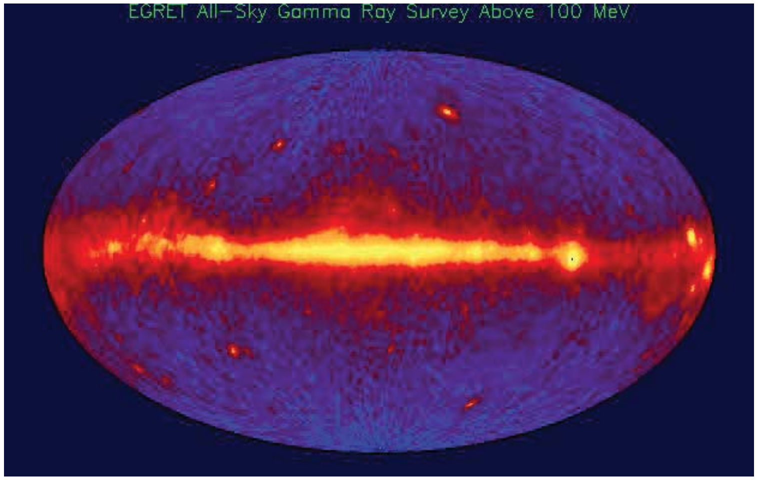
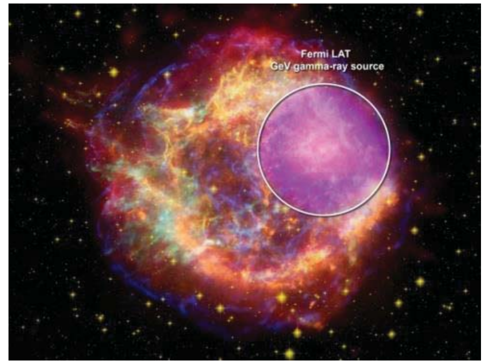
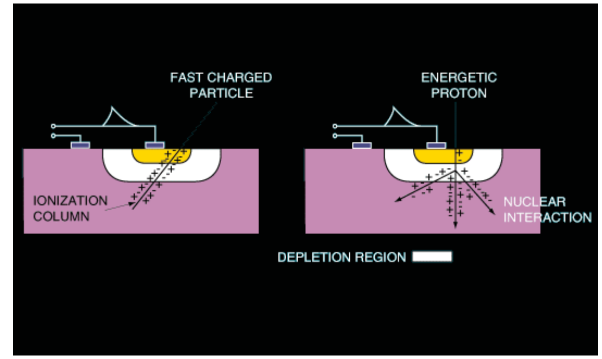
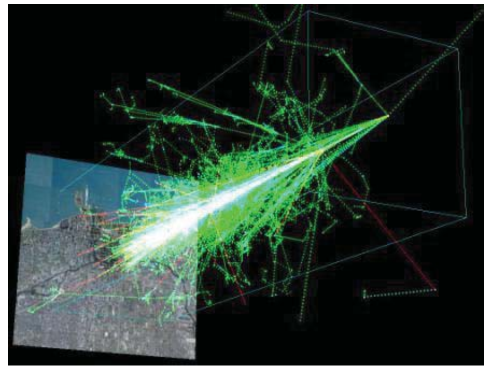
https://ntrs.nasa.gov/search.jsp?R=20150003480 2019-08-31T11:33:11+00:00Z

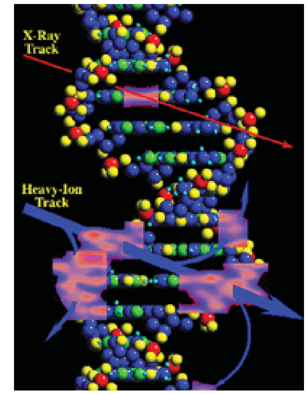


The image above is the [EGRET](#) gamma ray all-sky survey, courtesy of Dr. Carl Fichtel and the EGRET Instrument Science Team. Some GCRs interact with the [interstellar medium](#) and produce gamma rays.









Practical Applications of Cosmic Ray Science:

Spacecraft, Aircraft, Ground Based Computation and Control Systems and Human Health and Safety

University of Houston Clear Lake, Spring 2015

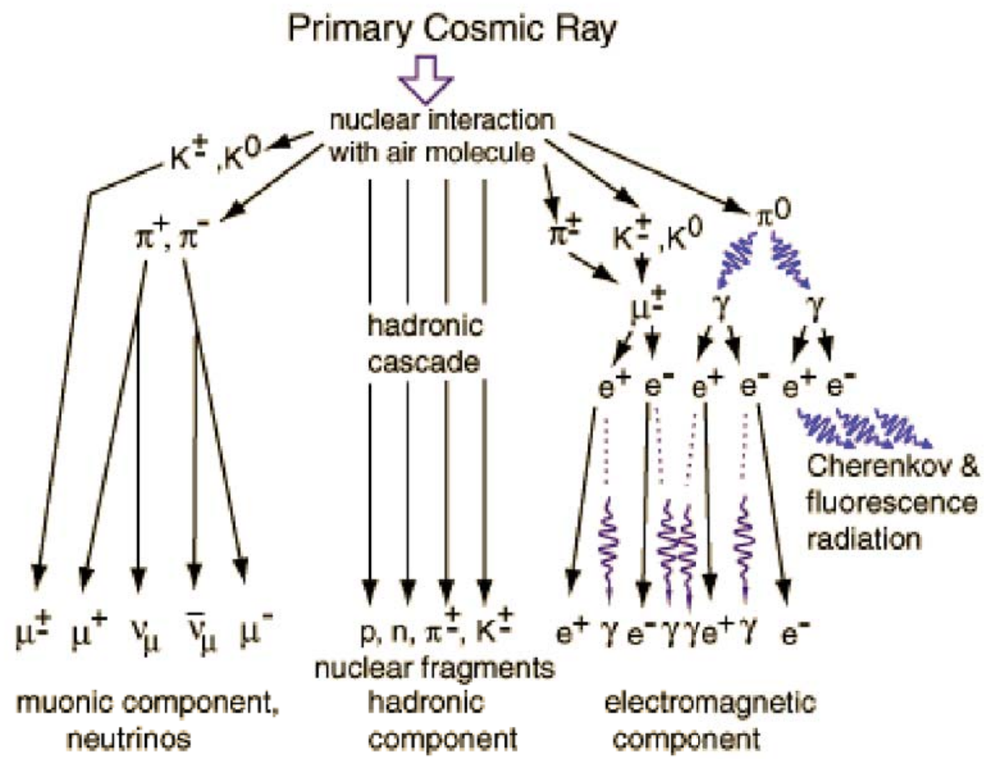
Steve Koontz - NASA, Johnson Space Center, Houston, Texas

Outline

- **1) Cosmic Rays: What are they and where do they come from?**
  - Discovery of Cosmic Rays
    - High energy (fast) charged particles and/or high energy photons?
      - Charged particles for the most part - the term "ray" is an historical misnomer from the early 1900s.
  - Varieties of cosmic rays – galactic, solar particle events, and "Trapped"
  - Where do they come from?
  - What does all of this look like?
- **2) How do cosmic rays interact with matter (i.e. us and our stuff)**
  - Direct Ionization/Excitation Particle Tracks (health effects and microelectronics)
  - Nuclear Reactions and Secondary Particle Showers (and more ionization tracks) – health effects and microelectronics
  - Displacement damage – Optoelectronics (solar cells, light emitting diodes, photodiodes etc.
- **3) What do Cosmic Rays do <u>to</u> us?**
  - Cosmic ray effects on contemporary electronic technology
    - Ground based computation and control systems
    - Commercial and military aircraft electronics systems
    - Spacecraft electronic systems
  - Cosmic ray effects on human health and safety
    - Earth Surface Environments
    - Commercial and Military Aircraft Environments
    - Manned Spaceflight Environments
- **4) What do Cosmic Rays do <u>for</u> us?**
  - Secondary particle shower products enable chemical analysis and search for resources – Moon, Asteroids, Mars
  - Secondary particle shower products for geophysical mapping and exploration
    - On Earth
    - Asteroids, Moon, and Mars
  - Secondary particle shower products for homeland security and nuclear reactor systems safety
    - Finding contraband nuclear materials and weapons
    - Supporting Kagoshima reactor core meltdown recovery
- **5) Summary and Conclusions**
- **6) Supporting Information and References**

Overview

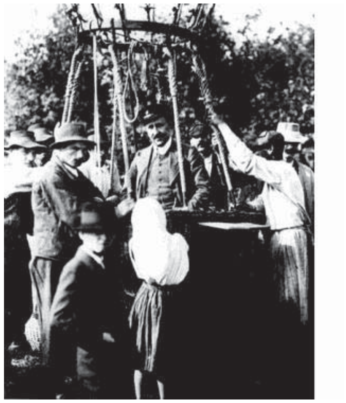
- Cosmic rays do things "to us" and "for us" because they collide at relativistic energies with electrons and/or nuclei in local solar system materials
- The products and effects of these collisions can be either beneficial or harmful depending on the target and why you care about it.



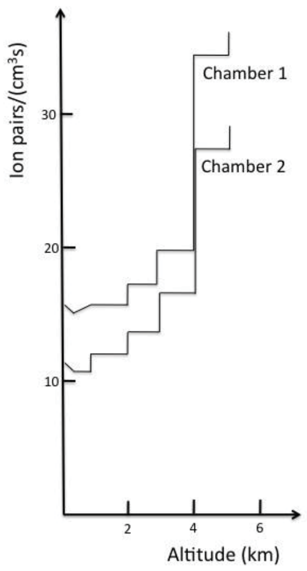
1.0: Cosmic Rays: What are they and where do they come from?

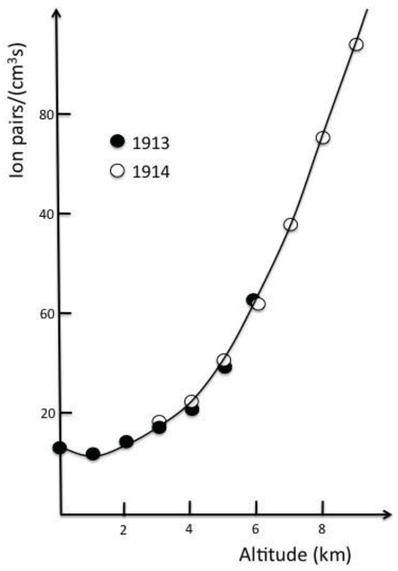
Discovery of GCR – observations from developing electrical technology (1785 to 1926) – something is causing ionization of air – what is it?

- 1785 - Coulomb: reports spontaneous capacitor discharge
- 1835 - Faraday: confirms spontaneous discharge
- 1879 - Crooks: reduced discharge rate at reduced pressure
- 1896 - Bequerel/Curie: radioactivity discovered
- 1910 - Wolf climbs Eiffel tower with electroscope
- 1910 - Pacini: Discharge rate lower under water
- 1912 - Hess: After an initial drop, discharge rate increases steadily with altitude during balloon flights – ionizing radiation is from out there – the cosmos
- **1920s – Compton (particles) and Millikan (photons): particles or photons?**
- By 1926 a consensus was reached on **what cosmic rays are (mostly energetic charged particles with some small number of energetic photons)**, and it all began with observations that capacitors can discharge in an unexpected way.



Victor Hess's Balloon Borne Electroscope
http://airandspace.si.edu/collections/artifact.cfm?id=A19910023000



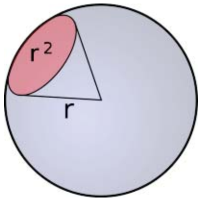


Varieties and characteristics of cosmic rays

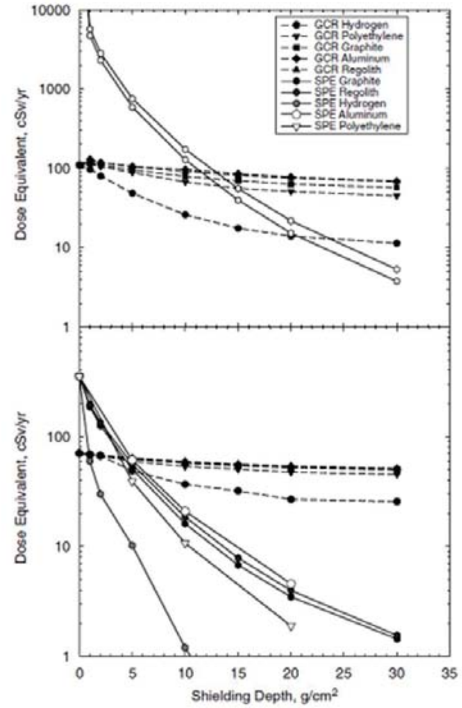
- **Important cosmic ray characteristics**
  - **Origin** - Where are they from and haw are they formed?
  - **Composition** - Ions or photons and of what kind?
  - **Flux and Fluence (abundance)** - how many per square cm per unit time (isotropic in free space)?
  - **Energy Spectrum** - how many particles in each energy interval over the relevant range of values. Energies measured in electron volts (eV) – usually millions (MeV), billions (GeV), and trillions (TeV) of electron volts
- **Galactic cosmic rays (GCR) – The main focus of this seminar**
  - Origin - outside the solar system but inside the Milky Way galaxy for the most part
  - Composition **- atomic nuclei (and a few gamma rays) - the all 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 by 11 year solar cycle
  - Energy spectrum - Most energetic charged particle population – most are relativistic or ultra-relativistic, traveling very close to the speed of light - Most in the energy range between **100 MeV and 100 GeV and greater**
- **Solar particle events – mostly energetic protons but much lower energy than GCR**
  - Origin - solar flares and coronal mass ejections (these can also produce high fluxes of of X-rays that can damage spacecraft surface materials)
  - Composition - **mostly protons with small amounts of heavier ions and electrons**
  - Flux and fluence - **10^3 to 10^4 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**
- **Trapped Radiation – also lower energy than GCR and confined to planetary radiation belts**
  - Origin – Uncertain at this time – some contribution from decay of neutrons produced by GCR interactions with Erth'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 10^5 per cm^2/sec**
  - Energy and spectrum – **10 MeV to 100 MeV**

Some General Features of Cosmic Rays and Space Radiation

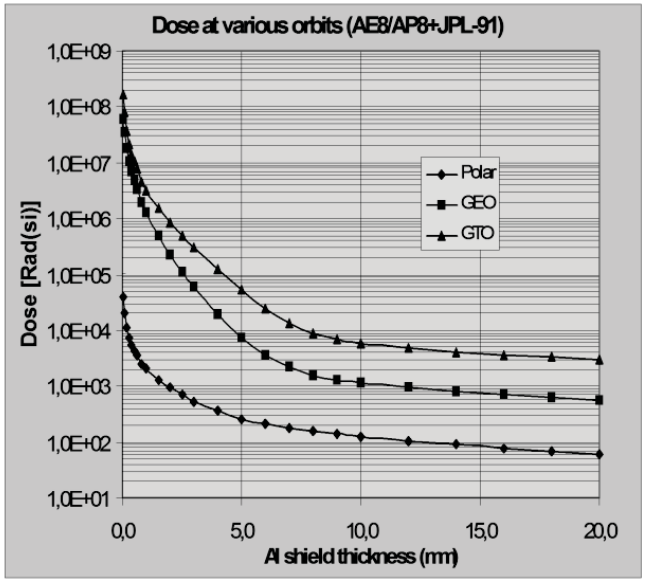
- **In free space, charged particle flux is approximately isotropic, or nearly so, in all cases , so no shadow shielding (except by planets, asteroids, moons etc.)**
  - **Fraction of 4π <u>steradians</u> covered by shielding mass is important**
    - Any area on a sphere, totaling the square of its radius and observed from its center, subtends precisely one steradian.



