rancoita; "Fluxes and nuclear abundances of cosmic rays inside the magnetosphere using a transmission function approach", Advances in Space Research 43 (2009) 385–393

4 years of ISS AMS-02 data

Veronica Bindi, Physics and Astronomy Department University of Hawaii at Manoa, NASA Advisory Committee, Human Exploration and Operations, NASA HQ, April, 7 2016
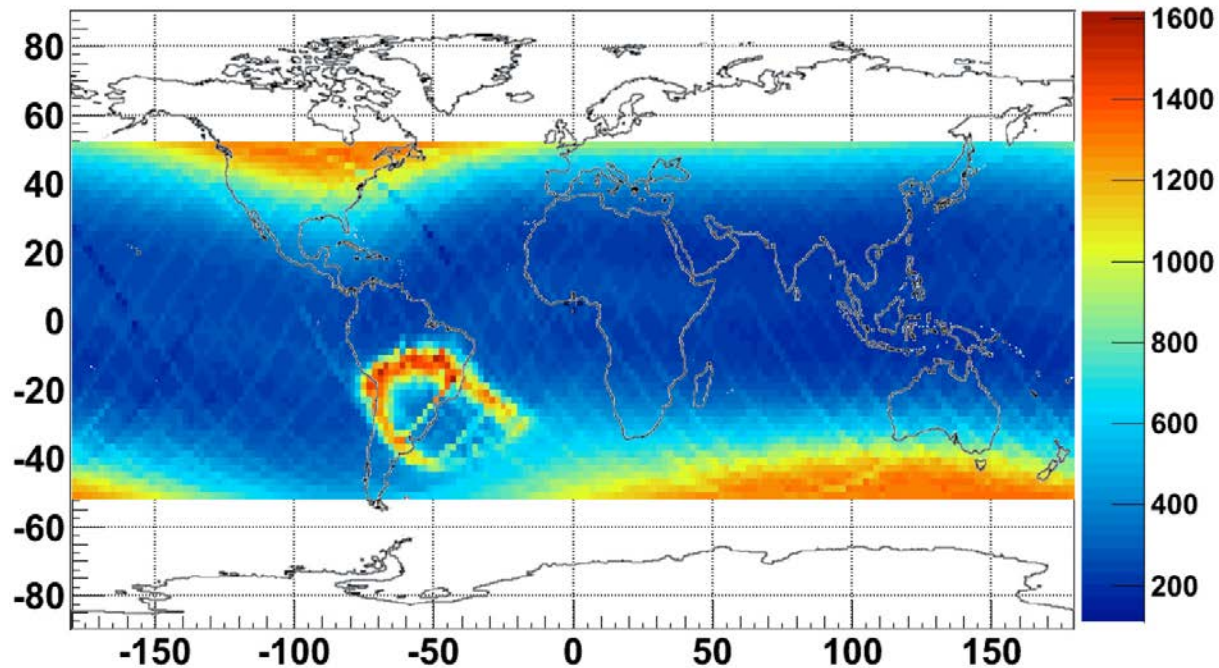
Shielding Performance – Internal to Pressurized Elements

- ISS Space Radiation Control Design Requirements (SSP-41000) - **None**
  - Primary/secondary structure determined by launch loads and dynamics, pressure vessel safety, thermal, and MM/OD protection
  - Materials and avionics to meet performance/safety requirements for the life of the vehicle without special shielding mass considerations
    - Natural Environment Definition for Design – SSP-30512, 500 km/51.6^o
      - Worst-Case – we don't fly above 420 km (Soyuz/Progress certification limits)
      - Worst-Case solar minimum GCR environment
    - ISS must "fail safe" and recover from the worst-case SPE defined in SSP-30512 and operate nominally otherwise
  - Crew Radiation dose administrative limits enforced by tracking accumulated crew dose and limiting crew exposure time (i.e., limiting stay time on ISS to limit total dose per expedition – "number of safe days in space"
    - Stay time must be compatible with planned crew change out flight rate
    - Safety requirements (SSP-50021) limits crew dose to **less than 40 cSv per year**
- So, how did this approach work?
  - No space radiation induced materials or avionics hard failures to date and none expected before end of program
  - No documented exception to expedition crew dose limits (that I know of – check with the SA/SD - JSC/SRAG on this)

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ISS Shielding Performance – Internal to Pressurized Elements

- **Shielding mass distribution functions** with ranges from 10 g/cm^2 to more than 100 g/cm^2 (aluminum with cargo, avionics and consumables) with median values of 20 to 50 g/cm^2 (e.g. US Lab module)

- Pre-flight **annual dose estimates** (using the SSP-30512 Design/Verification Environment) for the US Lab module range from <u>8 rads (Si) to 21 rads (Si) with a median value of about 14 rads (Si)</u> depending on location of the dose point

  - Variable environment – altitude, solar activity, and solar cycle effects

  - The design environment specifies 500 km altitude as a worst-case to compensate for any uncertainties

- In-flight TLD measurements during solar max ranged from <u>4.5 rads (Si) to 8.2 rads (Si) per year</u>.

- DOSTEL (particle hodoscope) measurements averaged to <u>7.1 rads Si per year</u> (Reitz et al., AIAA 2001-4903)

- In-flight solar max measurements (Kodiara et al., 2013) <u>11.1 rads (H2O)/year ~ 8.6 rads (Si)/year</u>
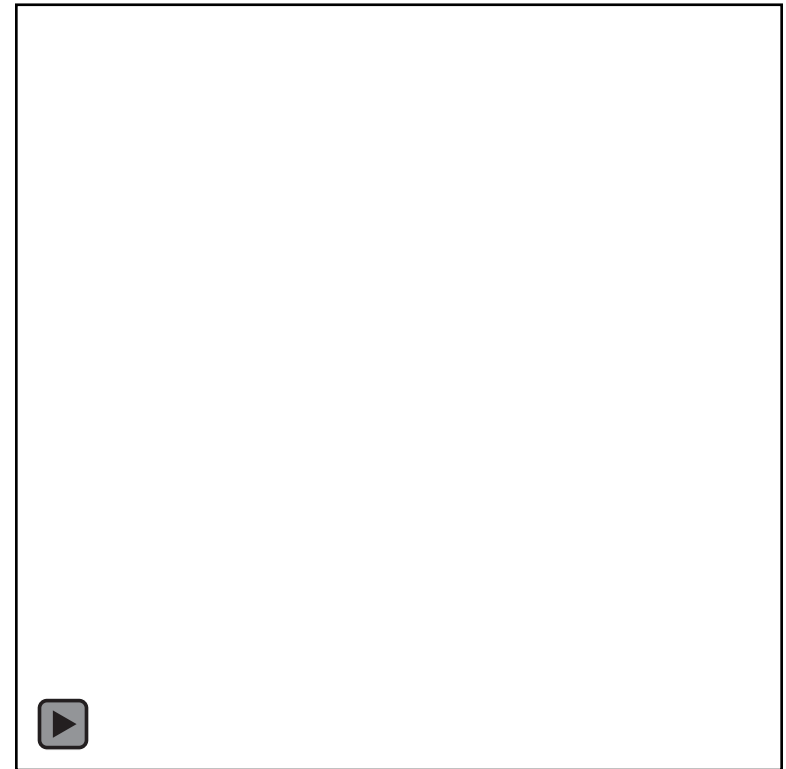
ISS Shielding Performance
Internal to Pressurized Elements
Secondary Neutrons

Mission	Date	Solar Cycle	Altitude (km)	Inclination	Shielding (g/cm²)	Neutron Detector
STS-28	8/8/1989	22	302	57°	20-50	Bonner Ball
STS-36	2/28/1990	22	246	62°	20-50	Bonner Ball
Mir	1990-1992	22	354-374	51.6°	40	Fission Foil
ISS	2001	23	-	-	20-50	Bonner Ball

- Good agreement from 0.01 MeV to 100 MeV
- Unknown whether agreement will continue at higher energies
- STS neutron flux consistently lower than ISS and Mir
  - May be a result of detector locations and less shielding at those locations
- Some uncertainty in vehicle thickness and neutron detector locations from the experimental data
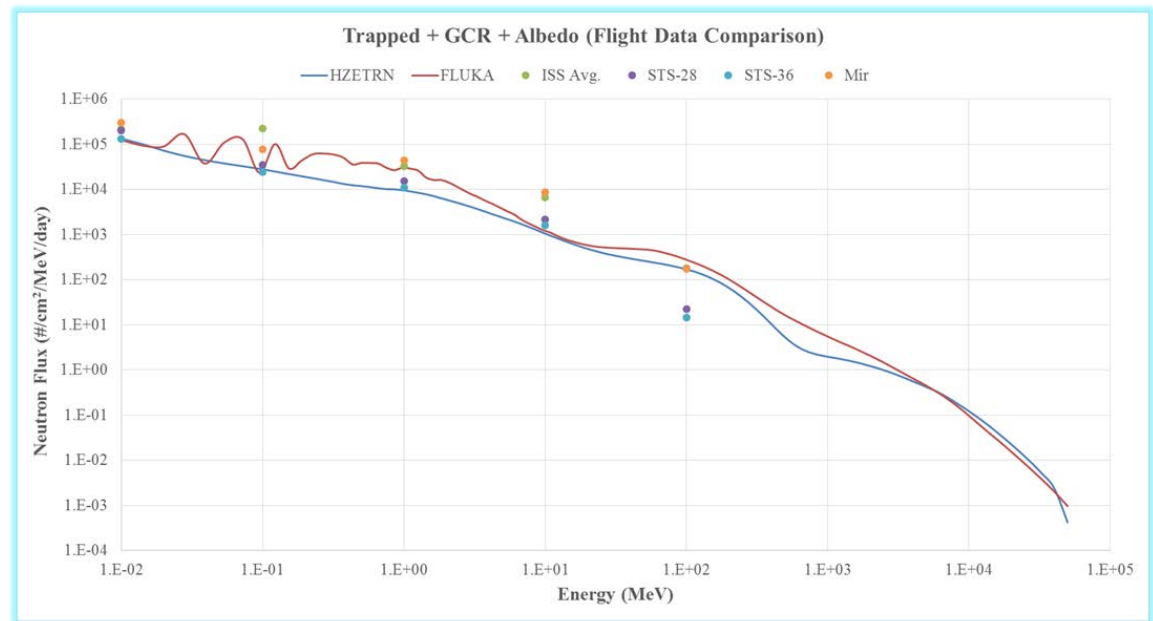
Kristina Rojdev, NASA-JSC, Brandon Reddell, NASA-JSC Steve Koontz, NASA-JSC, William Atwell, Boeing Technical Fellow, Retired, Paul Boeder, Boeing Research & Technology (Now with JPL); "Investigation of Secondary Neutron Production in Large Space Vehicles for Deep Space," AIAA Space 2016, Conference Proceedings

GCR Nuclear Collisions: Secondary Particle Showers and Shielding Effectiveness

ISS Crew Shielding Augmentation Work

- Modeled dosimetry – 4.7 g/cm^2 polyethylene, inside ISS, solar minimum – Annual dose to blood forming organs (BFO) in cGy (rads) - Calculated with HZETRN

Shavers, Mark; "Radiation Measurements and Shielding Analysis for ISS, Workshop on Radiation Monitoring for the International Space Station, Vienna Austria, Sept 8-10, 2004,
http://www.iss-casis.org/files/CASIS_RFP_2013-3_Radiation_Measurements_and_Shielding_Analysis_for_ISS.pdf

Radiation source	Without poly shield	With poly shield	Percent reduction
Trapped protons	4.234	2.664	37.2%
Galactic Cosmic Radiation	4.782	4.708	1.8%
Combined (GCR + Trapped)	9.016	7.373	18.4%
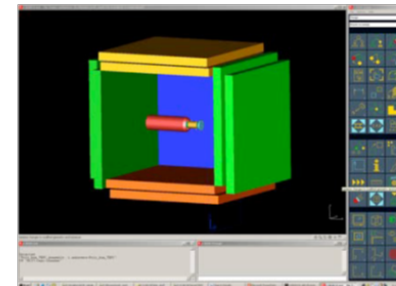
In-flight measurement results for "TeSS" poly shielded crew quarters:
1) ~ 20 percent reduction Equivalent dose in personal dosimeters
2) ~ 40% reduction in ISS crew chromosome damage via biodosimetry

Shielding Performance – External Surfaces

- Shielding mass distribution functions are highly anisotropic and median ranges from zero to more than 10 g/cm^2

- Trapped radiation (protons and electrons) dominates (SAA and high latitude regions) – GCR contribution negligible is compression

  - Highly variable environment – altitude, solar activity, and solar cycle effects

- Boeing Radiation Effect Lab thermo-luminescent dosimeter measurements on MISSE-1, 2, and 3 ISS payloads (Wert, Normand, Perry, Pippin, Bartholet; NSMMS, June 2010)

  - Median shielding mass ranges 0.0 to 0.9 g/cm^2

  - 4-year doses range from **3×10^3 rads** (Si) at 0 g/cm^2 to **10^2 rads** (Si) at 0.9 g/cm^2

  - All well below the annual worst-case Design/Verification Environment (SSP-30512) doses at the corresponding shielding thicknesses (10^6 rads (Si) @ 0.0 g/cm^2, and 3×10^5 rads (Si) @ 0.9g/cm^2)

Shielding Performance – External Surfaces

- **STP-H4 MARS radiation detectors – channel 9 – lower shielding mass**
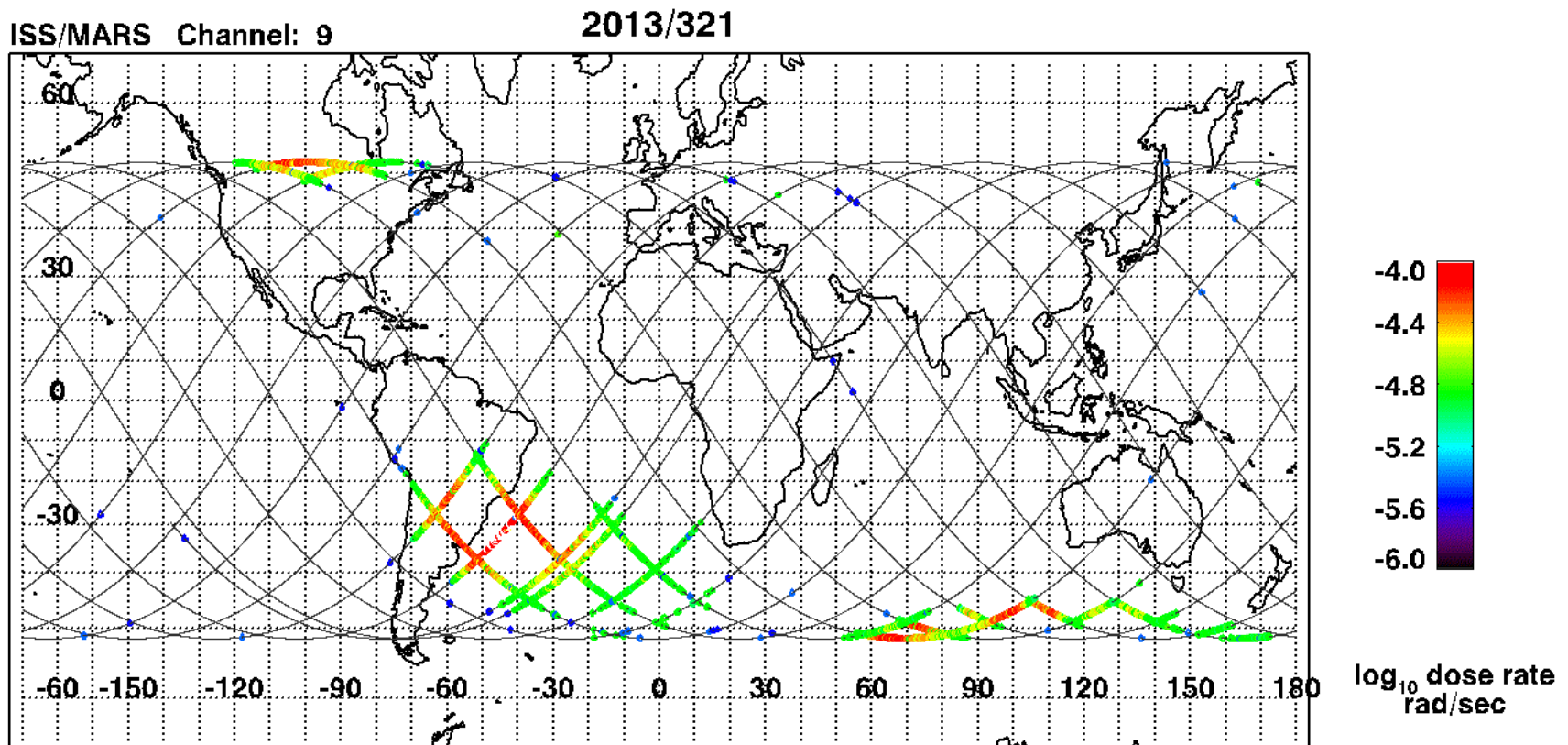
ISS/MARS Channel: 9   2013/321

$\log_{10}$ dose rate rad/sec

Applied Space Environments Conference, May 2017, ISS Miniature Array of Radiation Sensors Dosimeter Measurements and Modeling, *Andrew Nicholas (US Naval Research Laboratory), Mike Xapsos (NASA Goddard Space Flight Center), Peter, Walker (Computational Physics Inc), Craig Stauffer (AS&D), Joseph Minow (NASA Marshall Space Flight Center)*

Shielding Performance – External Surfaces

- STP-H4 MARS radiation detectors – channel 2 – higher shielding mass

Applied Space Environments Conference, May 2017, ISS Miniature Array of Radiation Sensors Dosimeter Measurements and Modeling, *Andrew Nicholas (U.S. Naval Research Laboratory), Mike Xapsos (NASA Goddard Space Flight Center), Peter, Walker (Computational Physics Inc), Craig Stauffer (AS&D), Joseph Minow (NASA Marshall Space Flight Center)*

A Graphic Example of How Different it is on ISS:
CR-39 Plastic Nuclear Track Detectors – 925 Days Inside the ISS U.S. Lab
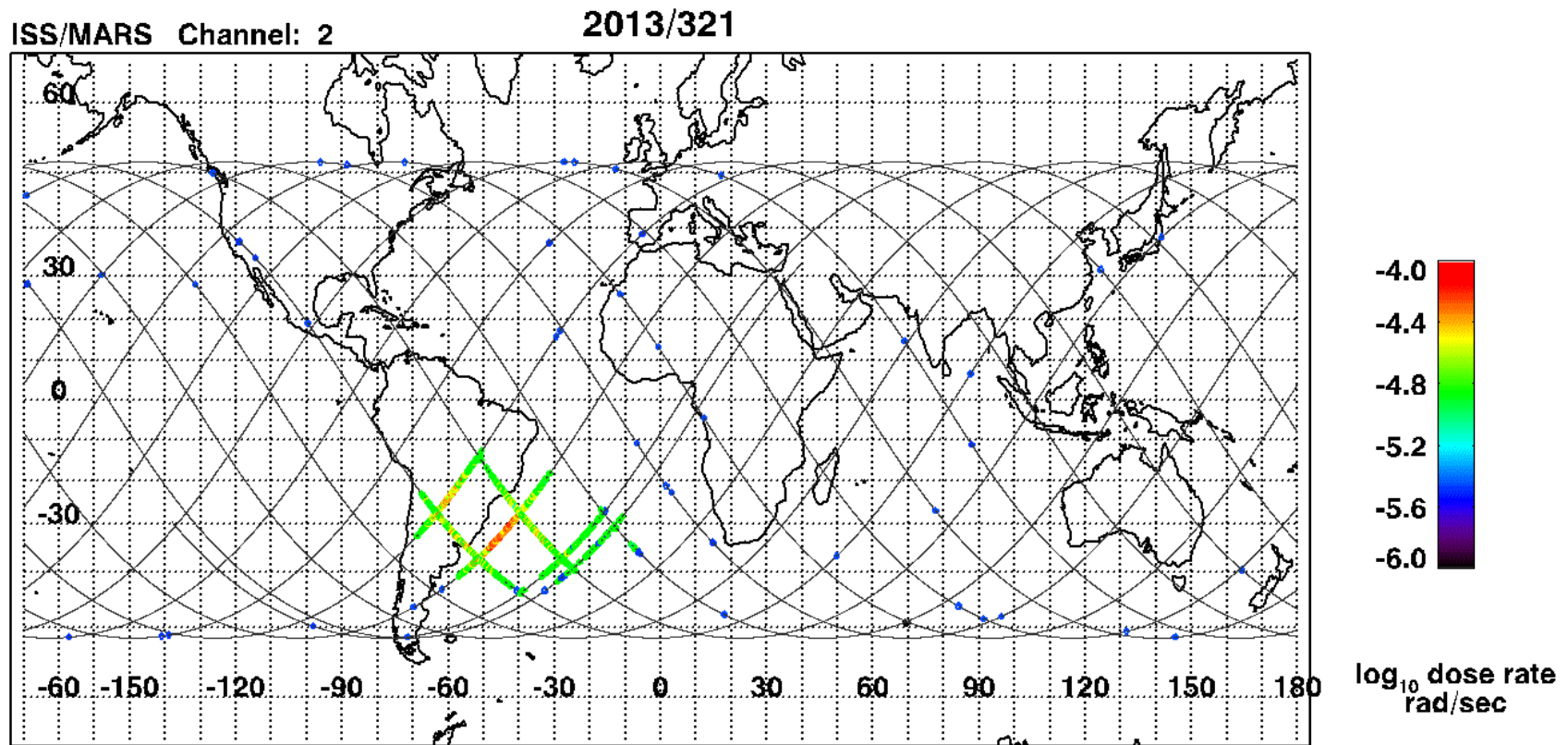