- **Energetic photons are not isotropic: line-of-sight to source**
  - **Shadow shielding can work**
- **Low energy particles/photons are much more abundant than high energy particles/photons**
  - **Penetration of active or passive shielding depends on particle energy:**
  - **high energy => greater penetration**
  - **High spacecraft skin dose - 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 objects configuration and materials**



Point dose equivalent (upper panel) and effective dose (bottom panel) behind various shields for solar minimum GCR and August 1972 SPE (the units for the SPE doses are for total event and not necessarily per year).
Cucinotta, F., Kim, M. Y., Ren, L.; "Evaluating shielding effectiveness for reducing space radiation cancer risks," Radiation Measurements 41 (2006) 1173 – 1185



Galactic Cosmic Rays

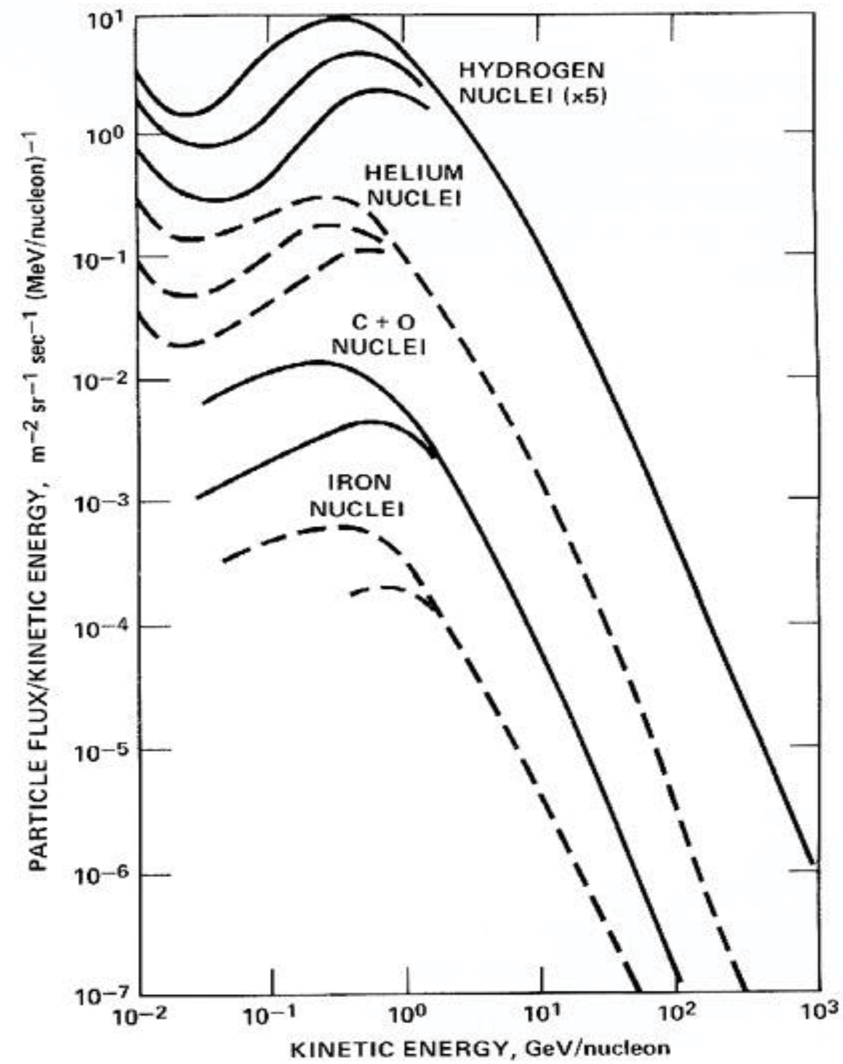
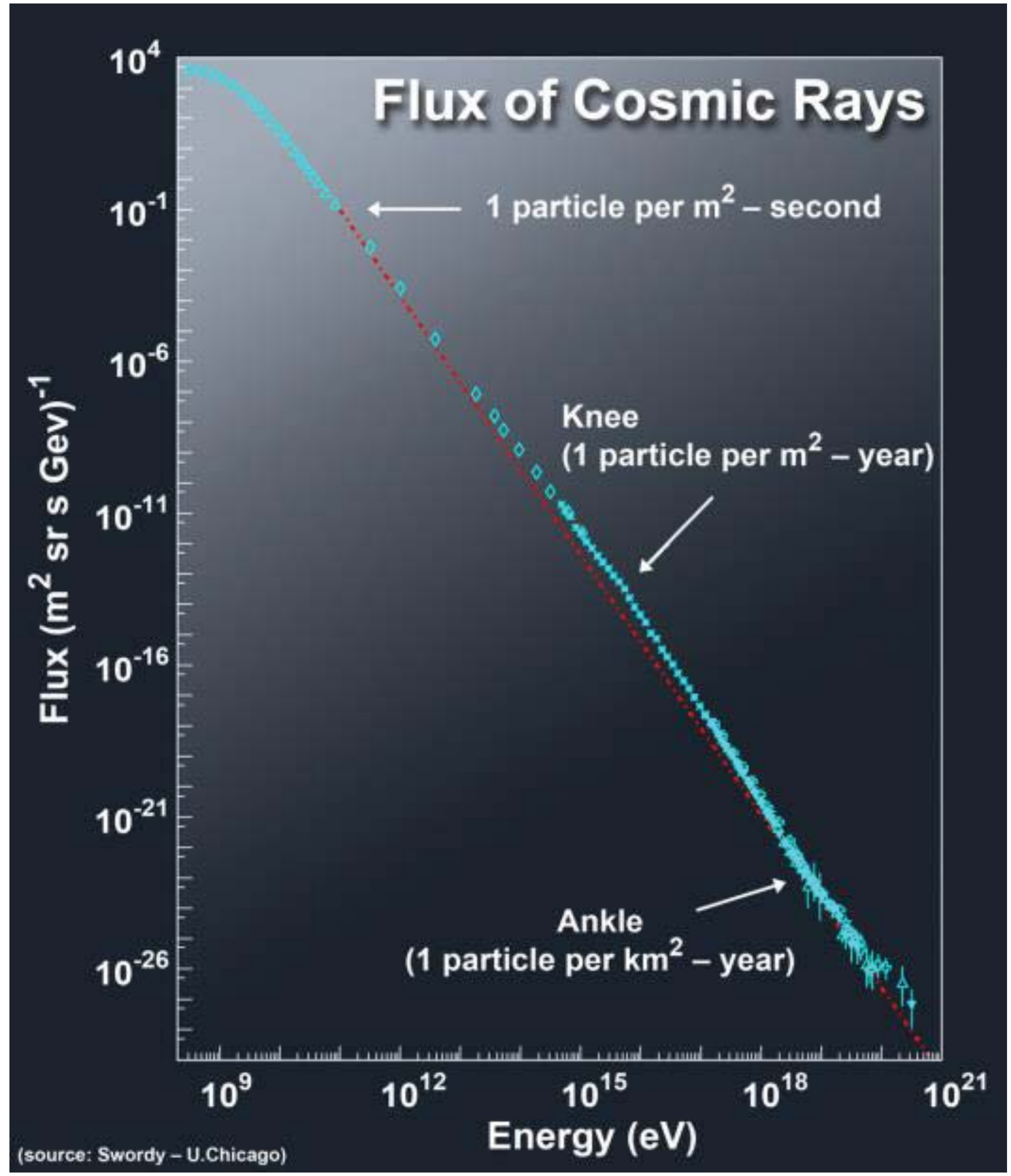
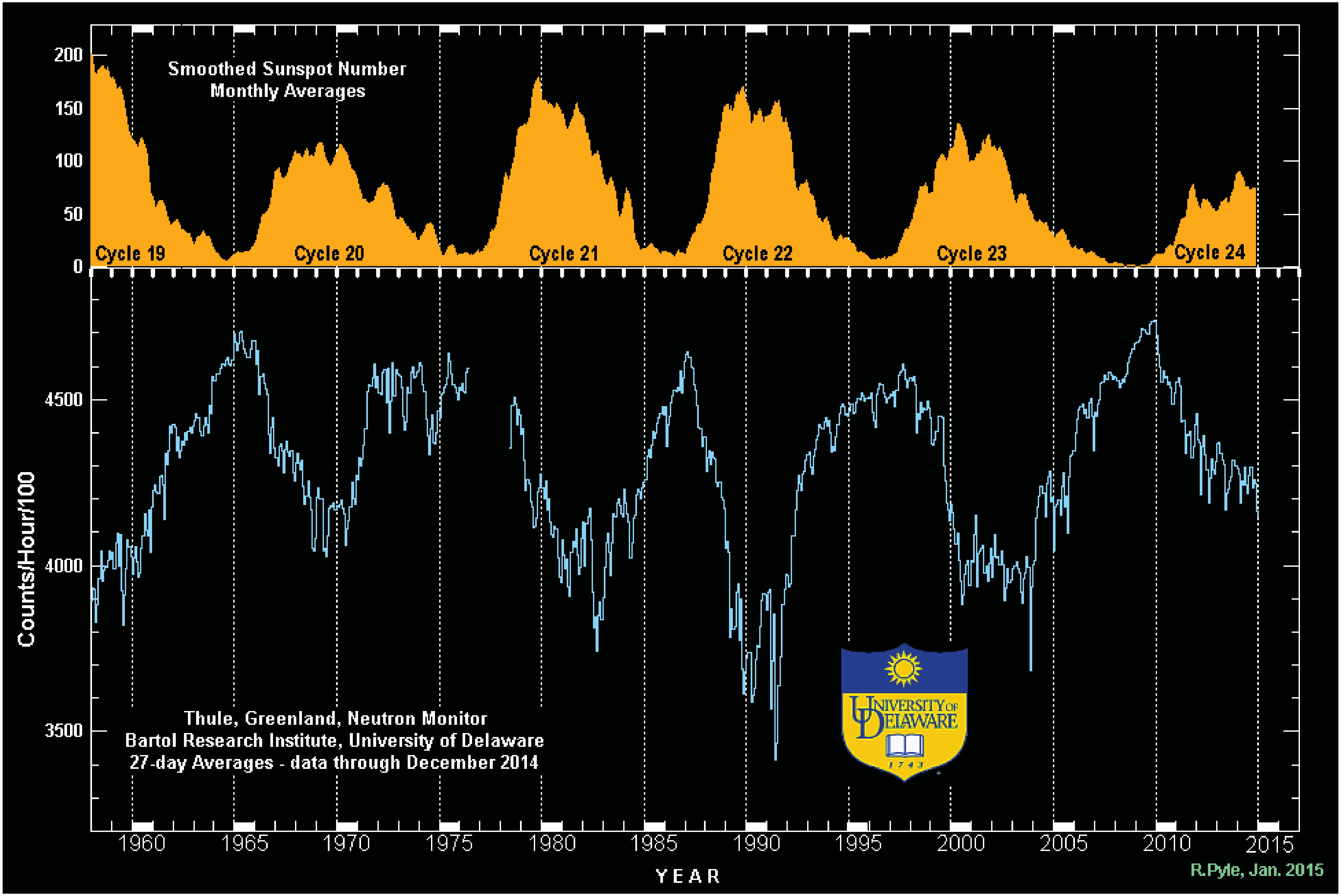


Figure 2-7.– *Distribution of energies of galactic cosmic rays. This is a graph of the more abundant nuclear species in cosmic rays as measured near the Earth. Below a few GeV/nucleon these spectra are strongly influenced by the Sun. The different curves for the same species represent measurement extremes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



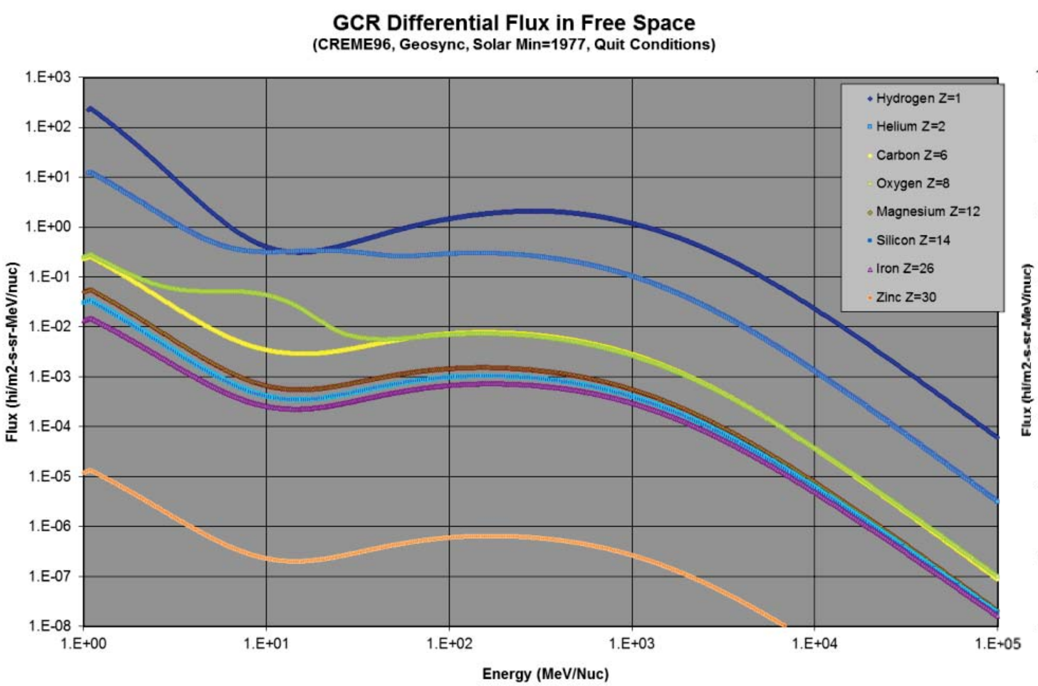
Solar Cycle Modulation of GCR Flux: Monitoring GCR secondary particle shower neutrons (http://neutronm.bartol.udel.edu/)

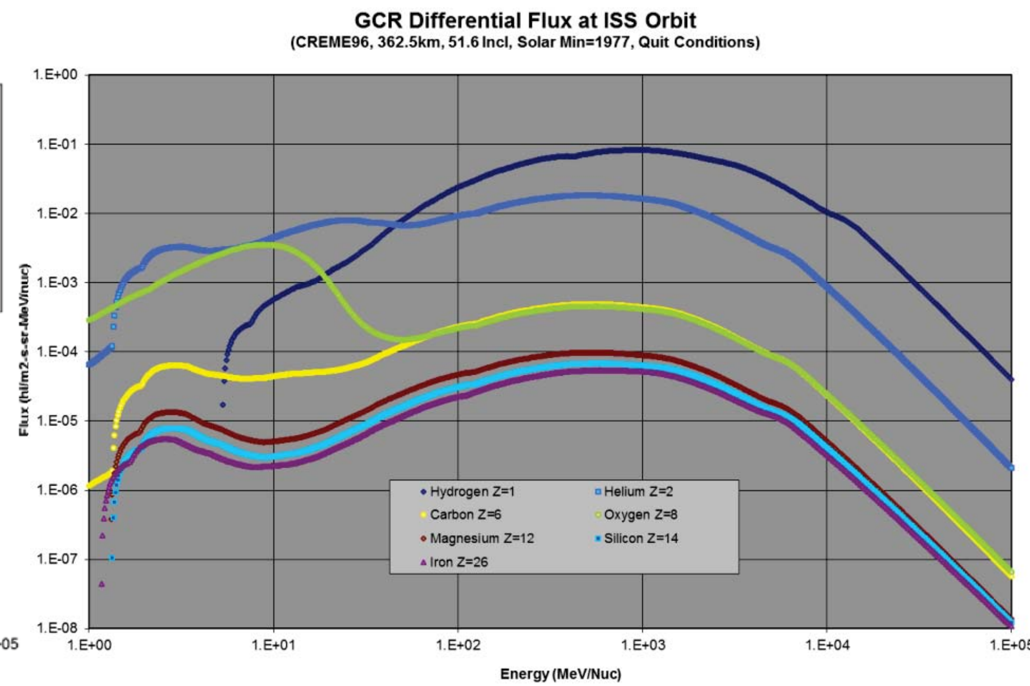


Cosmic Ray Exposure Environments: Low-Earth Orbit and Interplanetary Space at 1 AU