Ground Control Plastic Nuclear Track Detectors (PNTD)
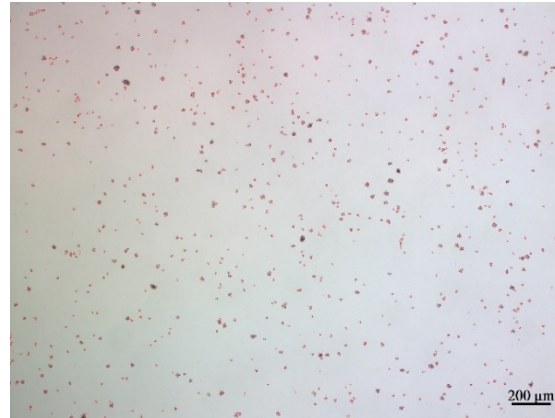
Flight PNTD
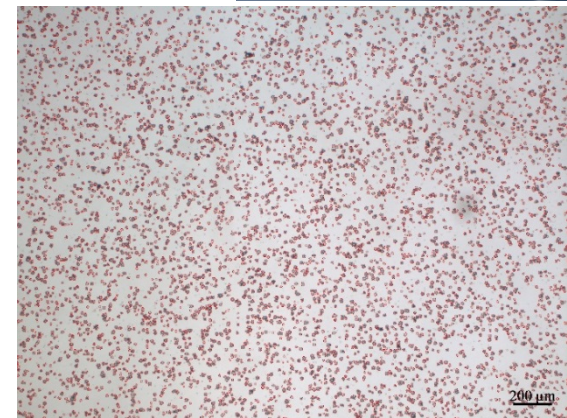
Flight PNTD surface in contact with 0.005 cm Pb foil

High Z elements, like Pb, produce more secondary particle shower products than low Z elements

Flight PNTD Track Size Histogram

number of tracks per size bin

FconBhistogram⟨1⟩

track area in square microns

Flight PNTD Track Size Histogram, PB Foil

number of tracks per size bin

FPbBhistogram⟨1⟩

track area in square microns
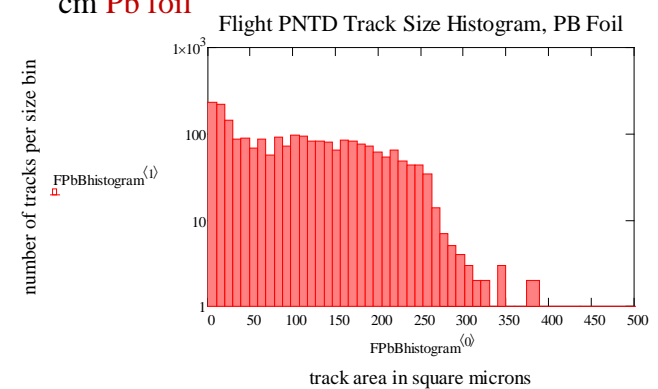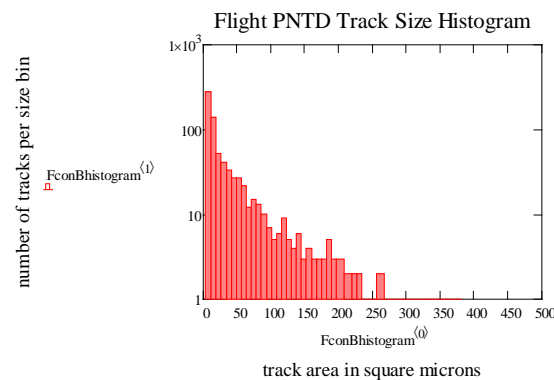
The obvious differences between the flight-PNTD and the Pb-foil-flight PNTD are expected as a result of nuclear reactions, caused by space radiation primary and secondary particles, in the Pb foil with smaller contribution from trace (ppm level) Th and U impurities in the Pb foil itself. Ag, Hf, and W foils produced many fewer nuclear reaction products in their PNTDs. Track area increases with increasing particle LET.

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Beyond GEO – The interplanetary radiation environment – GCR and SPE

GCR and SPE
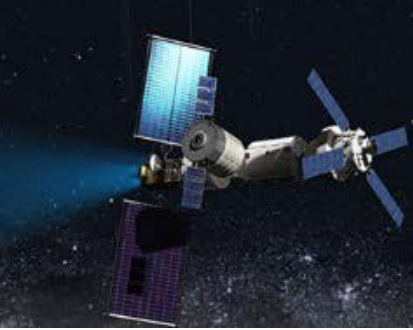
- **Two important radiation environments**
  - **GCR – continuously present**
    - **Varies slowly over 11-year solar cycle**
      - **No sudden increases in the observational record**
    - **Solar Max Environment << Solar Min Environment**
    - **Little radial dependence (< 10%/AU) between the orbit of Mercury and the Asteroid belt**
    - **"Hard" spectra – difficult to manage with shielding, active or passive**
    - **Total Ionizing Dose (TID) effects on materials and avionics largely negligible**
    - **Prime cause of avionics SEE effects**
  - **SPE – A few days at a time, about once or twice a year on average**
    - **During events, SPE particle flux >> GCR particle flux**
    - **"Softer" spectra, so more manageable with shielding**
    - **TID effects are significant and are reduced with shielding mass**
    - **Radial dependence is significant and highly variable**
      - **Peak intensities often fall off as R^{-3} while total event dose falls off as R^{-2}, but you can't count on it**
      - **CMEs are efficient charged particle accelerators and examples exist of SPEs that were more severe at Mars than at Venus or Earth**
      - **See the ESA SPE modeling, analysis and data archive web page - http://dev.sepem.oma.be/**

https://settlement.arc.nasa.gov/75SummerStudy/figure2.6.gif

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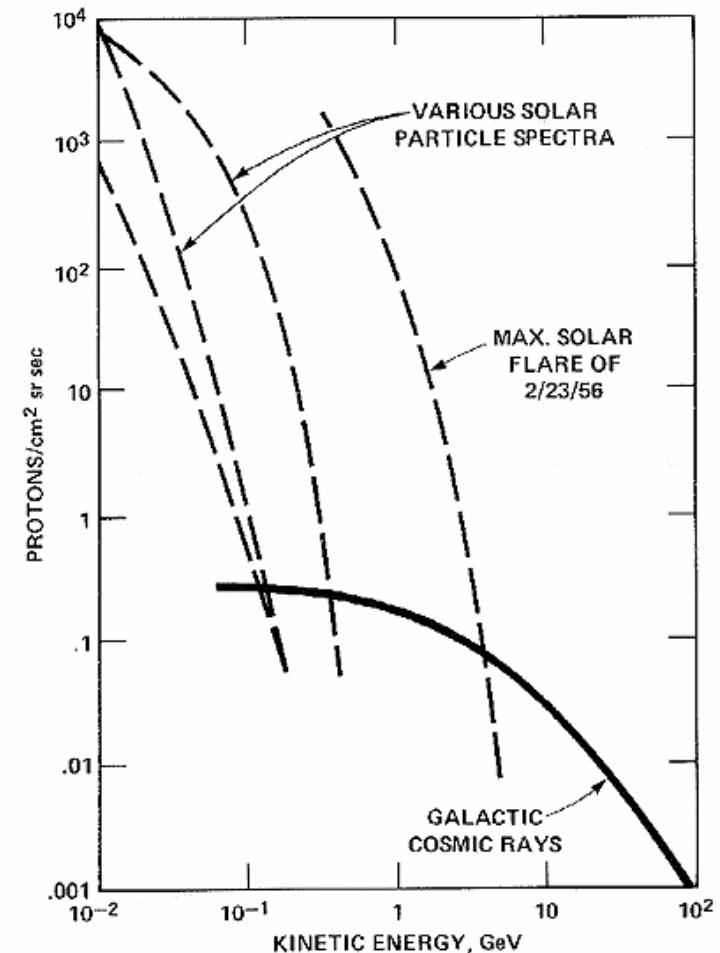
GCR: Solar Max, Solar Min, Shielding Mass and Shielding Material
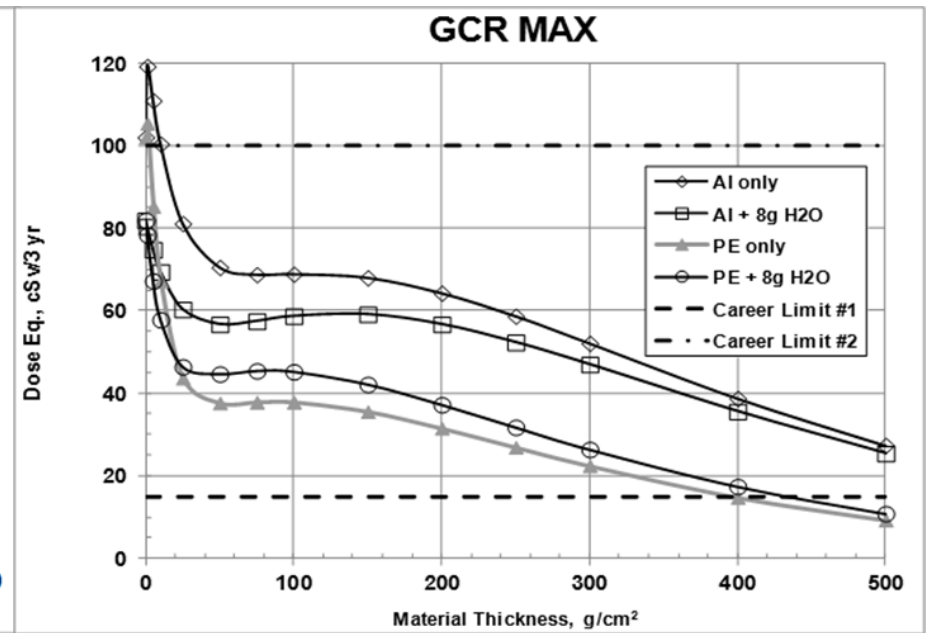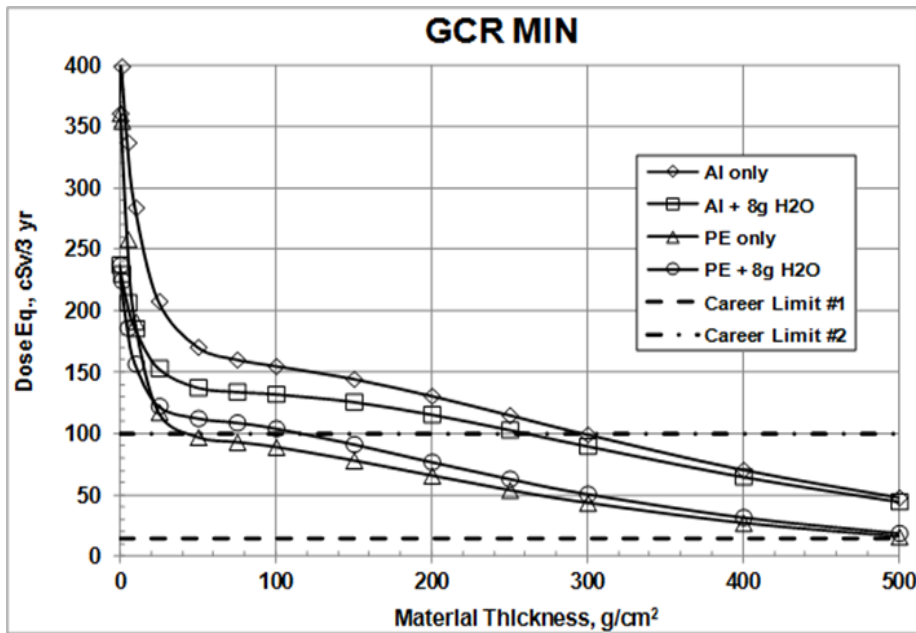
NASA HZETRN 2010 estimates of crew dose vs. shielding mass for a 3-year interplanetary mission assuming solar maximum and solar minimum GCR environments, no SEP event contributions, and both the 10 cSv and 100 cSv dose limits