Eight most abundant GCR nuclei (98+% of total flux) and trapped protons

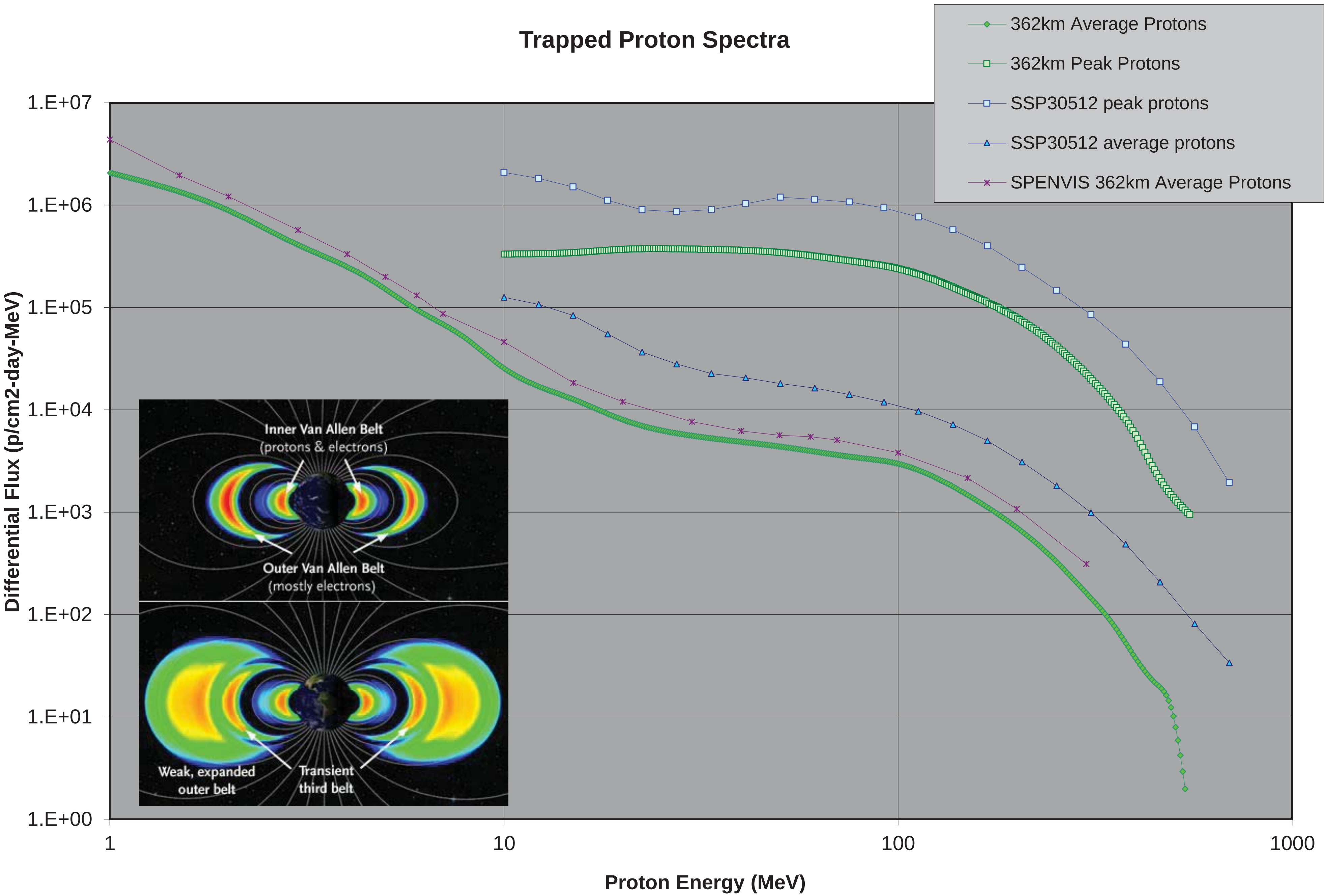
Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011 as well as Refs 1 and 2





Interplanetary Environment at 1 AU: No geomagnetic shielding; direct solar particle event exposure; solar cycle modulation

Low-Earth orbit (ISS) environment: Latitude dependent geomagnetic shielding; Latitude dependent solar particle event exposure


Trapped Proton Spectra
362km Average Protons
362km Peak Protons
SSP30512 peak protons
SSP30512 average protons
SPENVIS 362km Average Protons
Differential Flux (p/cm2-day-MeV)
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1
10
100
1000
Proton Energy (MeV)
Inner Van Allen Belt
(protons & electrons)
Outer Van Allen Belt
(mostly electrons)
Weak, expanded
outer belt
Transient
third belt

Solar particle events and GCR compared

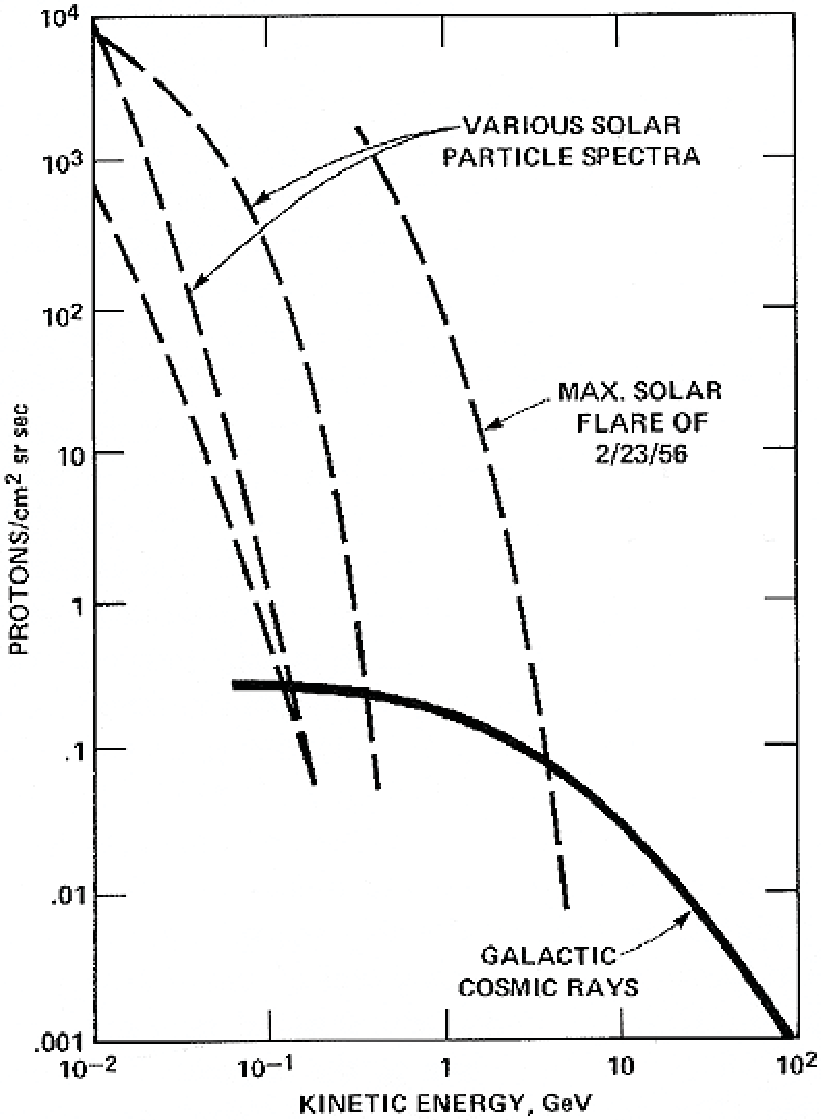
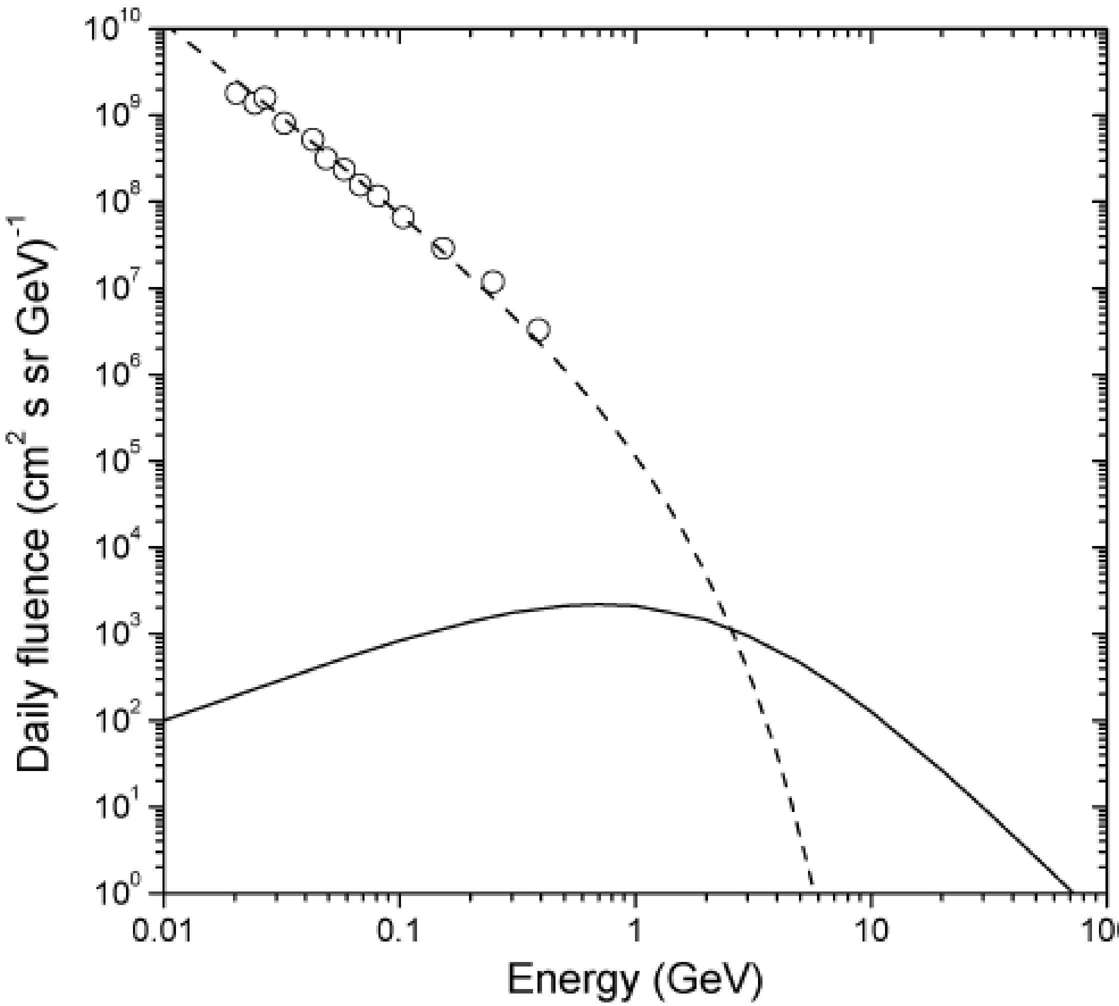


Figure 2-6.– *Energy spectra from several moderate size solar flares (dotted curves) compared with galactic cosmic ray spectrum.*



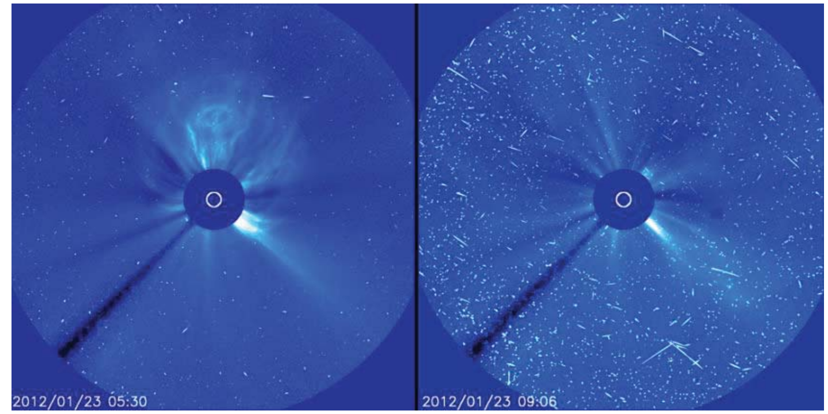
Daily fluence of solar energetic particles and galactic cosmic rays (solid curve) for the day of January 20, 2005. Open circles represent space-borne measurements http://solarphysics.livingreviews.org/Articles/lrsp-2013-1/fig_24.html

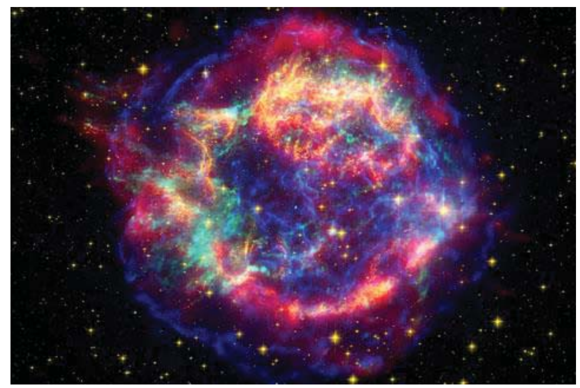
http://www.nss.org/settlement/nasa/75SummerStudy/Chapt.2.html

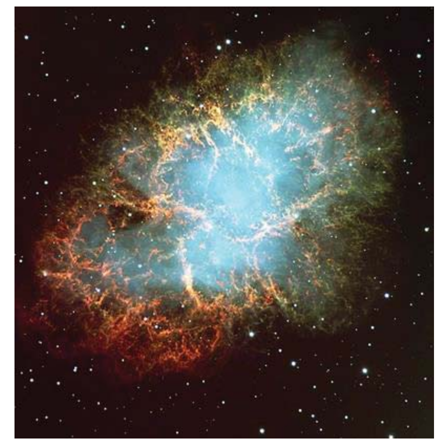
Where do they come from?

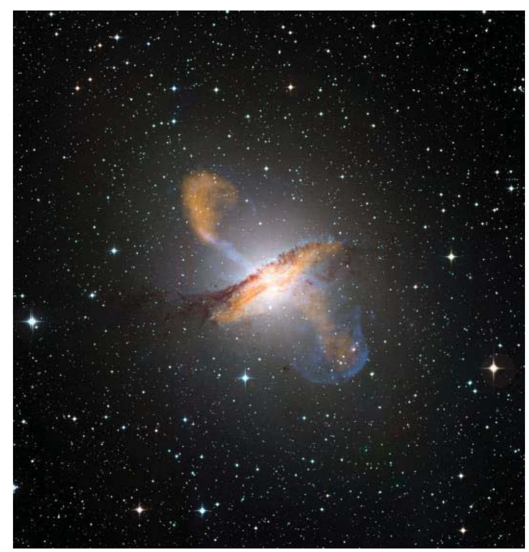
- **Low energy CR (less than 10 GeV) come from the sun.**
  - Solar particle events - solar flares and coronal mass ejections
- **GCR come from outside the solar system**
  - Galactic Supernovae are a likely be the source of GCR particles up to 10^{15} eV.
    - GCR particles accelerated slowly over thousands of years in expanding magnetized plasma shock fronts (few radioactive nuclei seen by ACE)
    - Fermi acceleration and diffusive shock acceleration
    - Note that photons (Gamma rays and X-rays) are emitted directly by the supernova blast
- **The sources for ultrahigh cosmic rays are probably, active galactic nuclei, gamma ray bursts (whatever they are ??) and other exotic source candidates e.g. neutron star mergers magnetars etc.**

(www.phys.washington.edu)

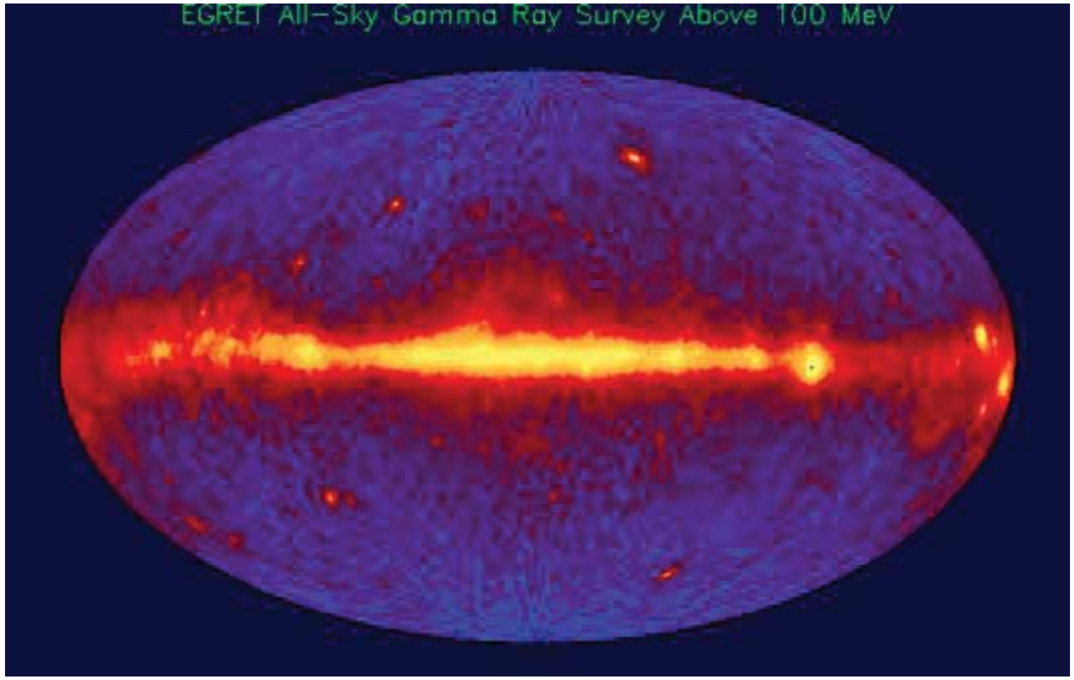








What is the Origin and Distribution of Galactic Cosmic-Rays?