GCR: LET Spectra Under Aluminum Shielding
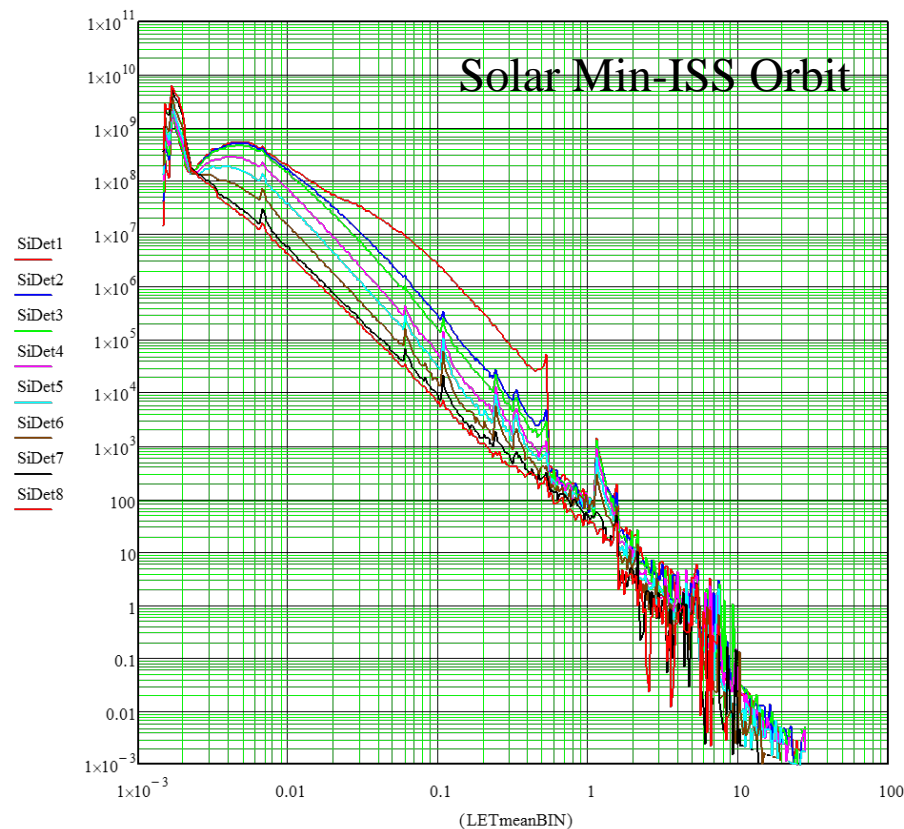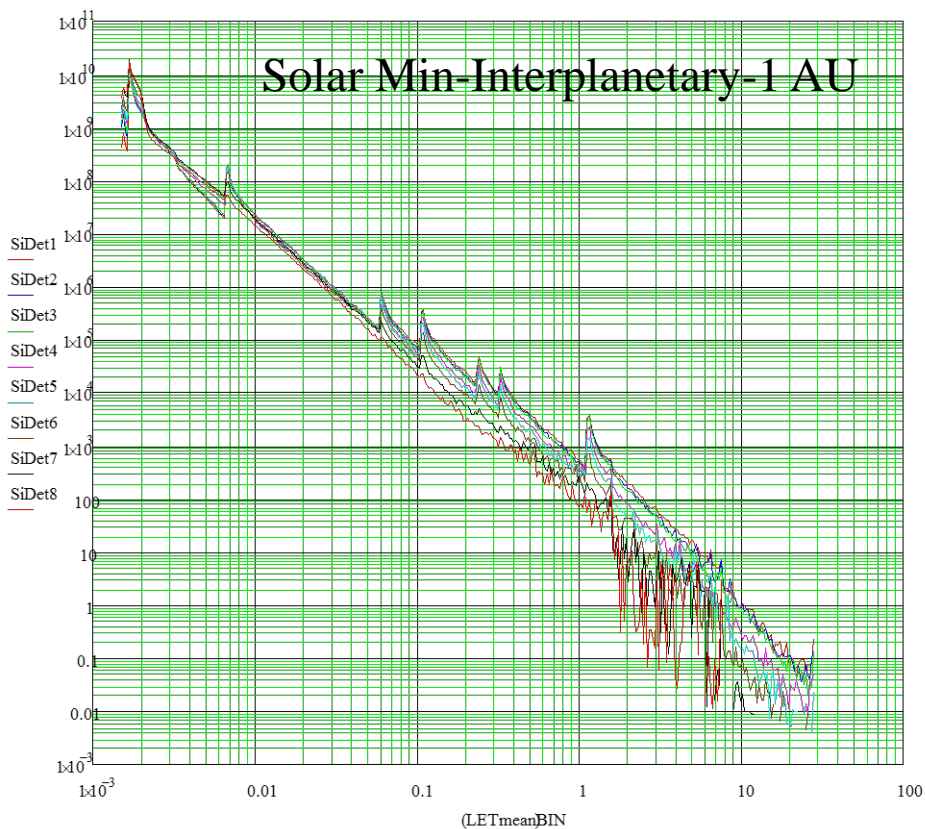
Solar Min-Interplanetary-1 AU

Solar Min-ISS Orbit

Detector Si Shell	SiDet1	SiDet2	SiDet3	SiDet4	SiDet5	SiDet6	SiDet7	SiDet8
Detector Shell Radius (cm)	5037.4	5037.3	5037.1	5035.6	5033.7	5030.0	5018.9	5000.0
Si Detector Median Al Shielding Mass in g/cm²	0.15	0.81	1.6	7.9	15.6	31.1	77.5	156.2

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- **TID vs polyethylene shielding mass and two different SPE spectra models needed to during the July 2000 and November 2001 SPEs**
- **Event dose at 0.1 g/cm^2 ~ 10^4 cGy for both events**
- **The Band model shows higher dose at low and high shielding mass and is more consistent with Earth surface neutron monitor data**

July 2000 - Dose Comparison
Band vs Exp - Polyethylene
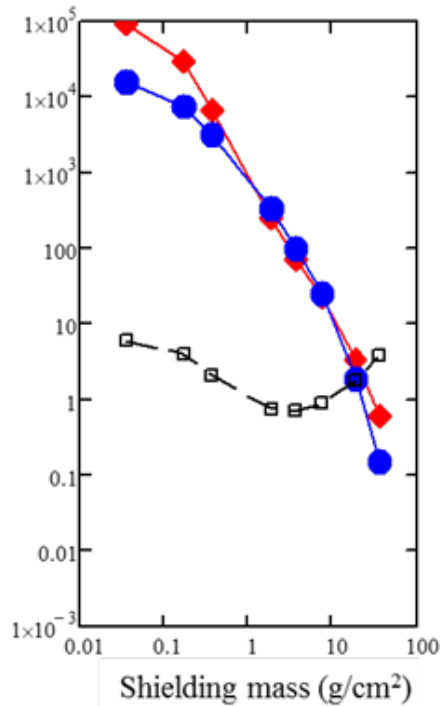
November 2001 - Dose Comparison
Band vs Exp - Polyethylene
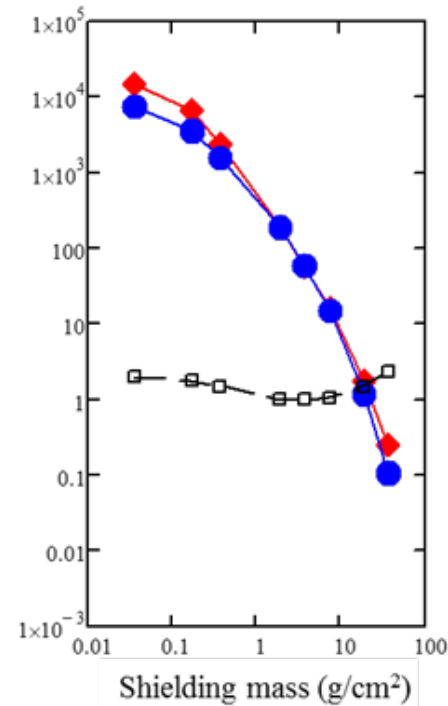
SPE: Spectra Model, Shielding Materials and Shielding Mass

- Shielding mass of four different materials needed to reduce TID to 1 cGy and 10 cGy during the July 2000 SPE using the Band spectrum model
- Event dose at 0.1 g/cm² ~ 10^5 cGy

Shield material	1cGy Band	10 cGy Band
Polyethylene	30 g/cm²	10 g/cm²
Carbon	37 g/cm²	12 g/cm²
Aluminum	40 g/cm²	13 g/cm²
Titanium	43 g/cm²	15 g/cm²

Environments Definitions (Models) for Design Development and Test

- **ISS: SSP-30512; Space Station Ionizing Radiation Design Environment**
  - **Revision C effective date: June 3, 1994**
  - **Applicable to ISS orbits only**
    - Orbital inclination = 51.6 degrees
    - Altitude = 500 km (worst case, ISS altitude < 420 km at all times)
    - NASA/GSFC AP8/AE8 trapped radiation models
      - No plans to update to DoD/Aerospace Corp. AP9/AE9 at this time, but we are considering it
    - Solar Minimum CREME-96 solar minimum GCR environment with a space weather index of M=4, (Moscow State University GCR model), worst case for GCR (until last minimum anyway)
    - SPE model – October 1989 SPE
    - Epoch 1964 geomagnetic field for both GCR and SPE

- **SLS-SPEC-159; Cross-Program Design Specification for Natural Environments**
  - **Revision D, effective date: November 4, 2015**
  - **Revision E, in work**
    - Presently applicable to SLS and MPCV (Orion)
    - Recommended for Future Capabilities Team (FCT)/Deep Space Gateway (DSG)
    - NASA/GSFC AP8/AE8 trapped radiation models
      - No plans to update to DoD/Aerospace Corp. AP9/AE9 at this time, but we are considering it
    - October 1989 solar particle event
    - CRÈME-96 GCR with near Earth/interplanetary option
  - **Includes ascent, LEO, radiation belt transit, interplanetary GCR and SPE design environments with definition of design reference mission (DRM) trajectories**

Interplanetary Spacecraft Measurements

- **Lunar Reconnaissance Orbiter (LRO) (Solar Minimum Conditions)**
  - "The total dose for the LRO mission over the first 333 days was only **12.2 cGy** behind ~3.3 mm of aluminum (because of the delayed rise of solar activity in solar cycle 24 and the corresponding lack of intense solar energetic particle events) => **~17 cGy per year in free space**.
  - "The dose rate in a 50 km lunar orbit was about 30 percent lower than the interplanetary rate, as one would expect from lunar obstruction of the visible sky."

- **Mars Science Laboratory (Curiosity Rover) interplanetary**
  - **~ 15 cGy per year during 2011-2012 – weak Solar Max (much higher during SPEs)**

- **Mars Science Laboratory (Curiosity Rover) on Martian surface**
  - **~ 8 cGy per year during 2012-2013 – weak Solar Max (much higher during SPEs)**

Interplanetary Spacecraft Measurements: LRO

millirad/hr x 240 = microGray/day

Figure 1. LRO/CRaTER microdosimeter measurements from launch in June 2009 to December 2014. (top) The minimum dose rate, below 2 mrads/h, originated from galactic cosmic rays that slowly varied and was within the range of Apollo measurements on the lunar surface and in lunar orbit indicated by the grey horizontal band (E. M. Jones et al., 2014, http://www. workingonthemoon.com). On this time scale, solar particle events appeared as spikes above the galactic cosmic ray dose rate. (bottom) The integrated total dose was about 70 rads after 5.5 years.

Interplanetary Spacecraft Measurements:
Curiosity interplanetary cruise

https://mars.nasa.gov/multimedia/images/index.cfm?ImageID=5321h

http://authors.library.caltech.edu/42648/1/RAD_Surface_Results_paper_SCIENCE_12nov13_FINAL.pdf
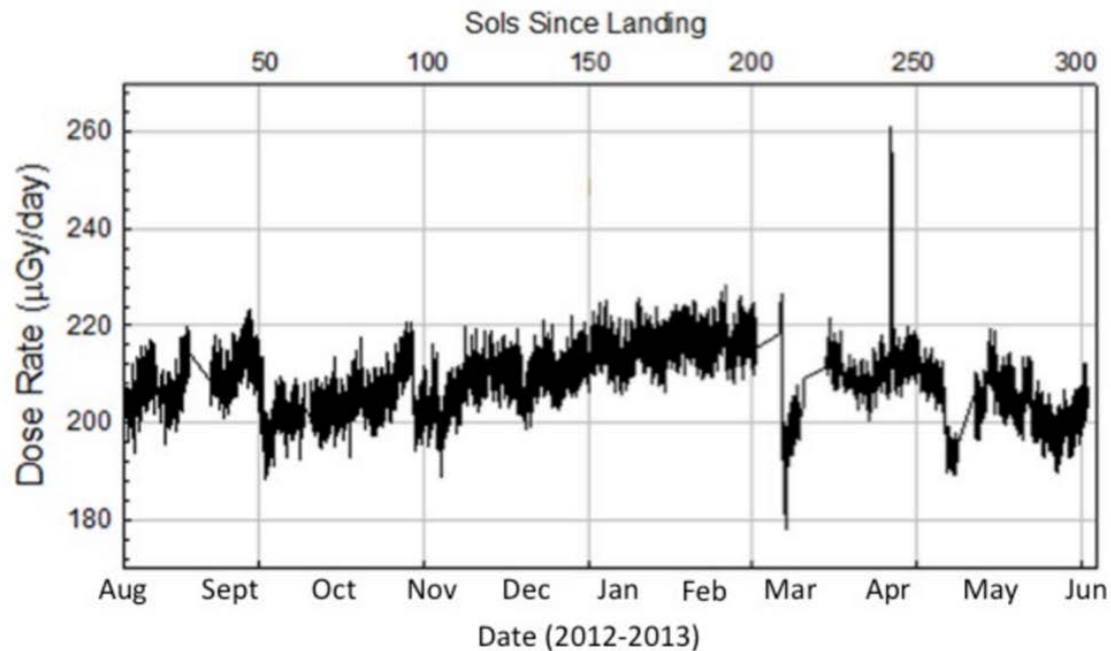
Figure 1. Time series of radiation dose rate measured by RAD on the surface of Mars. During this time, RAD observed a dose rate enhancement from one hard SEP event on Sol 242 (12-13 April 2013), and several Forbush decreases (32), resulting from soft SEP event-related Interplanetary Coronal Mass Ejections (ICMEs) on Sols 50, 97, 208, and 259. (These ICMEs serve as magnetic shields against the GCR, thus reducing the observed flux.) Occasional brief gaps can also be seen, usually caused by RAD having been powered off so that other activities could take place on the spacecraft without interference.

Some space radiation nuclear reaction and transport analysis tools

Space Radiation Nuclear Reaction and Transport Tools

- **Monte Carlo vs. "Deterministic" computer codes**
  - **Monte Carlo methods** (or **Monte Carlo experiments**) are a broad class of computational algorithms that rely on repeated (step-by-step) random (most often "pseudo random") sampling of physical probability distributions (i.e., reaction probability as cross sections) to obtain numerical results.
    - Digital simulation of real experiment – one particle at a time
    - Examples – FLUKA, MCNP, PHITS and others….
    - Long execution times and massive computational resource requirements (multiprocessor blade servers, supercomputers)
  - **"Deterministic" methods** describe how a variety of different types of particles travel through a material using statistical averages of reaction probabilities (cross sections) and look-up tables. It is generally considered the most accurate description of the statistical average density of particles in a system, as long as the particles do not interact with themselves. Operates like a deterministic calculation.
    - Quick execution, modest computational resources
    - Easy to install and run on your PC or Mac (or use the on-line web page)
    - Examples – Novice, CREME-96, HZETRN 2010, 2015, and Oltaris
- **Code comparison and validation (see references)**
  - The codes (both Monte Carlo and "deterministic") have been extensively validated against both ground-based accelerator and space flight data.

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Space Radiation Nuclear Reaction and Transport Tools

- **FLUcuating KAskades** (**FLUKA)** is a fully integrated particle physics Monte Carlo simulation package. It has many applications in high-energy experimental physics and engineering, shielding, detector and telescope design, cosmic ray studies, dosimetry, medical physics and radio-biology.
  - http://www.fluka.org/fluka.php

- **Monte Carlo N-Particle Transport Code** (**MCNP)** is a software package for simulating nuclear processes. It has been developed by Los Alamos National Laboratory since at least 1957[3] with several further major improvements. It is distributed within the United States by the department of energy Radiation Safety Information Computational Center in Oak Ridge, TN and internationally by the Nuclear Energy Agency in Paris, France.
  - https://mcnp.lanl.gov/

- **NOVICE** (Deterministic/Monte Carlo) – commercial product of EMPC.
  - http://empc.com/novice-software/

- **CREME-96** (Deterministic) – primarily an avionics single event effects and total ionizing dose code developed at the Navel Research Lab in the late 1990s – now maintained by Vanderbilt University and available as an on-line tool.
  - https://creme.isde.vanderbilt.edu/
  - https://creme.isde.vanderbilt.edu/CREME-MC/help/how-to-run-creme96

- NASA/LARC/**HZETRN** (Deterministic).
  - https://software.nasa.gov/software/LAR-18803-1
  - https://spaceradiation.jsc.nasa.gov/irModels/

- NASA/LARC/**Oltaris** (Deterministic) – On-line version of HZETRN.
  - https://oltaris.nasa.gov/

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Summary

Summary

- Energetic photons (X-rays) are a threat to relatively thin surface layers of exposed materials. The X-ray energy flux can be as high a 10^{-3} W/m^2 during solar flares. The natural gamma ray flux is low enough to be a non-issue.

- SPEs are transient events (localized in time), seldom lasting more than a week, that can increase particle flux, TID rates, and SEE rates by orders of magnitude; however, "soft" energy spectra make management with shielding mass practical.

- Trapped radiation is localized in space, consists primarily of energetic electrons (electron belt) and protons (proton belt), and can drive annual dose rates as high a 10^5 cGy through 4 mm Al near GEO. Shielding is effective, even at 1 to 2 cm Al, but costly (up-mass). The very high flux of lower energy particles can determine surface dose of exposed materials.

- GCRs are most important for long-term (> few weeks or months) crew dose and the avionics single event environment. The much harder spectra makes management with shielding mass impractical. The avionics part of this problem is workable with reasonable cost and schedule constraints by selecting radiation resistant components and fault-tolerant, redundant system architectures.

- Shielding mass processes (modifies) the natural environment so shielding mass effects must be accounted for when assessing the real space radiation environment to which spacecraft hardware and crew are exposed.
  - Remember the secondary neutrons produced by space radiation in any material.

Back-up and References

References
On-line tools

- http://www.swpc.noaa.gov/ National Oceanic and Atmospheric Administration Space Weather Prediction Center (space radiation events)

- https://nepp.nasa.gov/ NASA Electronic Parts and Packaging Program home page (SEE/TID effects, testing and analysis

- https://srag.jsc.nasa.gov/ JSC Space Radiation Analysis Group (Human Health)

- https://software.nasa.gov/software/LAR-18803-1 HZETRN 2015 home page

- http://www.fluka.org/fluka.php FLUKA home page

- https://creme.isde.vanderbilt.edu/ CREME-96 home page (avionics SEE/TID)

- http://tec-ees.esa.int/ProjectSupport/ISO/CREME96.html ESA CREME-96 page

- https://www.spenvis.oma.be/ ESA space environments modeling and analysis tools home page

- http://dev.sepem.oma.be/ ESA Solar Particle Event modeling and analysis home page

- http://holbert.faculty.asu.edu/eee560/see.html Arizona State university space flight environments effects and analysis home page

- http://lansce.lanl.gov/ DOE Los Alamos National Laboratory atmospheric Neutron and High Energy Proton Testing Facility home page

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- The Poisson distribution is an appropriate model if the following assumptions are true.
    - n is the number of times an event occurs in an interval and n can take values 0, 1, 2, …
    - The occurrence of one event does not affect the probability that a second event will occur. That is, events occur independently.
    - The rate at which events occur is constant. The rate cannot be higher in some intervals and lower in other intervals.
    - Two events cannot occur at exactly the same instant.
    - The probability of an event in a small interval is proportional to the length of the interval.
    - The actual probability distribution is given by a Binomial distribution and the number of trials is sufficiently bigger than the number of successes one is asking about.
- If these conditions are true, then n is a Poisson random variable, and the distribution of n is a Poisson distribution.