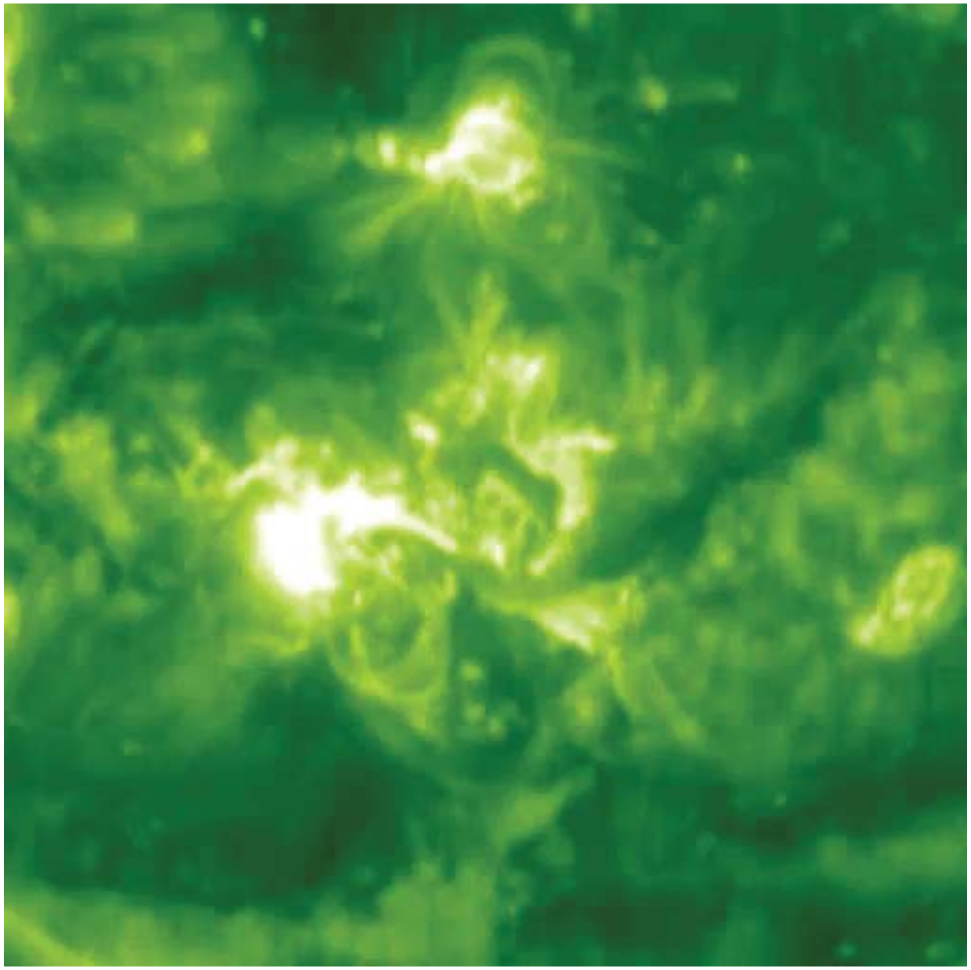
- The Galactic diffuse gamma-ray emission, the dominant feature of the gamma-ray sky, is produced primarily by cosmic ray electron and proton interactions with the matter (via electromagnetic and nuclear interactions) and photons (via inverse Compton scattering) in the interstellar medium.

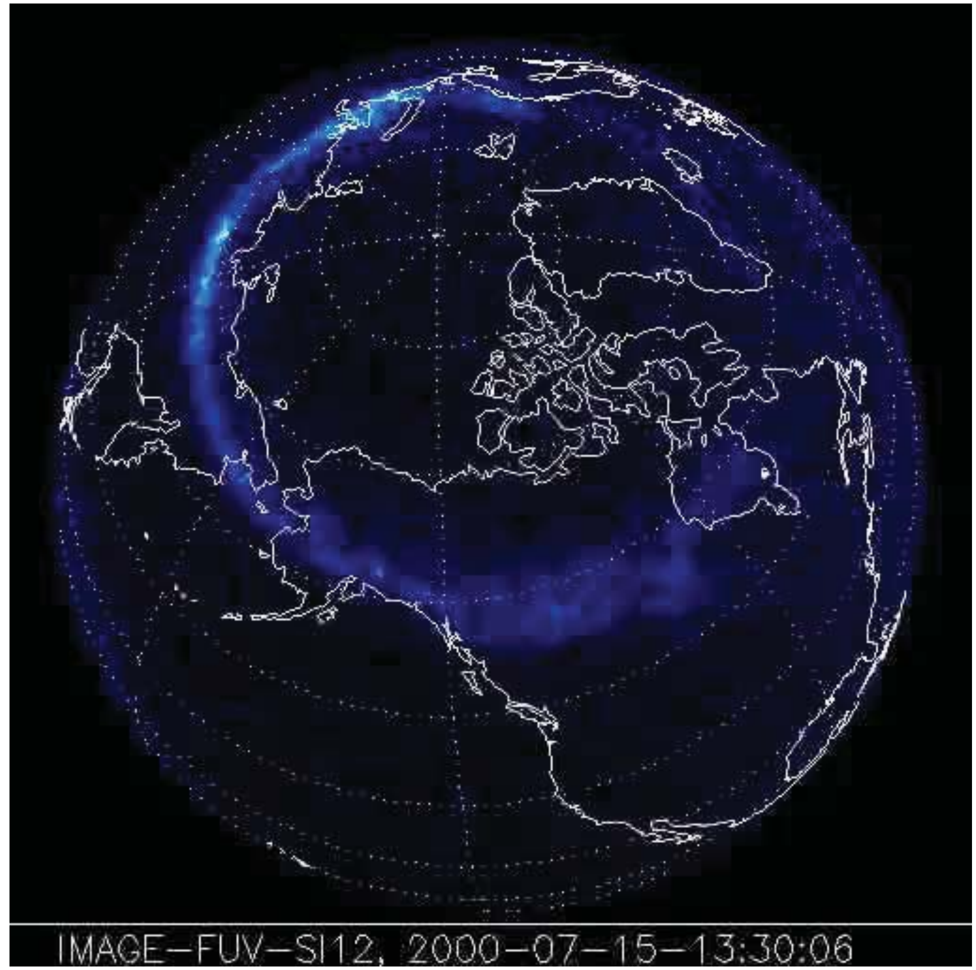
- The spatial distribution of the Galactic diffuse emission observed with EGRET traces, and can be fairly accurately explained in terms of the distribution of atomic and molecular gas and photons in the interstellar medium using reasonable assumptions about the distribution of cosmic rays in the Galaxy.

- The spectrum of the Galactic diffuse emission, however, is not completely explained in terms of the theoretical prediction of cosmic rays interacting with matter and photons in the Galaxy.

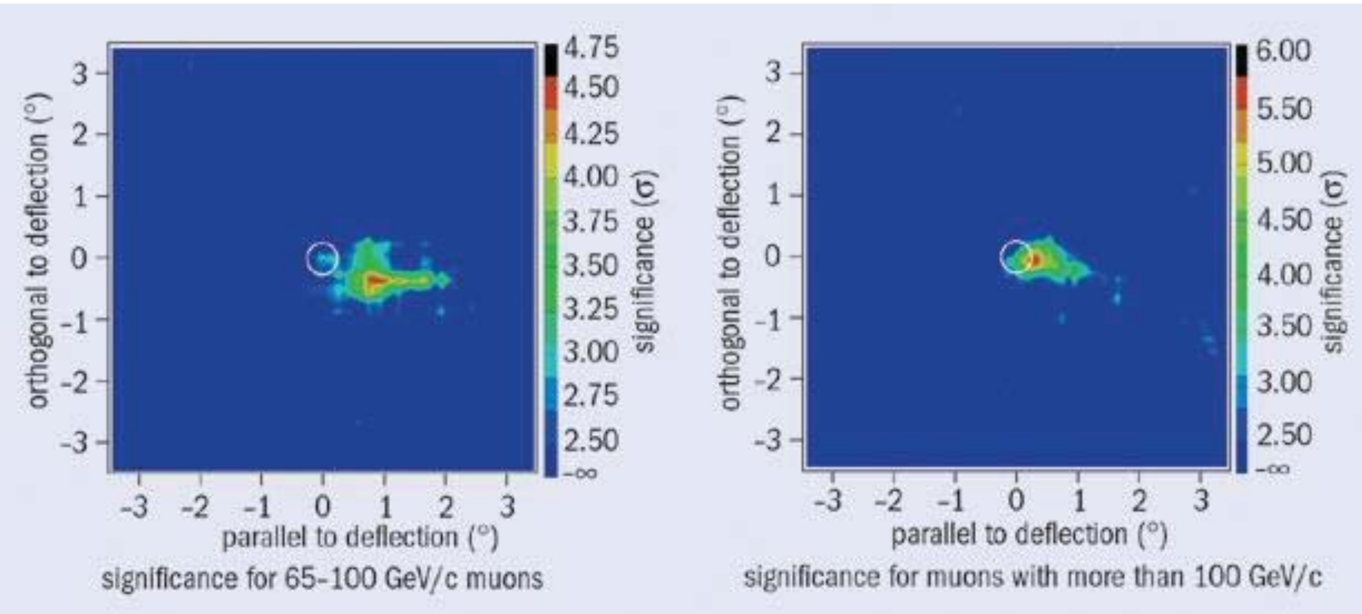
- https://heasarc.gsfc.nasa.gov/docs/cgro/epo/brochures/new_win/nw15.html

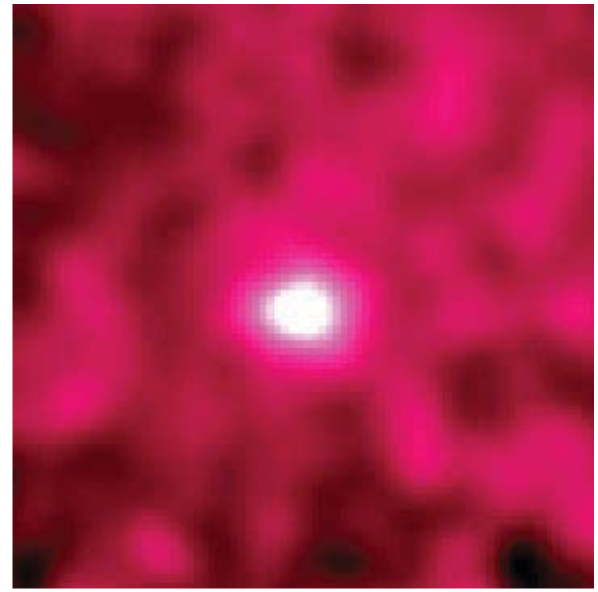
And what does all this look like?





And what does all this look like? The moon in galactic cosmic rays





The deficit of primary cosmic rays is clear in these pictures, covering two muon energy ranges. In each, a circle indicates the real position of the Moon. The axes correspond to the parallel and perpendicular directions of the deflection in degrees. The Moon's shadow is displaced more in the sample corresponding to the lower-energy cosmic rays (left). http://cerncourier.com/cws/article/cern/28658

The moon as seen by the Compton Gamma Ray Observatory, in gamma rays with energies greater than 20 MeV. These are produced by cosmic ray bombardment on its surface. "EGRET Detection of Gamma Rays from the Moon". NASA/GSFC. 1 August 2005. Retrieved 2010-02-11.

And what does all this look like?

2.0: How do cosmic rays interact with us and out stuff?

The natural space radiation environment consists primarily of energetic charged particles: Galactic cosmic rays, solar cosmic rays, and magnetically trapped radiation

Energetic charged particle interactions with target materials:
Three basic physical processes

1. Energy loss (dE/dx) by direct ionization/excitation of material along the particle track (The Electromagnetic Force – collision with electrons)

- Direct ionization effects – linear energy transfer (LET) – "slowing down"
- Primary cause of single event effects (SEE) in susceptible electronic devices
- Primary cause of total ionizing dose effects in susceptible electronic devices
- Primary cause of human health effects

2. High energy collisions (inelastic/hadronic) triggering nuclear reactions (The Strong or Nuclear Force – collision with atomic nuclei)

- Nuclear hadronic reactions initiate secondary particle showers in the target mass
- Further collisions of secondary particles with target nuclei lead to expansion and propagation of the secondary particle shower
- Secondary particles can produce direct ionization and more nuclear reactions

3. Collisions with material nuclei that produce displacement damage (The Electromagnetic Force again – collision with nuclei without nuclear reaction)

- Displacement of target atoms so as to disrupt crystal structure (solids materials only – important for spacecraft optoelectronics)

The Electromagnetic Force - Direct ionization & excitation (electromagnetic force) of target substance

- **High speed charged particles decelerate by loosing energy to target substance electrons during columbic collisions leaving an ionization/excitation damage track**
  - Nuclear collisions make little contribution to deceleration except at the lowest kinetic energies near end of track 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
  - http://tvdg10.phy.bnl.gov/LETCalc.html Brookhaven National Laboratory on-line LET and range calculator
- **Quantified by the relativistic Bethe-Bloch equation**

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

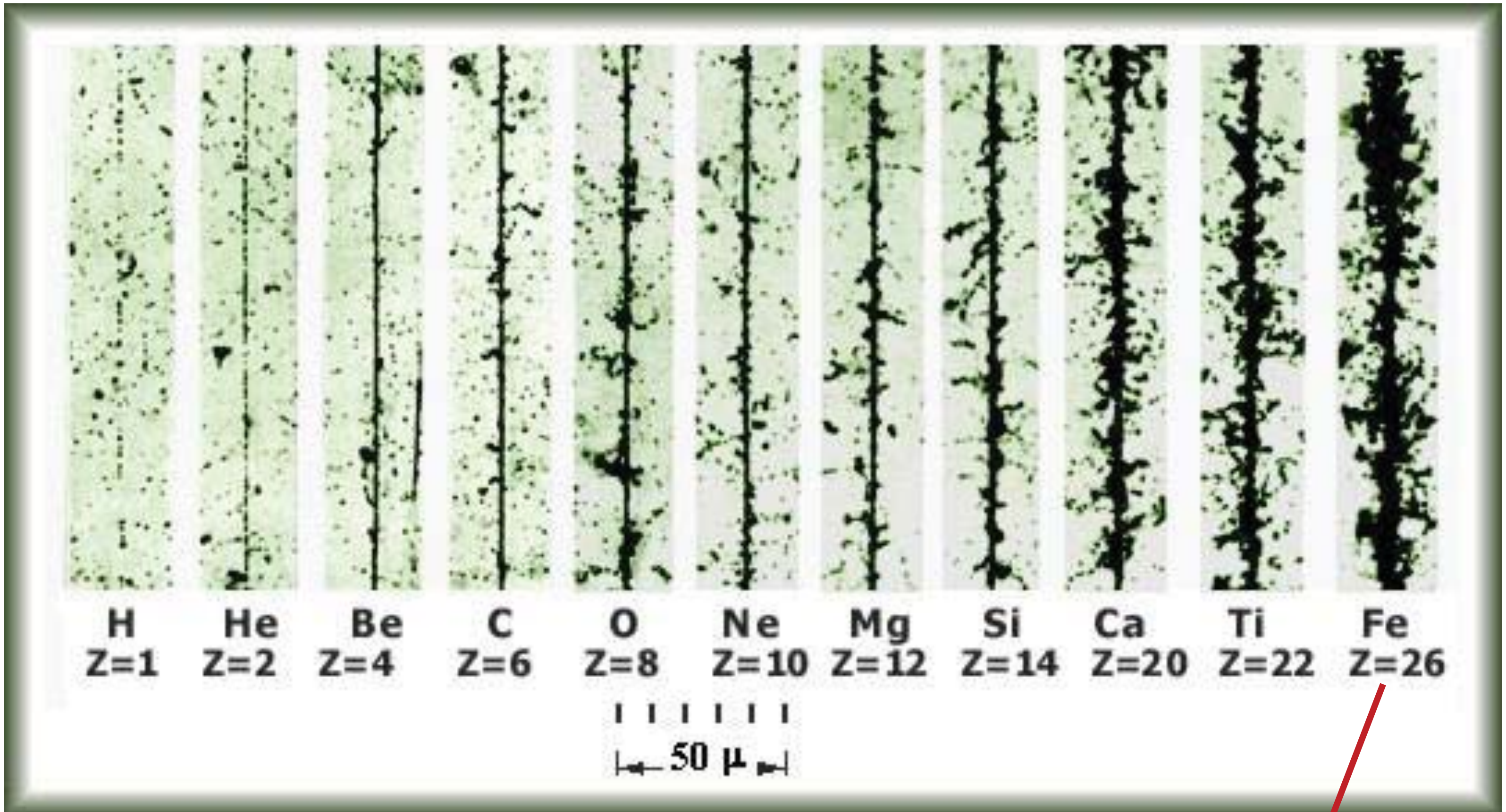
Projectile (cosmic ray particle) dependencies