- **Poisson equation**
    - $P(n) = (\mu^n/n!)e^{-\mu}$ where μ is the long-term average value of n
    - $\mu = \lambda\, t$ where λ is the long-term average count per unit time, so
    - $P(r) = ((\lambda t)^n/n!)e^{-\lambda t}$
    - For the Poisson distribution, $\mu = \text{mean}(n)$, $\mu = \text{variance}(n)$, $\sqrt{\mu} = \text{Std Dev}(n)$
    - In the limit of large n, this becomes the Gaussian distribution
    - Event counts are described by Poisson distribution, but time between events in a real random processes are described by an exponential distribution
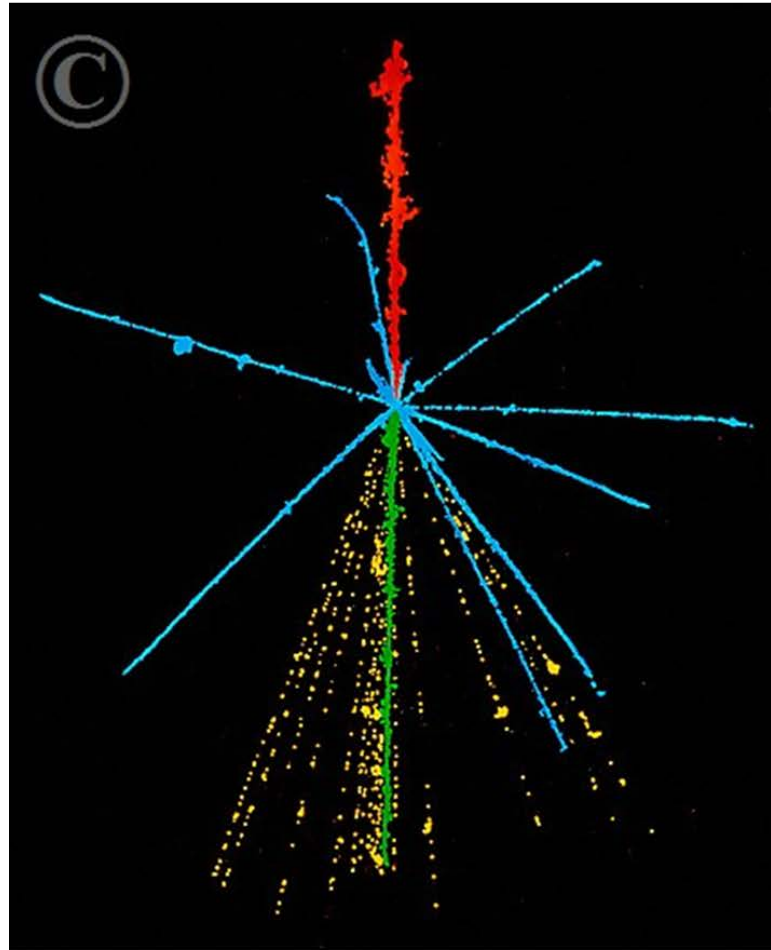   - $P(\Delta t, \lambda) = (\lambda t)e^{-\lambda \Delta t}$

GCR Environment Characterization Data Sources
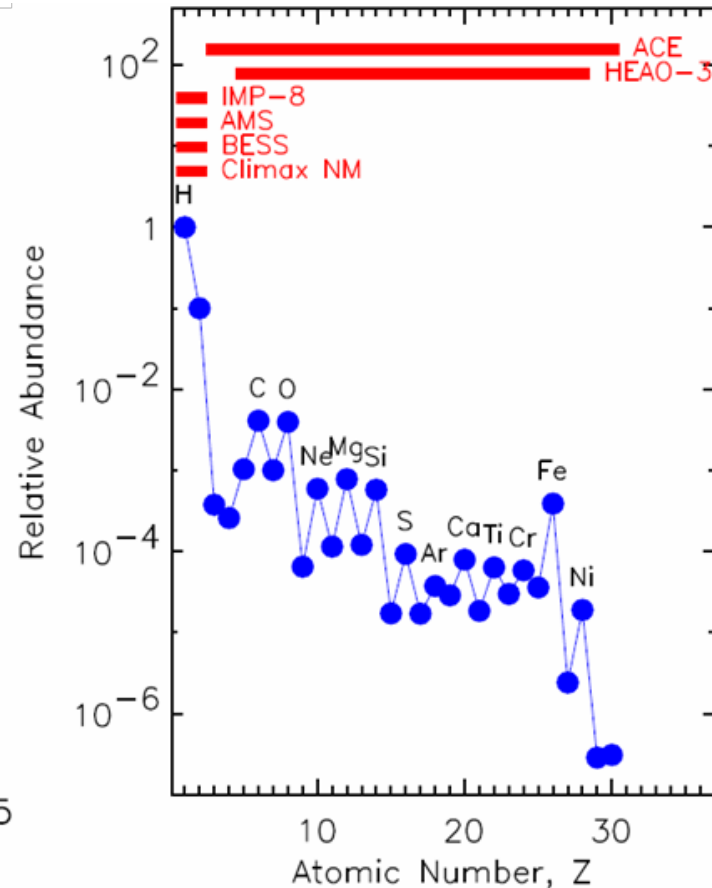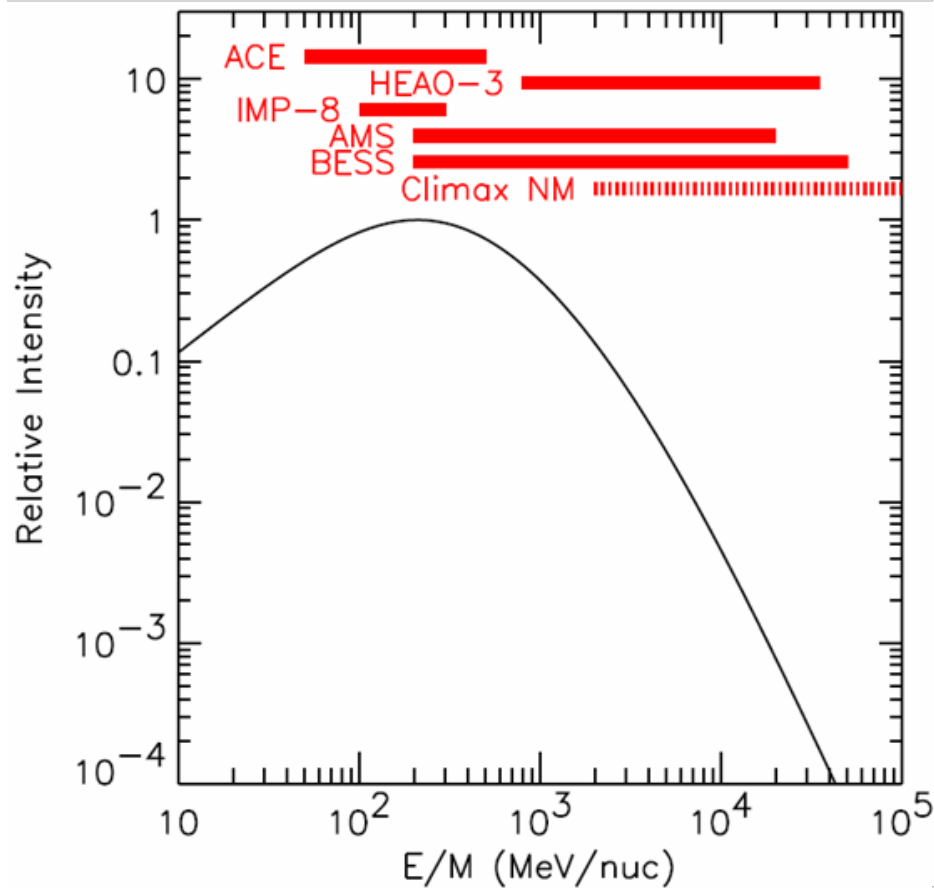
Mark E. Wiedenbeck, Jet Propulsion Laboratory, California Institute of Technology mark.e.wiedenbeck@jpl.nasa.gov
http://www.srl.caltech.edu/personnel/dick/cos_encyc.html   http://pdg.lbl.gov/2010/reviews/rpp2010-rev-cosmic-rays.pdf

a134005 [RM] © www.visualphotos.com

False- color emulsion photo of a cosmic ray sulfur nucleus (red) colliding with a nucleus in the emulsion. The collision produces a spray of other particles: a fluorine nucleus (green), other nuclear fragments (blue) & 16 pions (yellow). The length of the sulfur track is 0. 11 mm. The curlicues which adorn the track of the sulfur nucleus are electrons which it has knocked out of atoms in passing. The photograph was taken in 1950 by Cecil Powell, the English physicist who pioneered the use of photographic emulsions to record the tracks of electrically charged particles.

GCR: Calculating LET Spectra Under Aluminum Shielding with FLUKA

The differential LET spectra [#/(cm^2 week LET)] at various shielding depths in a concentric spherical shell model spacecraft (**50 meter radius, 37.4 cm thick**).

LET spectra are calculated, using the **FLUKA Monte Carlo radiation transport code**, as the number of particles entering each of the Si detector shells placed at various depths in the concentric spherical shell model (see the table below).
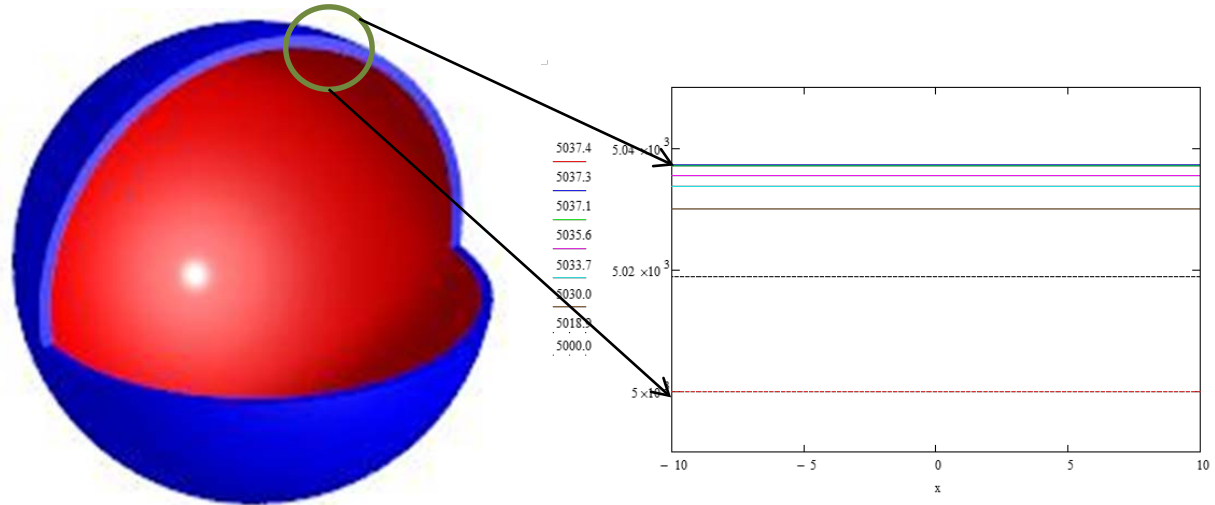
All secondary particle shower processes are enabled and the full shielding mass distribution function for each Si shell is used in a fully three-dimensional calculation.