$\beta = v / c$; 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

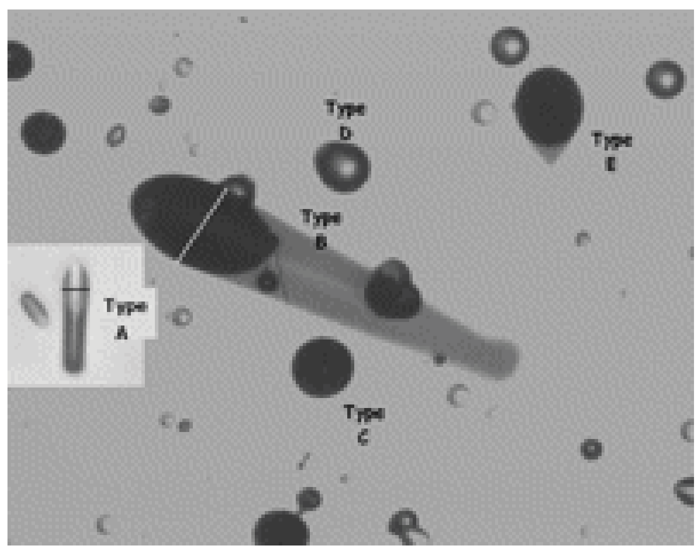
Target substance dependencies

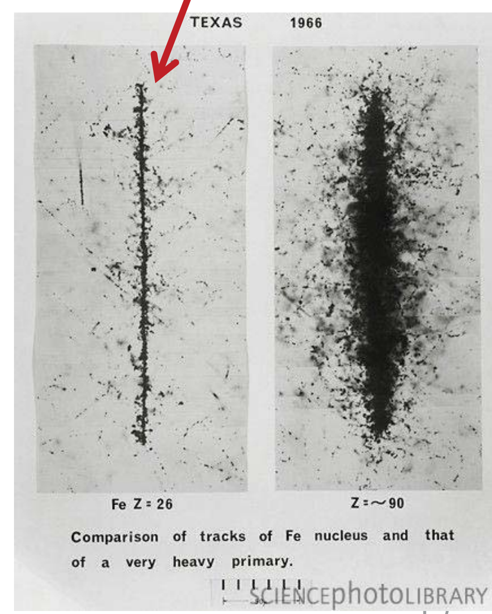
I = mean excitation potential of the target = 10eV(Z), n = electron density of the target = $(N_A Z \rho)/A M_\mu$; ρ = density of the target; Z = target atomic number; A = target atomic mass number; N_A = Avogadro number; and M_u = Molar mass constant = 1 in Si units; e = charge of the electron; m_e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

Photographic/nuclear emulsion tracks - Image Credit - PROF. P. FOWLER, UNIVERSITY OF BRISTOL



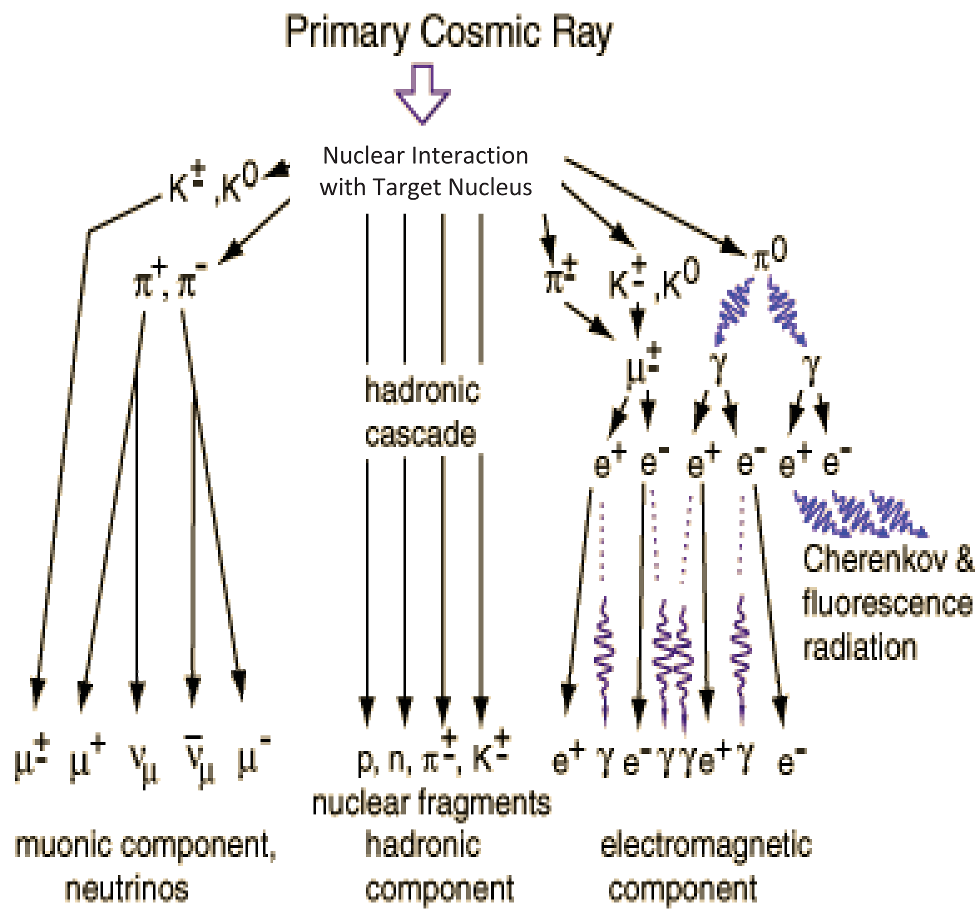
CR-39 (polycarbonate thin plastic sheet) solid state nuclear track detector SSNTD – ISS Tracks are revealed by etching the plastic post flight





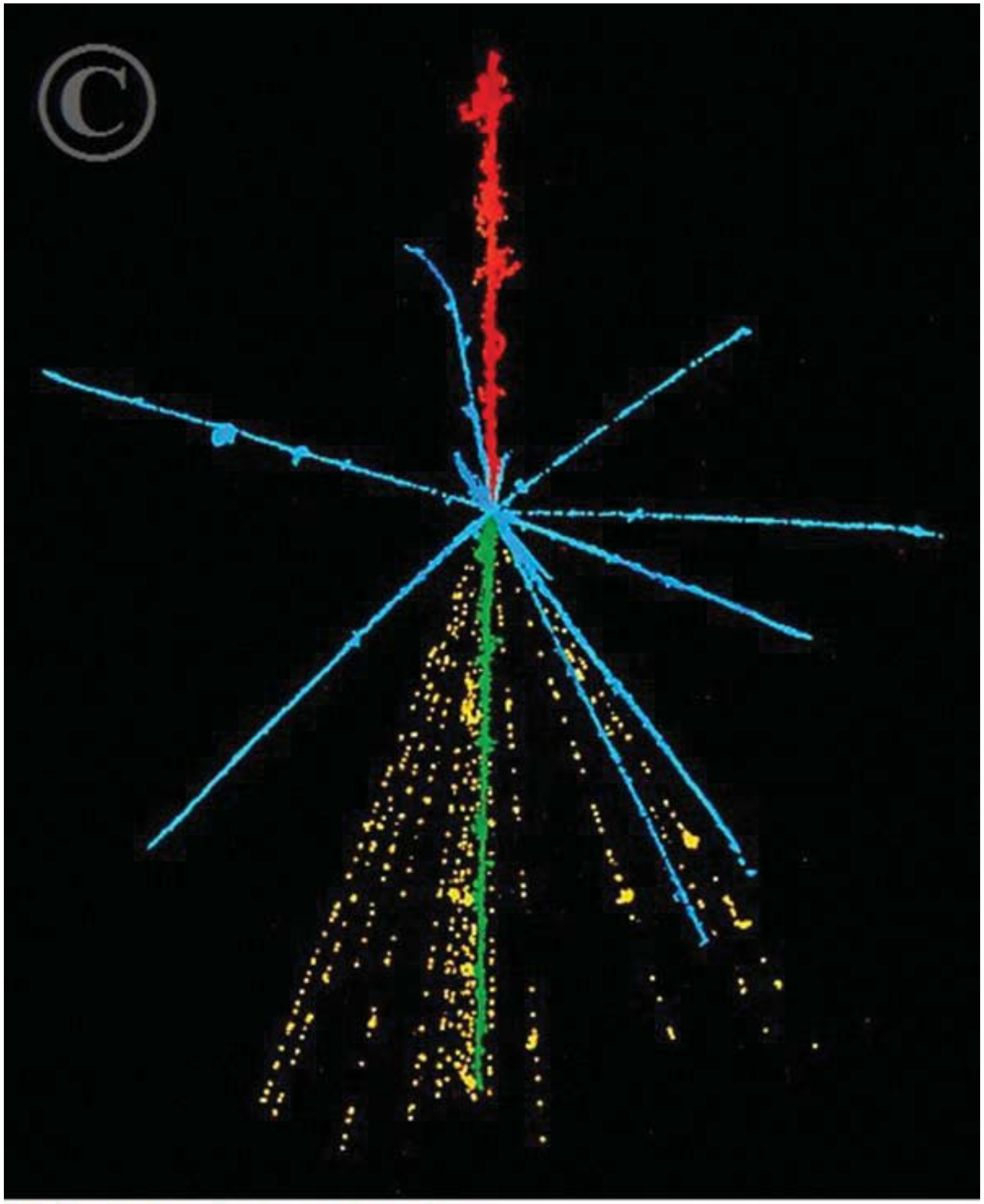
Nuclear Reactions and Secondary Particle Showers

- **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**
    - 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)$^{0.77}$**
    - λ increases with target atomic number
- **$\langle n_{event} \rangle$ = average number of secondary particles per collision event**
- **$\langle n_{collision} \rangle$ 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**



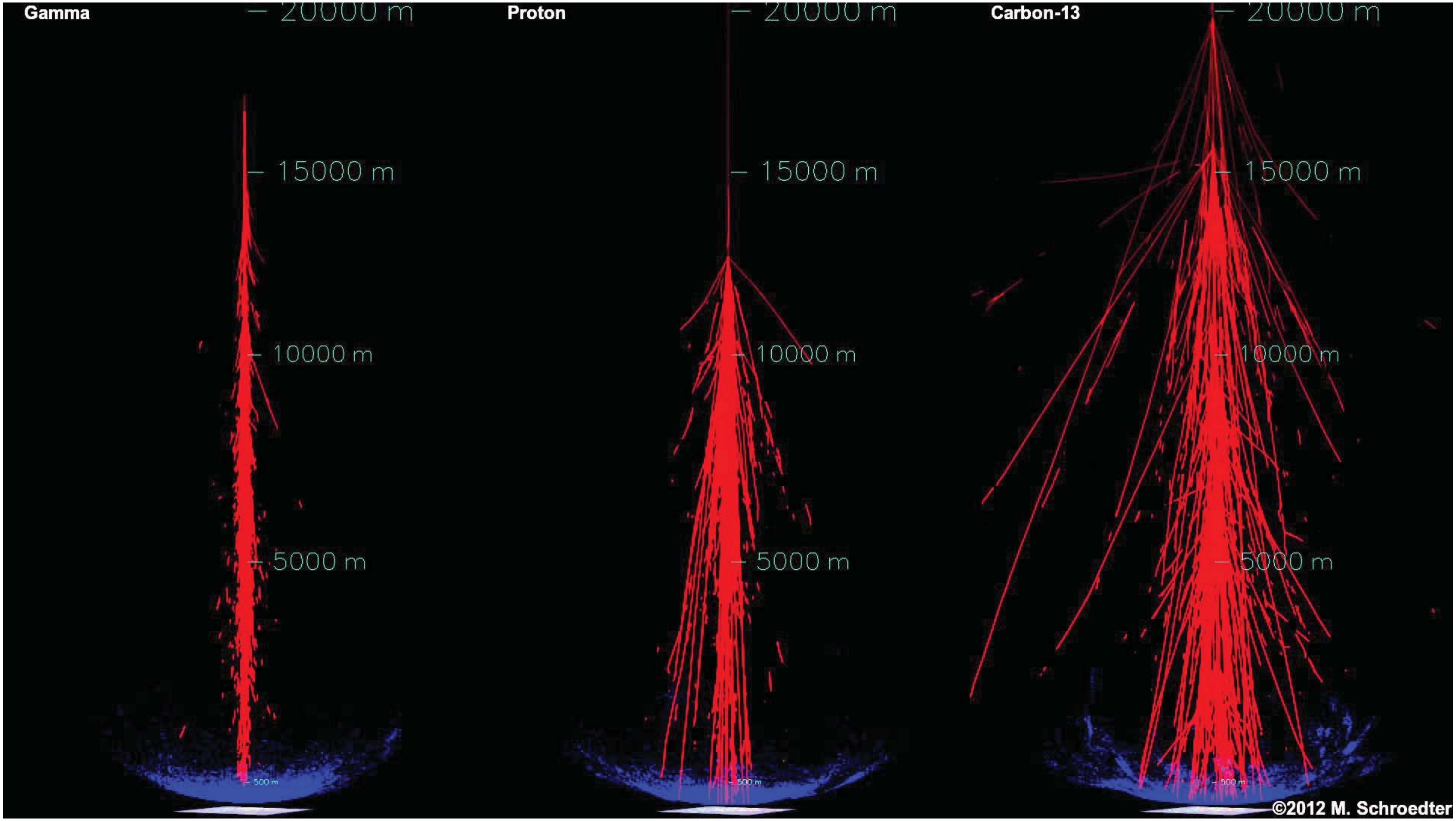
Generic GCR secondary particle shower nuclear reaction products

Nuclear Reactions (Strong Force) and Secondary Particle Showers


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.

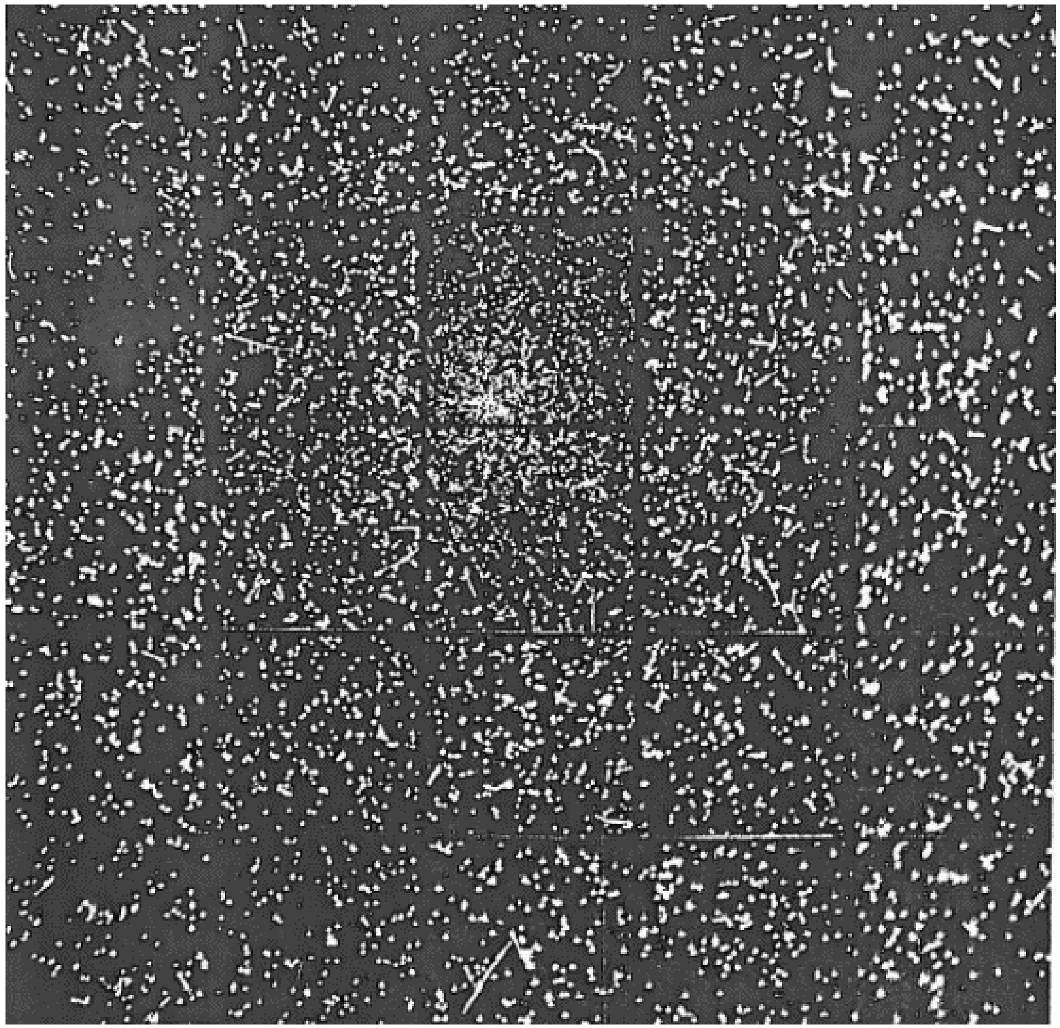
And what does all this look like? (https://www.youtube.com/watch?v=j-BBzWlOai0)



The interactions of 3 types of very-high-energy particles (gamma-ray, proton and Carbon-13 nucleus) were simulated. The fully developed atmospheric particle showers (red) are shown including the Cherenkov light (blue) just before impact on the ground. Even though the 3 particle had the same initial energy, the most intense Cherenkov light is produced by the gamma ray, less by the proton, and the least by the Carbon nucleus. Each time a very-high-energy particle interacts in the atmosphere, fluctuations cause the shower to develop differently. Shown here are pretty 'average' looking showers. (2012 Martin Schroedter, VERITAS and Harvard Smithsonian Center for Astrophysics

And what does all this look like?

5 meters

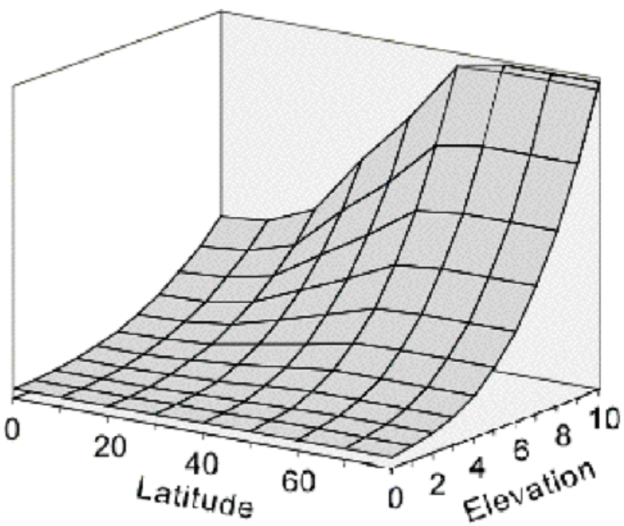


5 meters

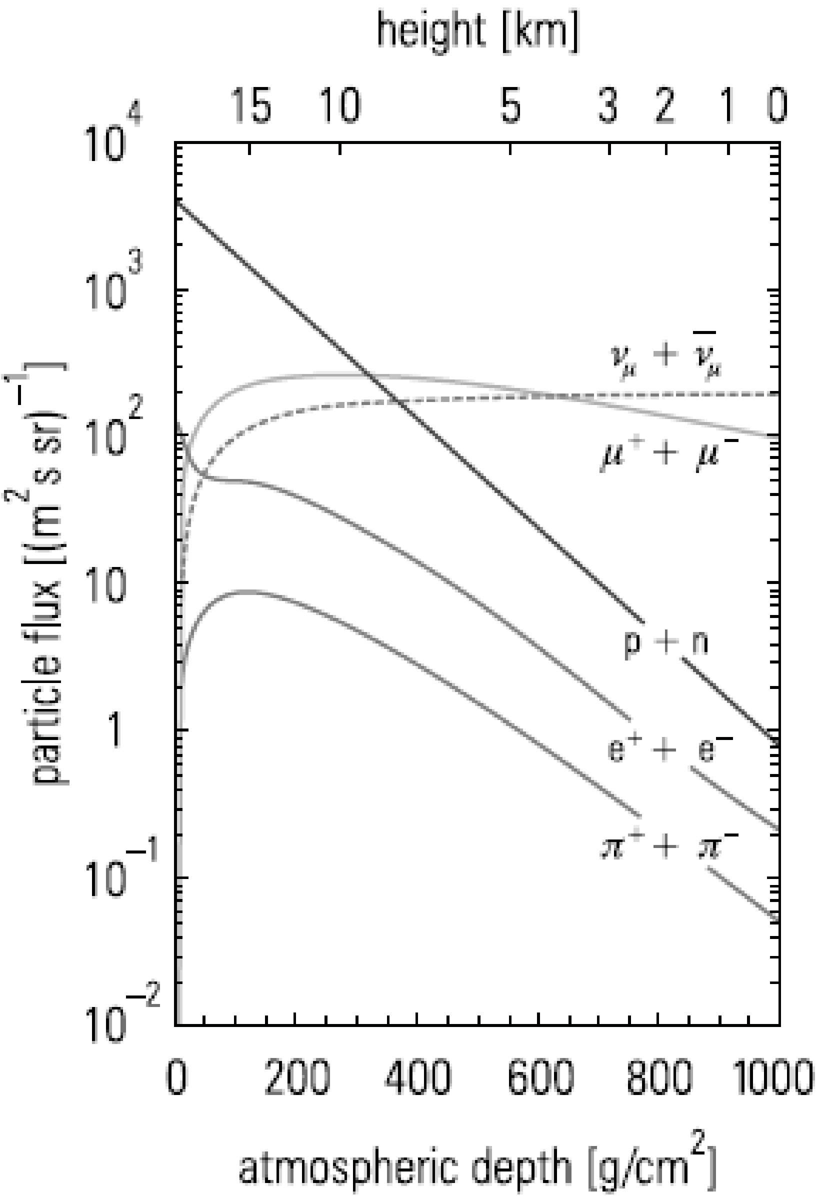
A photograph of the central region of a small, vertically incident air shower as seen by the University of leads close packed horizontal array of discharge chambers (5 x 5 meters) Leslie Hodson 1990

GCR Exposure Environments – Earth's Atmosphere

- **Earth surface/atmospheric environments**
  - **1000 grams/cm^2 air shielding mass at sea level**
  - **latitude dependent geomagnetic shielding**
  - **GCR secondary particle shower products dominate**
- **Commercial and military aviation environments**
  - **Altitude dependent air shielding mass**
  - **latitude dependent geomagnetic shielding**
  - **Solar cycle modulation of GCR environment**
  - **Latitude dependent solar particle event exposure**
  - **Pfotzer secondary shower particle maximum at about 20 km altitude (mid latitudes)**



Relative variation of cosmic ray flux at the earth's surface as a function of altitude and latitude (Cosmogenic Nuclide Laboratory - University of Glasgow - http://web2.ges.gla.ac.uk/~dfabel/CN_explain.html)



GCR secondary shower particle fluxes in Earth's atmosphere (http://pdg.lbl.gov/2011/reviews/rpp2011-rev-cosmic-rays.pdf)

GCR Exposure Environments: Earth Surface and Atmospheric Environments: Dominated by secondary particle showers

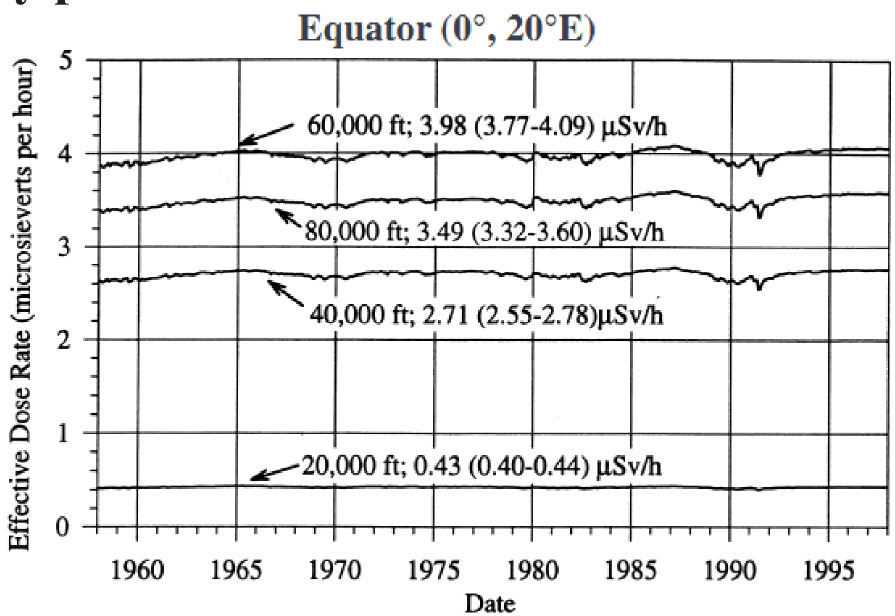
Earth surface/atmospheric environments

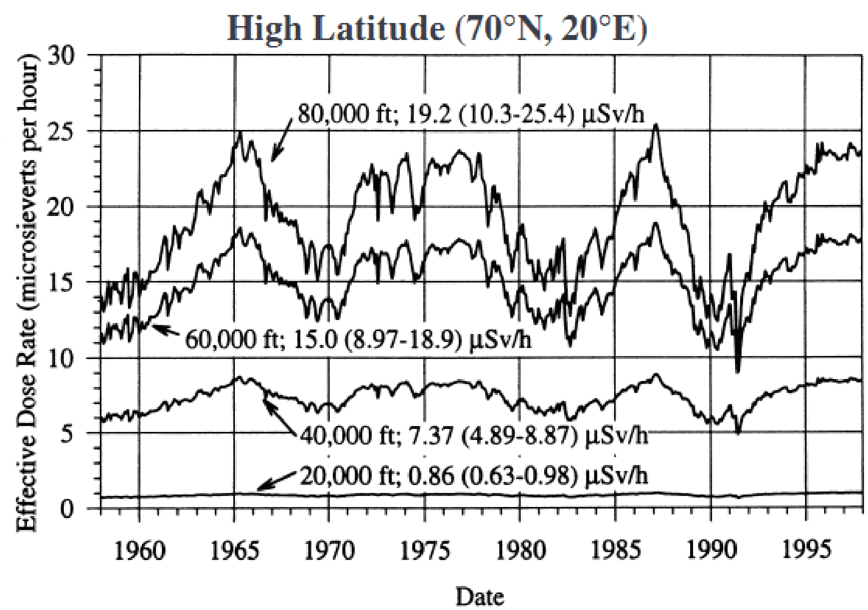
- -1000 grams/cm^2 air shielding mass at sea level
- -latitude dependent geomagnetic shielding
- -GCR secondary particle shower products dominate

Commercial and military aviation environments

- -Altitude dependent air shielding mass
- -latitude dependent geomagnetic shielding
- -Solar cycle modulation of GCR environment
- -Latitude dependent solar particle event exposure
- -Pfotzer secondary shower particle maximum at about 20 km altitude (mid latitudes)
- -Average ISS hourly crew dose rates are on the order of 20 µSv/hr - comparable to commercial aircraft dose rates on polar routes at solar minimum

Image Credit -The Boeing Company



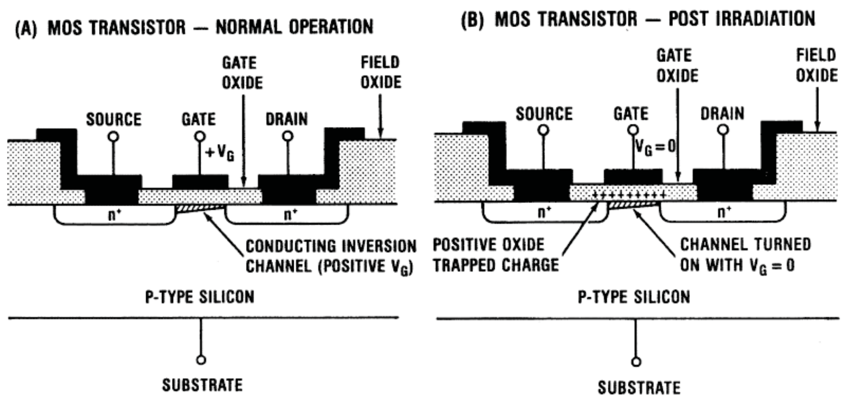


Susan Bailey, "Air Crew Radiation Exposure and Overview," Nuclear News, pp 32-40, January 2000 http://www.ans.org/pubs/magazines/nn/docs/2000-1-3.pdf

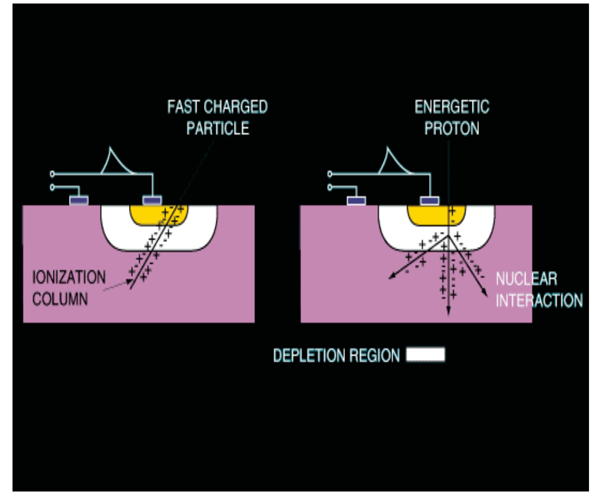
3.0: What do cosmic rays do to us?

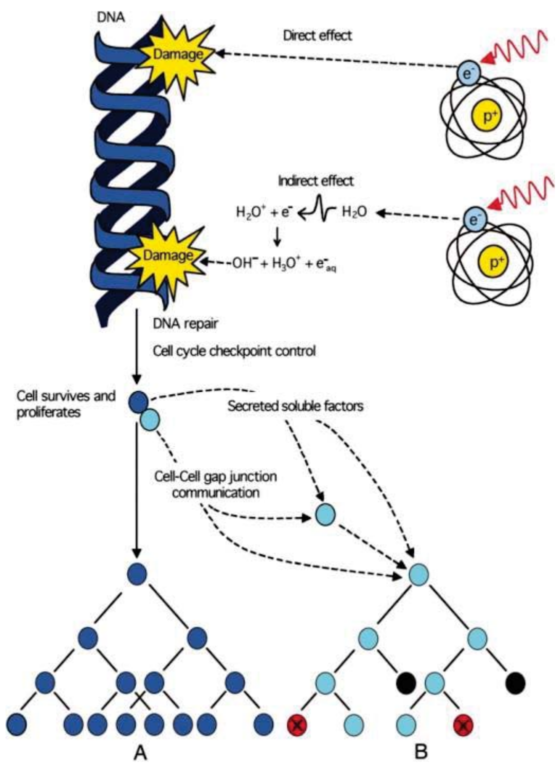
- Effects on solid state electronic devices and systems
  - Correctable soft errors
  - Recoverable soft failure or lock-up
  - Destructive failures
- Ionizing radiation effects on human health and welfare
  - DNA damage
  - Cell killing
  - Inflammation
  - Cancer
  - CNS damage
  - And TBD

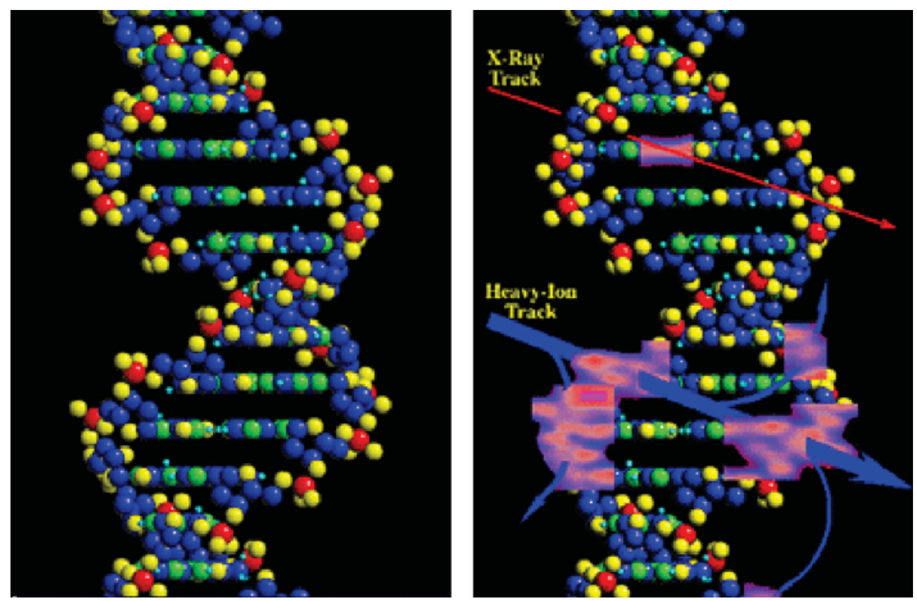
Total ionizing dose



Single event effects







3.1: Cosmic Ray Effects on Contemporary Electronic Technology

- **Ground based computation and control systems**
  - SEE caused principally by GCR shower generated secondary neutrons
  - TID effects negligible in this natural environment
- **Aircraft electronic systems**
  - SEE caused principally by GCR shower generated secondary neutrons and protons
  - TID Effects negligible in this natural environment
- **Spacecraft electronic systems**
  - Single event effects caused principally by GCR heavy ions, GCR protons, trapped protons, and solar particle events (SPE)
    - Neutrons and other secondary shower particles increasingly important as spacecraft shielding mass increases, especially when the electronic device contains heavy elements - e.g. Pb, Hf, W
  - TID effects are important in specific high-dose-rate natural environments, e.g. planetary radiation belts and/or solar particle events