Radial distance of Si detector shells in cm from the center of the sphere (determines Si shell shielding depth as measured from the external surface) – Each concentric shell is a FLUKA "region" with specific boundary surfaces

Detector Si Shell	SiDet1	SiDet2	SiDet3	SiDet4	SiDet5	SiDet6	SiDet7	SiDet8
Detector Shell Radius (cm)	5037.4	5037.3	5037.1	5035.6	5033.7	5030.0	5018.9	5000.0
Si Detector Median Al Shielding Mass in g/cm^2	0.15	0.81	1.6	7.9	15.6	31.1	77.5	156.2

GCR Nuclear Collisions: Secondary Particle Showers and Shielding Effectiveness
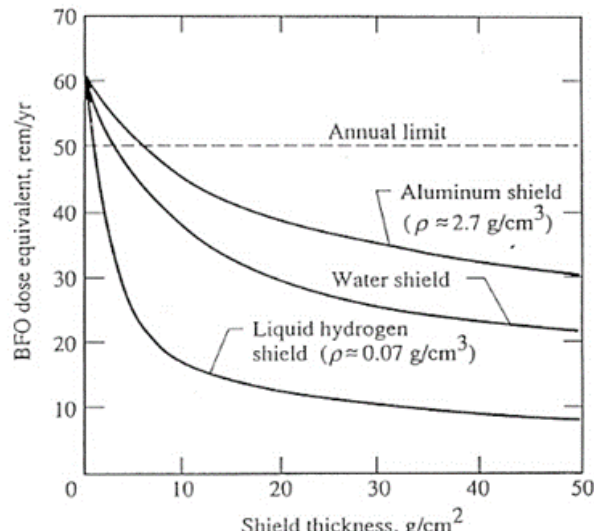
Figure 6. Shielding effectiveness of GCR at solar minimum.

Effective dose for Male behind Shielding
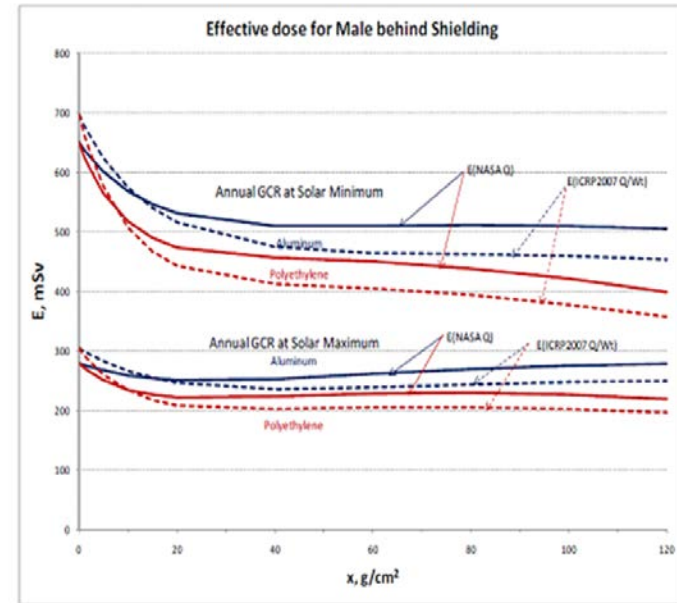
Point dose vs. shielding mass calculations excluding human shielding mass
http://srag.jsc.nasa.gov/Publications/TM104782/techmemo.htm

Dose vs shielding mass including human body shielding mass
(Cucinotta, Space Radiation Cancer Risk Projections and Uncertainties, 2010)

- Point dose calculations make differences between shielding materials look better than they really are.
- Note that liquid hydrogen isn't a simple shielding material. It is a shielding system because maintaining a cryogenic liquid adjacent to a manned crew cabin for several years implies liquid containment and an as yet TBD thermal control system, neither of which will be weightless. Also, the density of LH2 is 0.07 g/cc => 7 meters of LH2 at 50 g/cm^2 shielding mass.

Estimated Mars Surface Radiation Dose Map
## (Confirmed by MRO and Curiosity)

Cosmic Ray Environment
Dose Equivalent Values (rem/yr)
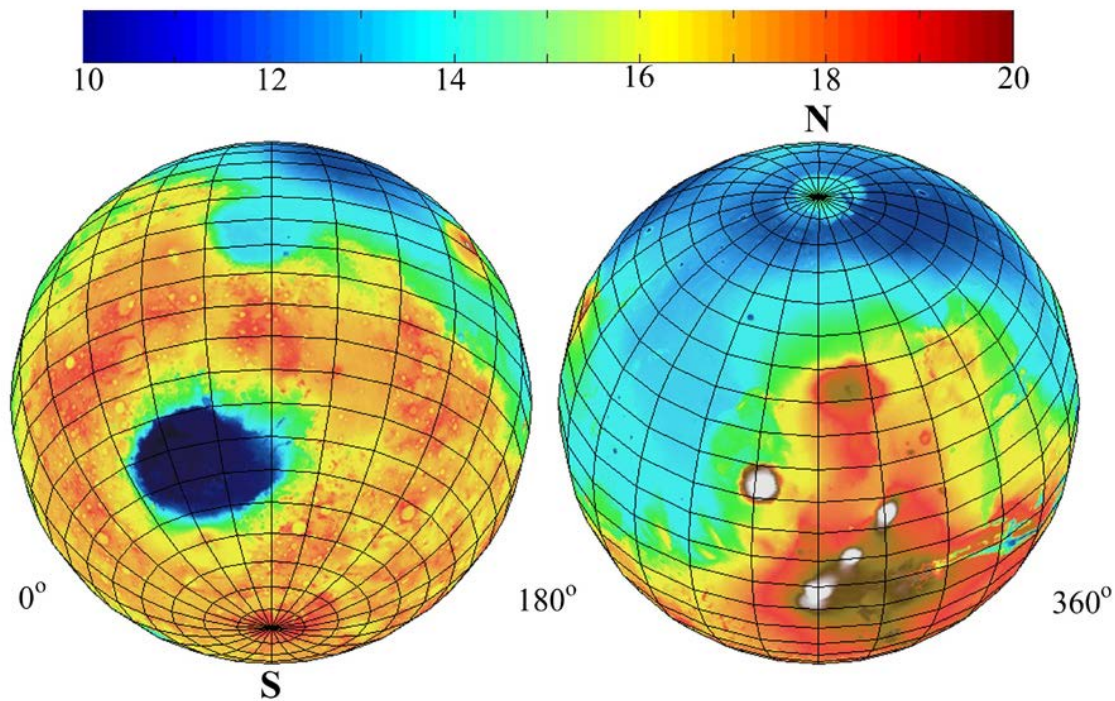
Martian Surface Cosmic Ray Environment map – This map was produced based on cosmic radiation data by the Mars radiation environment experiment (MARIE), an instrument on NASA's Mars 2001 Odyssey spacecraft. Those data were combined with Mars altimetry from the MOLA instrument aboard MGS (Mars Global Surveyor. Lowest elevations are anticipated to have lowest radiation levels because more atmosphere exists above them to prevent penetration to the surface. The color scale is 10 rems (dark blue) to 20 rems (dark red). Astronauts on the International Space Station in Earth orbit encounter radiation equivalent to an annual rate of 20-40 rems. JPL Press Release, March 1, 2002. Credit: NASA/JPL/JSC

Origin of GCRs confirmed
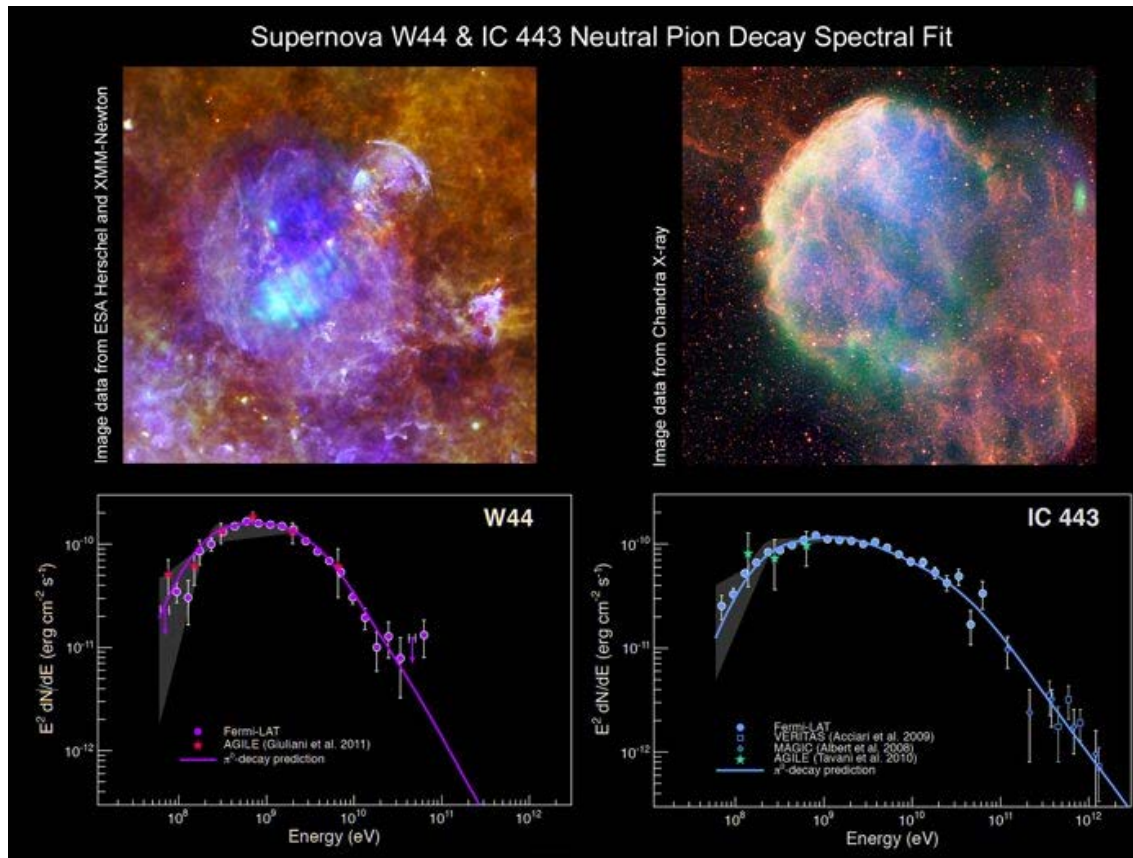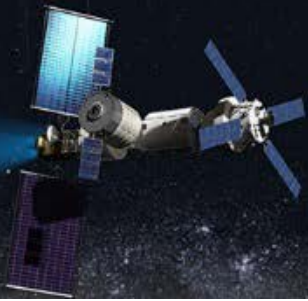
The first direct evidence that galactic cosmic rays are accelerated within supernova remnants has been provided by observations by the Fermi Large Area Telescope collaboration. The results make use of four years of data collected by the telescope observing two supernova remnants – IC 443 and W44 – within our galaxy. The observations fit very neatly with predictions of neutral pion decay. http://physicsworld.com/cws/article/news/2013/feb/14/supernova-origin-of-galactic-cosmic-rays-confirmed