Ground based computational and control systems - History

- **Observations of satellite electronic anomalies lead to the first report of SEE effects in solid state electronics**
  - D. Binder, E. C. Smith, A. B. Holman; “Satellite anomalies from galactic cosmic rays,” IEEE Transactions on Nuclear Science, Vol. NS-22, No. 6., pp 2675-2680, December 1975
- **Memory parity errors observed in the first Cray supercomputer at Los Alamos in 1976 were later determined to be SEUs caused by atmospheric neutrons**
  - E. Normand, J. L. Wert, H. Quin, T. D. Fairbanks, S. Michalak, G. Grinder, P. Iwanchuk, J. Morrison, S. Wender, S. Johnson; “First record of single event upset on ground, Cray-1 Computer at Los Alamos in 1976,” IEEE Transactions on Nuclear Science, Vol. 57, No. 6, December 2010
- **Modeling and prediction of cosmic ray (atmospheric neutron) effects on computer memories**
  - J. F. Ziegler, W. A. Lanford; “The Effects of Cosmic Rays on Computer Memories,” Science, 206, 776, 1979
- **Summary of IBM investigations into soft errors in microelectronic devices including atmospheric neutrons**
  - IBM Journal of Research and Development, Vol. 40, Number 1, January 1996
- **JEDEC Standard developed for test and measurement of alpha particle and atmospheric cosmic ray shower induced soft errors in semiconductor devices**
  - Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray Induced Soft Errors in Semiconductor Devices, JEDEC Standard JESD89A, October 2006

Recent commercial aircraft incident highlights atmospheric neutron risks (Steve Wender, LANL 2013)

Recent avionics incident highlight Single Event Effects (SEE) problem

- On October 7, 2008 , Quantas 72 was enroute from Singapore to Perth, Australia
- "While ..at 37,000 ft, **one of the aircraft's three air data inertial reference units started outputting intermittent, incorrect values**…Two minutes later … the aircraft flight control primary computers **commanded the aircraft to pitch down. … At least 110 of the 303 passengers and nine of the 12 crew members were injured**: 12 of the occupants were seriously injured and another 39 received hospital medical treatment." (Pg. vii)
- "The other potential **triggering event was a single event effect (SEE)** resulting from a high-energy atmospheric particle striking one of the integrated circuits within the CPU module. There was insufficient evidence available to determine if an SEE was involved, but **the investigation identified SEE as an ongoing risk for airborne equipment**." (pg. xvii)
- "Testing was conducted with neutrons at 14 MeV …the test was not sufficient to examine the …. susceptibility to the full range of neutrons at the higher energy levels that exist in the atmosphere". (pg. 147)

ATSB Transport Safety Report Aviation Occurrence Investigation AO-2008-70

- "The ATSB received expert advice that **the best way of determining if SEE could have produced the data-spike failure mode was to test the affected units at a test facility that could produce a broad spectrum of neutron energies**. However, the ADIRU manufacturer and aircraft manufacturer did not consider that such testing would be worthwhile for several reasons, including that:
- There were significant logistical difficulties in obtaining access to appropriate test facilities"

NNSA Slide 2 Los Alamos

Recent Example of atmospheric neutron effects on supercomputer systems (Steve Wender, LANL 2013)

Results of LANSCE/WNR measurements determine problem with ASCI Q-Machine

- The ASCI Q-Machine has 2048 nodes with a total of 8192 processors.
- During commissioning, it was observed that the Q-machine had a larger than expected failure rate. Approximately 20 fails / week (~3 fails / day).
- The question was whether this could be the result of neutron single-event upset.

ASCI Q-Machine at Los Alamos National Laboratory

Fails/day ~ [# of fails/neutron] * [# neutrons/day]

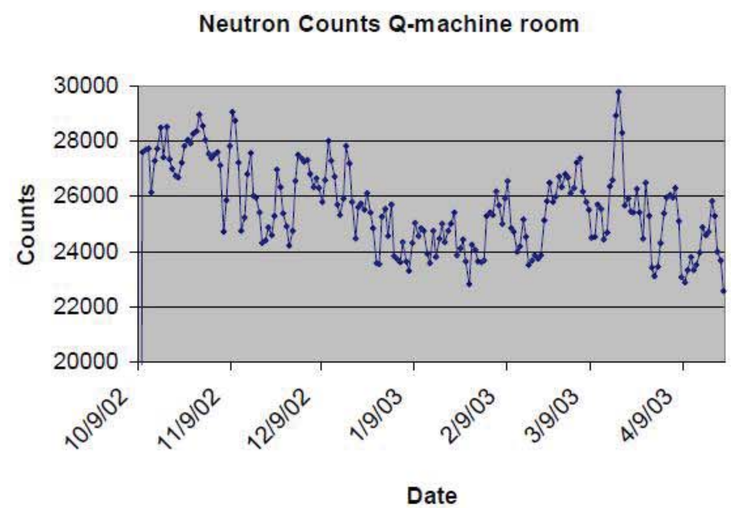
Measured at LANSCE → [# of fails/neutron]

Cosmic-ray neutron flux → [# neutrons/day]

Recent Example of atmospheric neutron effects on supercomputer systems

The neutron environment and the system response was measured

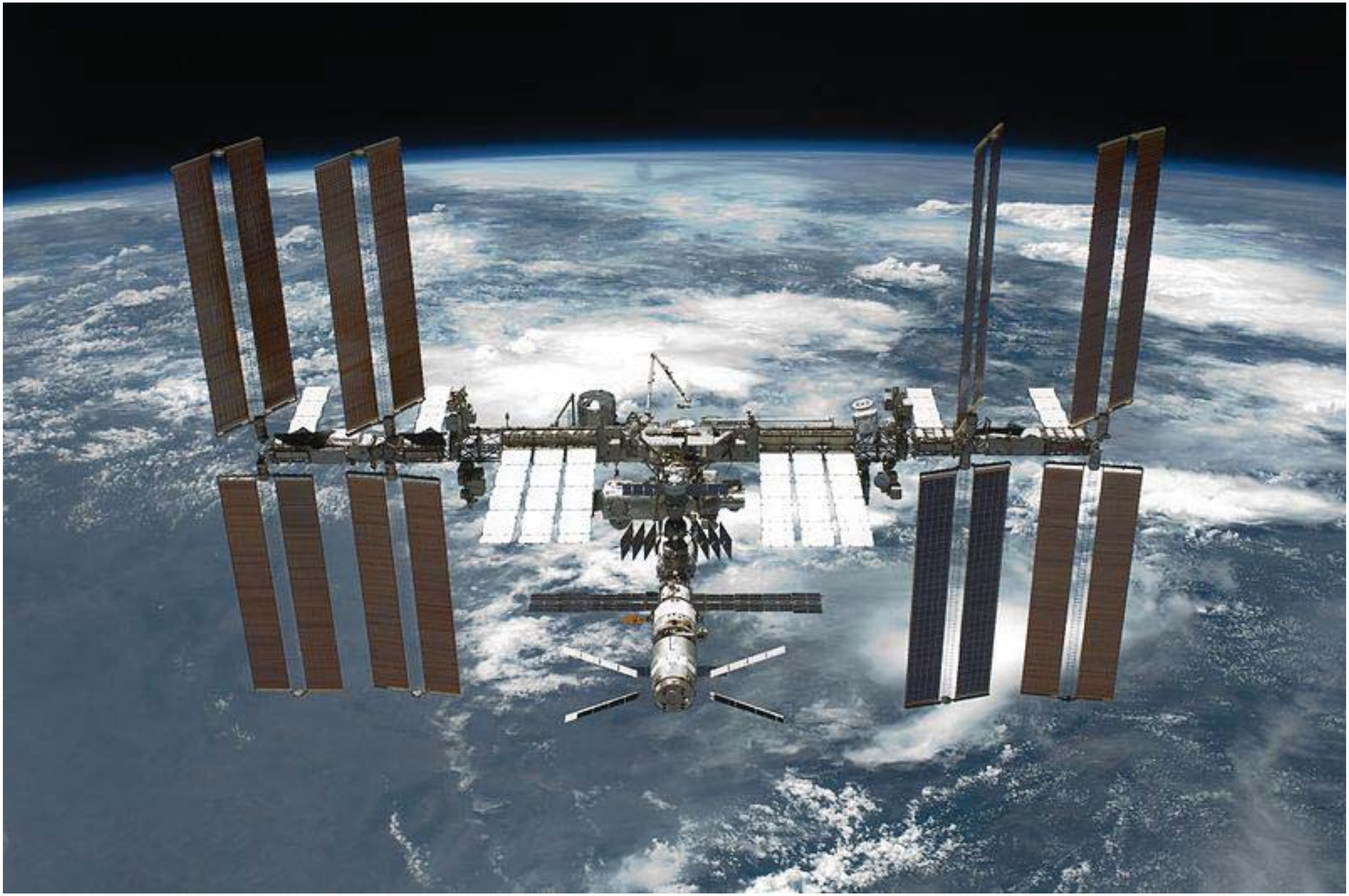
- The neutron intensity was measured in the Q-Machine room. The values obtained agreed with the Goldhagen values
- The system response was measured by putting one module of the Q-Machine in the LANSCE/WNR beam.
- Results of measurement accounted for approximately 80% of the failures. (IEEE Trans. Dev. Mat. Reliab. 5 2005)
- The failures were traced to a cache memory that was not error corrected.
- This result may have significant impact on future large computer systems



One neutron can stop a calculation

Santa Fe New Mexican February 2004
"..Q's weakness is the result of…cosmic ray bombardment…a microprocessor that doesn't have a backup system .."

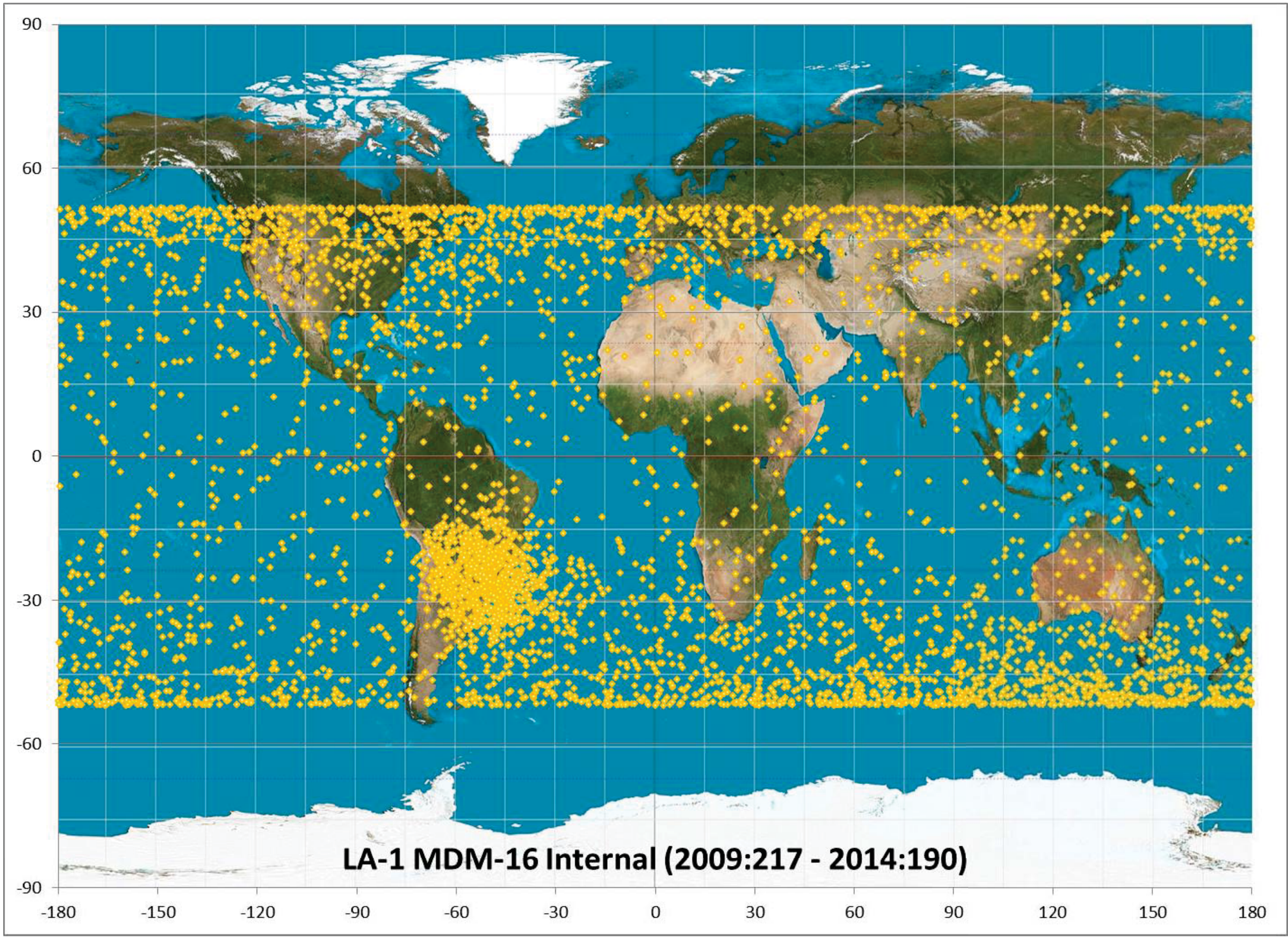
Spacecraft electronic systems



http://www.spaceflight.nasa.gov/gallery/images/shuttle/sts134/html/s134e010137.html

GCR and trapped proton single event upsets detected and corrected by Error Detection And Correction (EDAC) firmware in ISS computer system (aka MDM) Dynamic Random Access Memory (DRAM). EDAC operation is part of the nominal system design, and does not indicate a failure or anomaly.

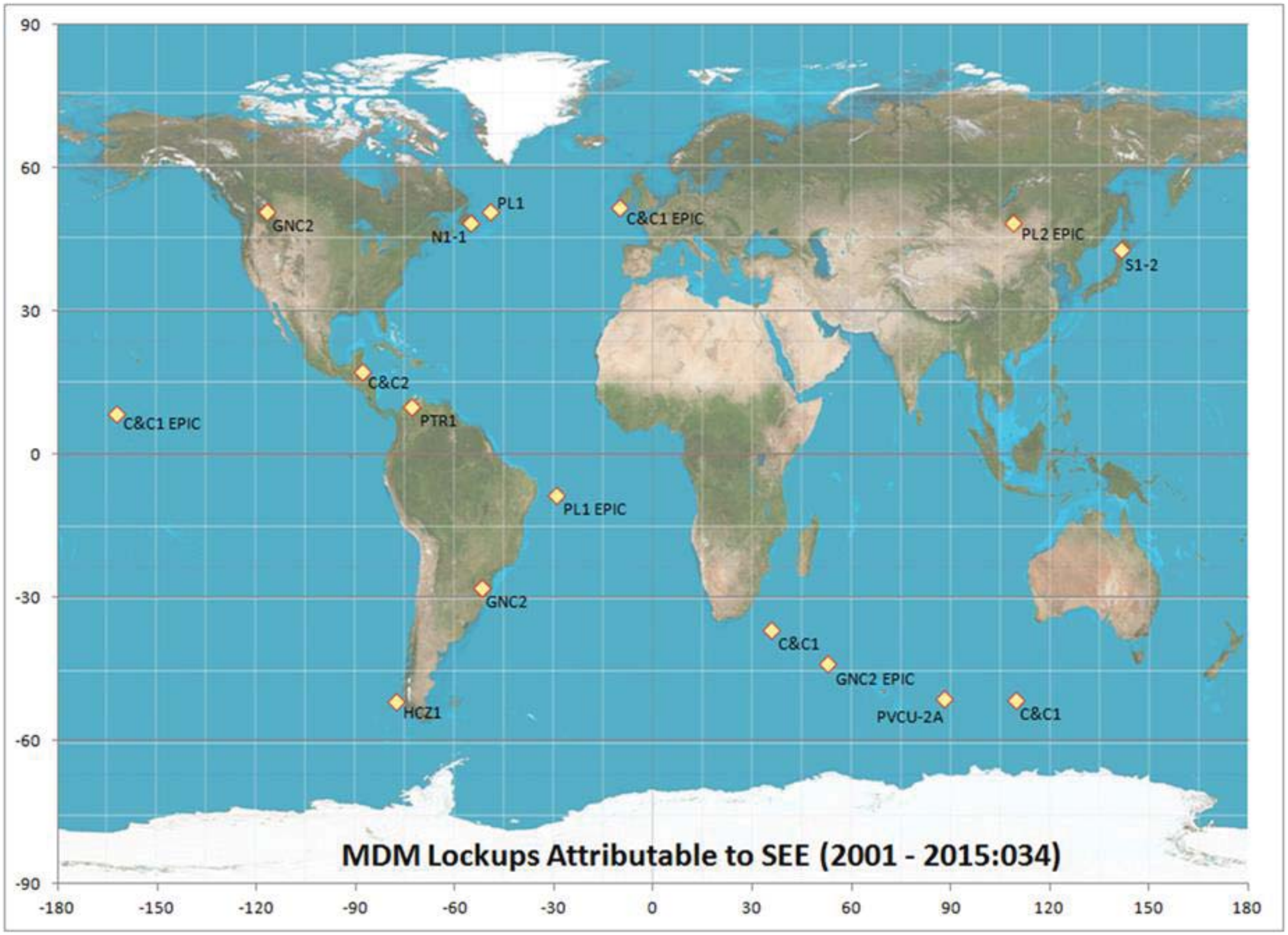
Multiplexer-De-Multiplexer (MDM)