GCRs in the galaxy
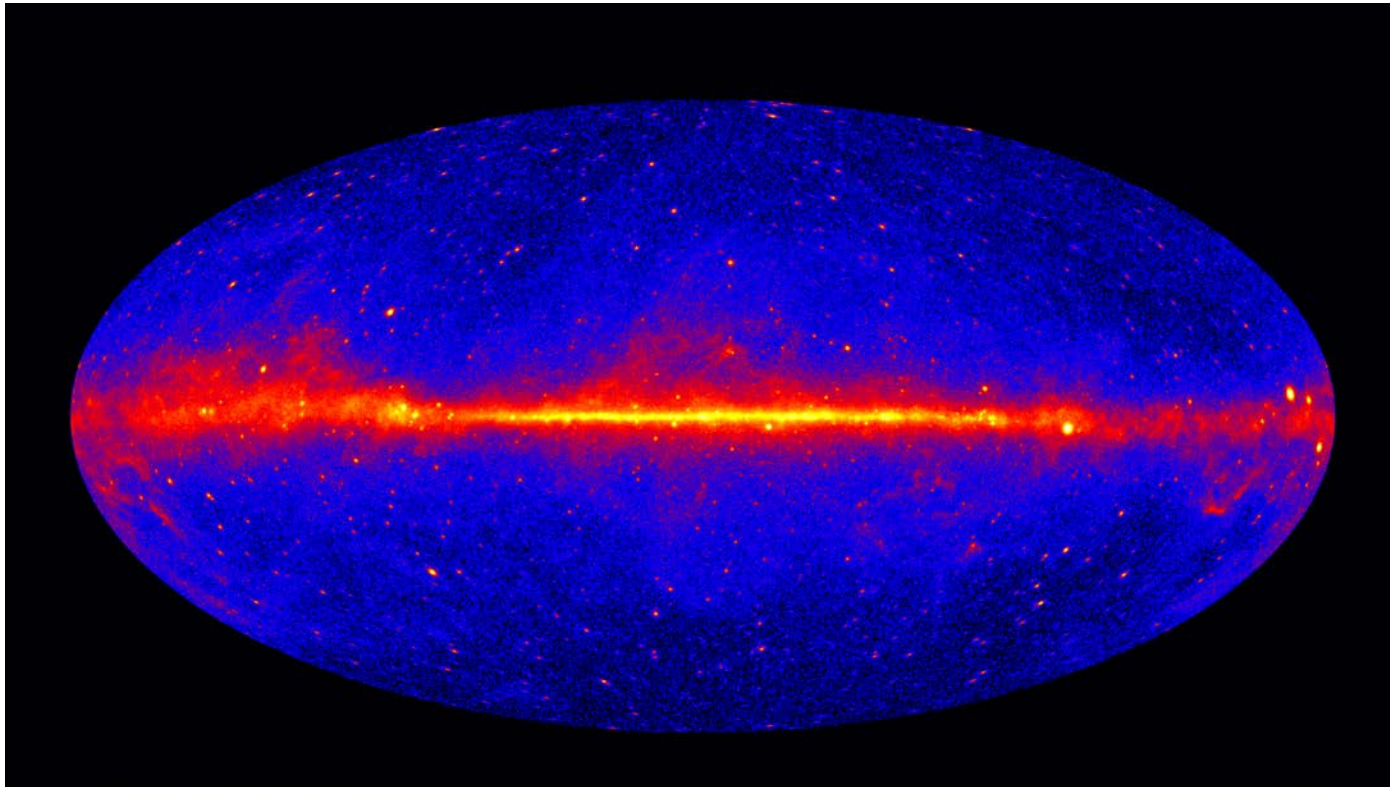
The Fermi LAT 60-month image, constructed from front-converting **gamma rays with energies greater than 1 GeV**. The most prominent feature is the bright band of diffuse glow along the map's center, which marks the central plane of our Milky Way galaxy. The gamma rays are mostly produced when energetic particles accelerated in the shock waves of supernova remnants collide with gas atoms and even light between the stars. Hammer projection.
Image credit: NASA/DOE/Fermi LAT Collaboration
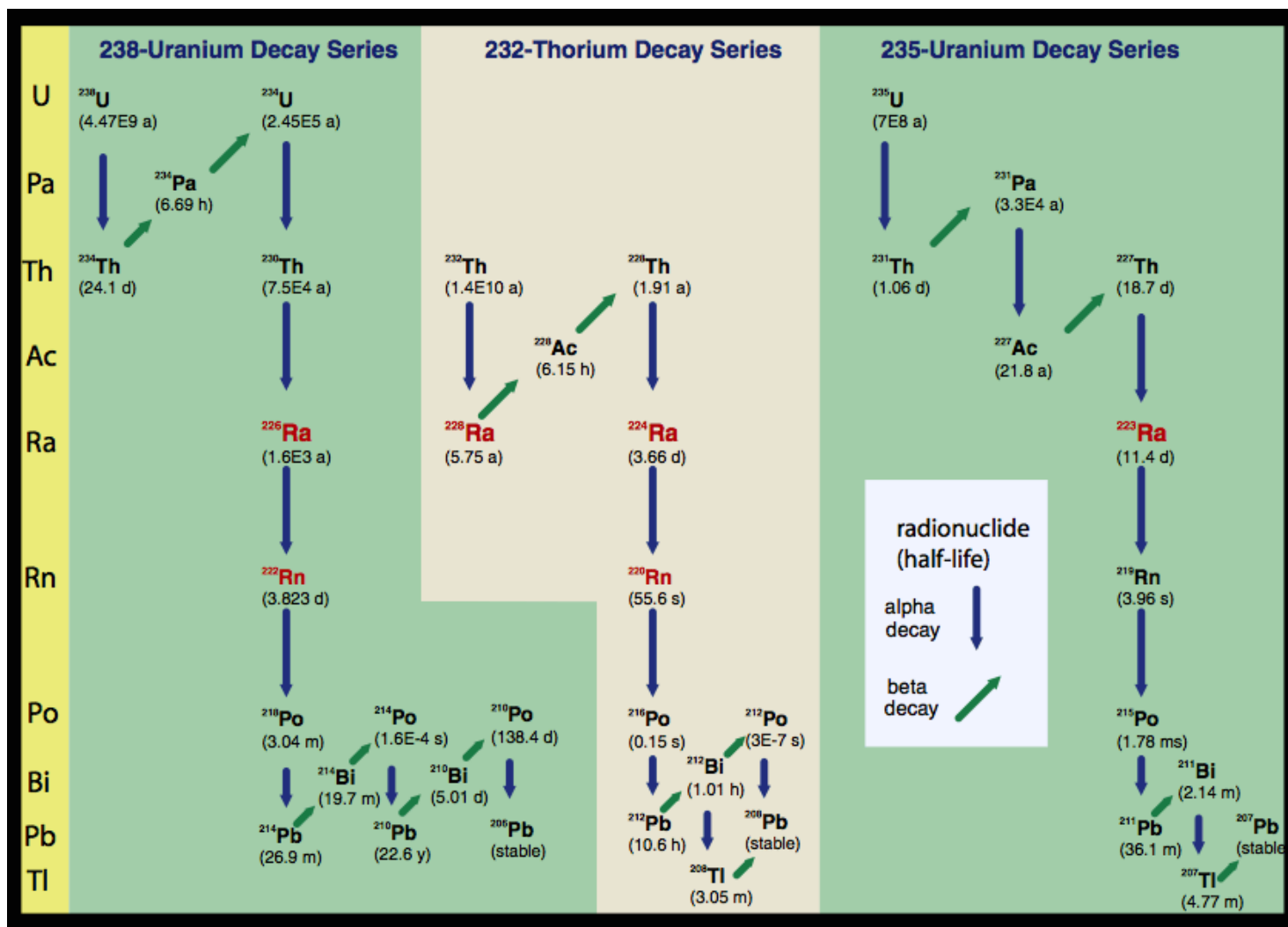
Acronyms & Abbreviations
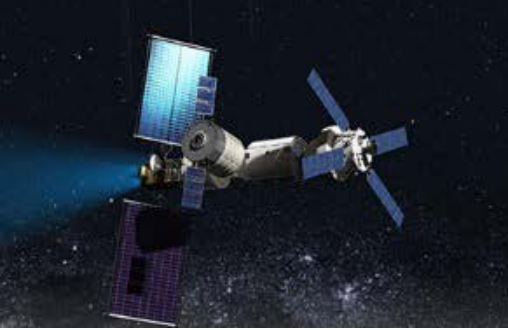
- Ag — Silver
- Al — Aluminum
- AMS — Alpha Magnetic Spectrometer
- AU — Astronomical Unit (mean radius of earth's orbit
- CARI — The CARI-7 computer program, developed at the FAA's Civil Aerospace Medical Institute, calculates the effective dose of galactic cosmic radiation received by an individual (based on an anthropomorphic phantom) on an aircraft.
- cGy — centi Gray
- cm — centimeter
- CME — Coronal Mass Ejection
- CR — Cosmic Ray
- cSv — centi Sievert, a unit of biological "equivalent" ionizing radiation dose
- DDD — Displacement Damage Dose
- dE/dx — energy loss per unit length in reference to linear energy transfer (LET)
- DoD — Department of Defense
- DOSTEL — Dose Telescope (ISS flight experiment)
- DSG — Deep Space Gateway
- EDAC — Error Detection And Correction
- ESA — European Space Agency
- eV — electron Volt
- FAA — Federal Aviation Agency
- FCT — Future Capabilities Team
- FLUKA — FLUktuierende KAscade
- g/cm^2 — grams per square cm
- GEO — Geosynchronous/Geostationary Orbit
- GCR — Galactic Cosmic Rays
- GeV — giga (10^9) electron volts
- GSFC — Goddard Space Flight Center
- Hf — Hafnium
- HQ — Headquarters
- ISS — International Space Station
- JPL — Jet Propulsion Laboratory
- keV — kilo (10^3) electron volt
- km — kilometer
- LED — Light Emitting Diode
- LEO — Low Earth Orbit
- LET — Linear Energy Transfer

Acronyms & Abbreviations

- LH2   Liquid Hydrogen
- LRO   Lunar Reconnaissance Orbiter
- MCNP   Monte Carlo N-Particle Transport Code
- MeV   mega (10^6) electron Volt
- Mg   Magnesium
- MM/OD   Micro Meteoroid/Orbital Debris
- MOS/CMOS   Metal Oxide Semiconductor/Complimentary Metal Oxide Semiconductor
- MPCV   Multi Purpose Crew Vehicle (Orion)
- NIEL   Non-Ionizing Energy Loss
- Pb   Lead
- PHITS   Particle and Heavy Ion Transport code System
- PNTD   Plastic Nuclear Track Detector
- ppm   parts per million
- SAA   South Atlantic Anomaly
- sec   second
- SEE   Single Event Environments (Effects)
- SEP   Solar Energetic Particle
- SEU   Single-Event Upset

- Si   Silicon
- SLS   Space Launch System
- SOHO   Solar Heliospheric Observatory
- SPE   Solar Particle Event
- SPENVIS   Space Environment Visualization System
- TBD   to be determined
- TeV   trillion (10^{12}) electron Volts
- Th   Thorium
- TID   Total Ionizing Dose
- TLD   Thermo Luminescent Detector
- U   Uranium
- UV   Ultraviolet Light
- W   Tungsten