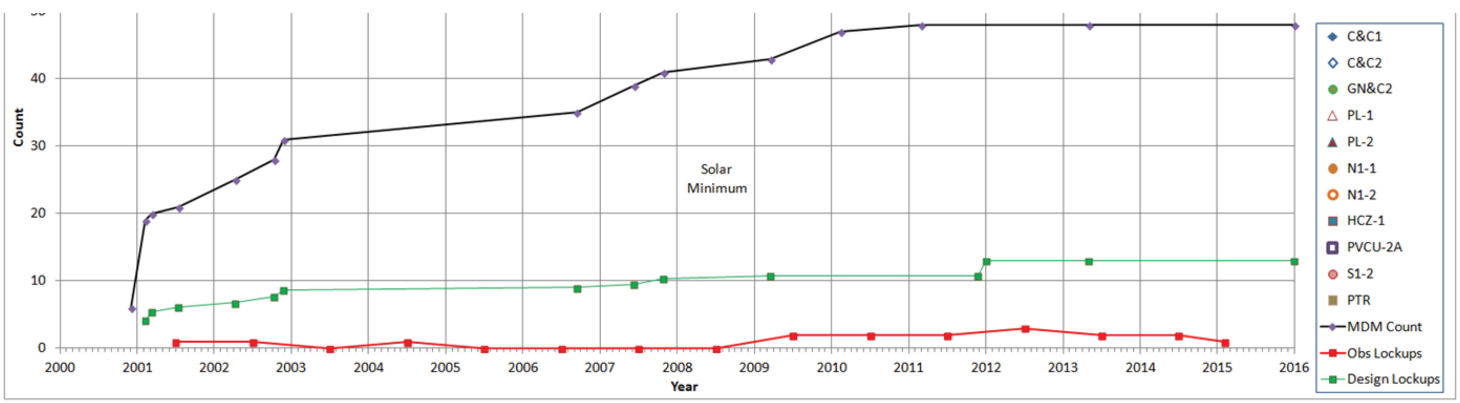


Image/data Credit: NASA

Image Credit: NASA

GCR appears to be the leading cause of ISS SEE attributable MDM functional interrupts or "lock-ups" that require power cycling and rebooting/ resynchronizing to correct, a process requiring 8 to 12 hours to complete.



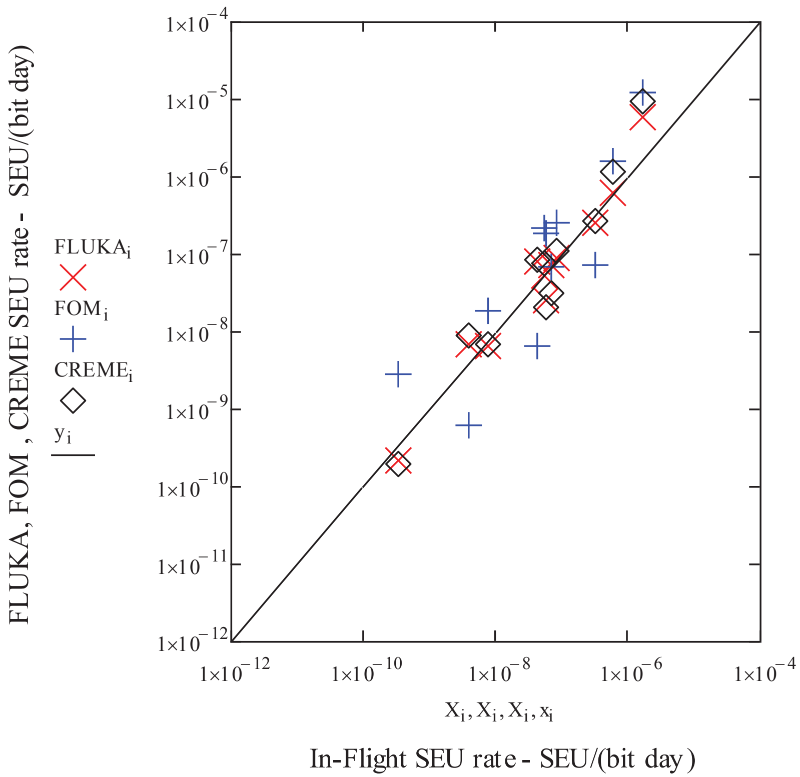


Image/data Credit: NASA

Image/data Credit: NASA

In-flight vs. calculated spacecraft device SEU rates

Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011



Shielding Mass Rate Ratio =(10 g/cm² Rate)/ (40 g/cm² Rate)

Device	Rate Ratio - Flight	Rate Ratio - FLUKA	Rate Ratio - CREME 96	Rate Ratio - FOM
TI (1M x 4) TMS44400	1.2	1.2	3.5	3.7
TI (4M x 4) TI SMJ41640	0.9	1.8	3.4	5.3

Note that only FLUKA correctly quantifies the shielding mass (i.e. secondary particle shower) effects for the ISS TI CMOS DRAM.

$$\sum_i \left[\frac{(X_i - FLUKA_i)^2}{(X_i)^2}\right]^{0.5} = 5.7 \qquad \sum_i \left[\frac{(X_i - CREME_i)^2}{(X_i)^2}\right]^{0.5} = 10.6 \qquad \sum_i \left[\frac{(X_i - FOM_i)^2}{(X_i)^2}\right]^{0.5} = 26.8$$

Using the same device parameter, the FLUKA based rate calculations show the smallest least squares error and overall acceptable performance compared to CREME-96 and the Peterson FOM, providing some validation for the FLUKA based methods described here.

A comparison of observed in-flight SPE SEU counts with estimates of SPE SEU counts calculated using the FLUKA radiation transport code and the concentric spherical shell spacecraft model

For purposes of spacecraft design and verification, the agreement between the FLUKA based SPE rate estimate sand the observed in-flight SPE upset rates are satisfactory, as shown below.

Spacecraft/System and Device (ref)	**Nov. 1997 SPE** **Upsets/bit**	**July 2000 SPE** **Upsets/bit**	**Nov. 2001 SPE** **Upsets/bit**	**Oct. 2003 SPE** **Upsets/bit**
Cassini/Solid State Recorder DRAM (16) 1) Observed event upsets 2) Estimated event upsets 3) Estimated/Observed 4) Quiescent (no-event) daily upset rate	1) 4.4×10^{-7} 2) 1.4×10^{-7} 3) 0.32 4) 5.8×10^{-8}	NA	NA	NA
SOHO /Solid State Recorder DRAM (17) 1) Observed event upsets 2) Estimated event upsets 3) Estimated/Observed 4) Quiescent (n0 event)daily upset rate	1) 4.4×10^{-6} 2) 2.110^{-6} 3) 0.48 4) 5.9×10^{-7}	1) 4.7×10^{-5} 2) 2.1×10^{-5} 3) 0.4 4) 5.9×10^{-7}	NA	NA
Thuraya/ DSP DRAM (15) 1) Observed event upsets 2) Estimated event upsets 3) Estimated/Observed 4) Quiescent (no event) daily upset rate	NA	NA	1) 2.0×10^{-6} 2) 2.8×10^{-6} 3) 1.4 4) 5.3×10^{-8}	1) 1.5×10^{-6} 2) 3.8×10^{-6} 3) 2.5 4) 5.3×10^{-8}

3.2: CR effects on human health and safety

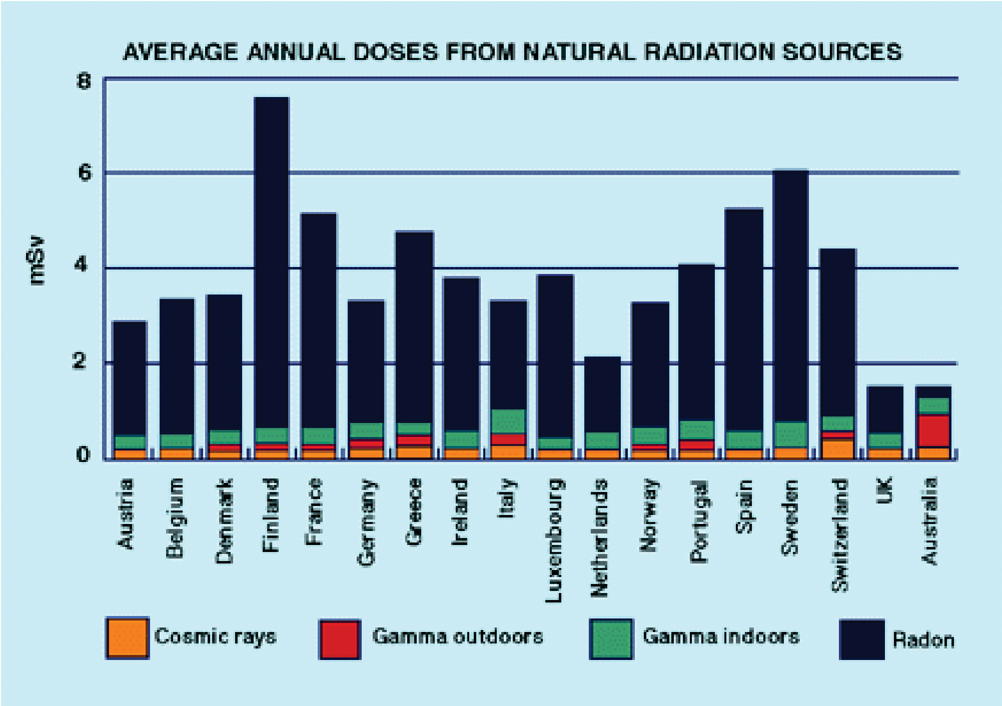
Some comparative (Earth environment) radiation doses and their effects

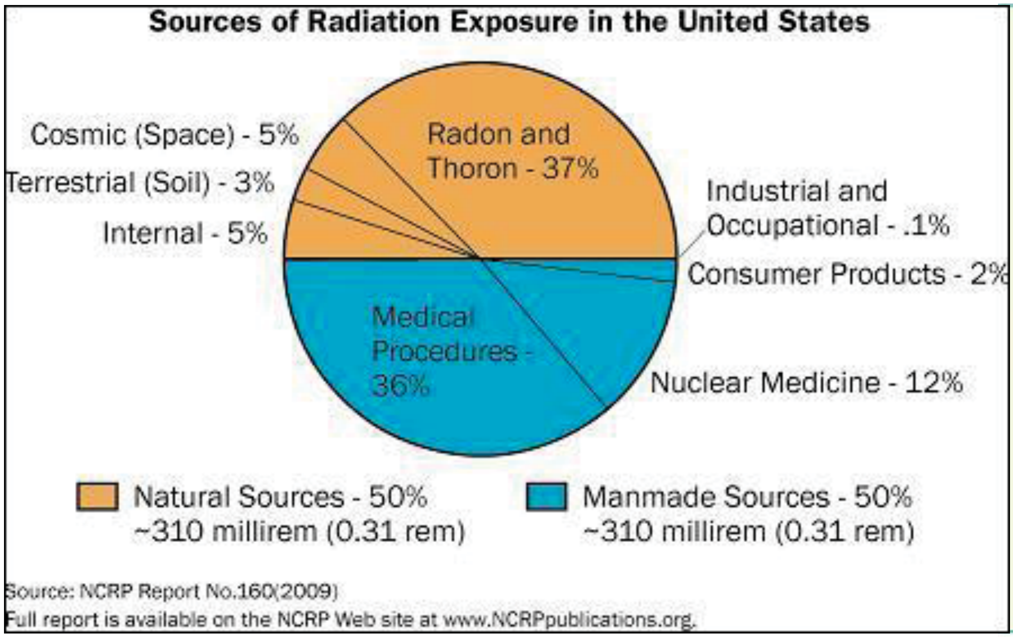
2.4 mSv/yr	Typical background radiation experienced by everyone (average 1.5 mSv in Australia, 3 mSv in North America).
Up to 5 mSv/yr	**Typical incremental dose for aircrew in middle latitudes.**
9 mSv/yr	**Exposure by airline crew flying the New York – Tokyo polar route.**
20 mSv/yr	Current limit (averaged) for nuclear industry employees and uranium miners.
50 mSv/yr	Former routine limit for nuclear industry employees. It is also the dose rate which arises from natural background levels in several places in Iran, India and Europe.
50 mSv	Allowable short-term dose for emergency workers (IAEA).
100 mSv	Lowest level at which increase in cancer risk is evident (UNSCEAR). Above this, the probability of cancer occurrence (rather than the severity) is assumed to increase with dose.
250 mSv/yr	**Natural background level at Ramsar in Iran, with no identified health effects.**
350 mSv/lifetime	Criterion for relocating people after Chernobyl accident.
500 mSv	Allowable short-term dose for emergency workers taking life-saving actions (IAEA).
1,000 mSv short-term	**Assumed to be likely to cause a fatal cancer many years later in about 5 of every 100 persons exposed to it. If the normal incidence of fatal cancer were 25%, this dose would increase it to 30%.**
1,000 mSv short-term	**Causes (temporary) radiation sickness (Acute Radiation Syndrome) such as nausea and decreased white blood cell count, but not death. Above this, severity of illness increases with dose.**
5,000 mSv short-term	Would kill about half those receiving it within a month.
10,000 mSv short-term	Fatal within a few weeks.

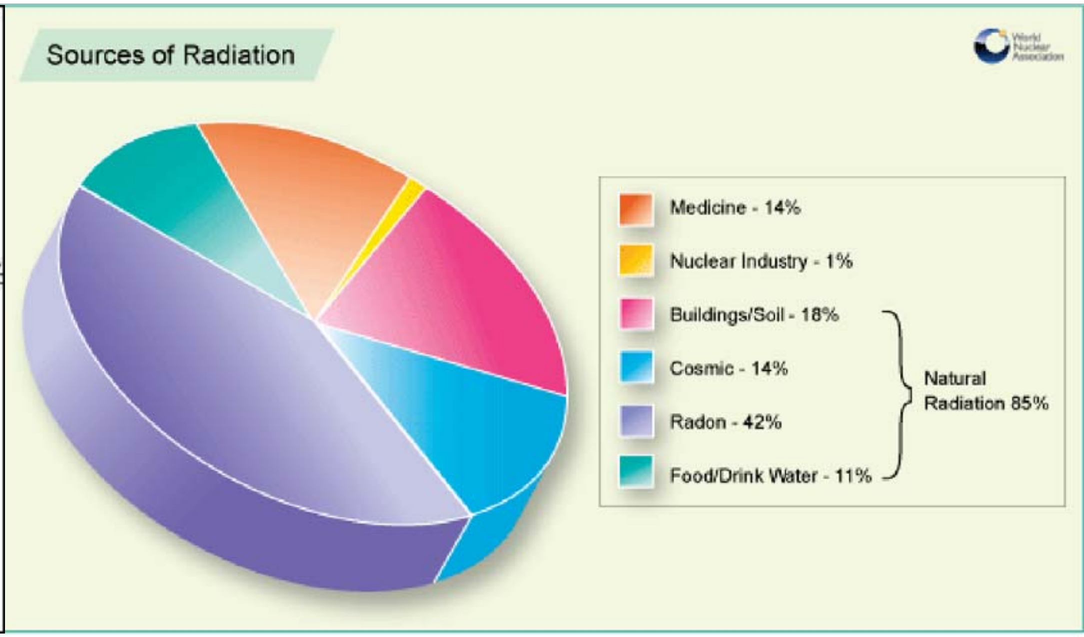
http://www.world-nuclear.org/info/inf05.html

3.1: Biological Effects of Cosmic Radiation – Earth 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
- CR contributions are on the order of 10% of the natural environment



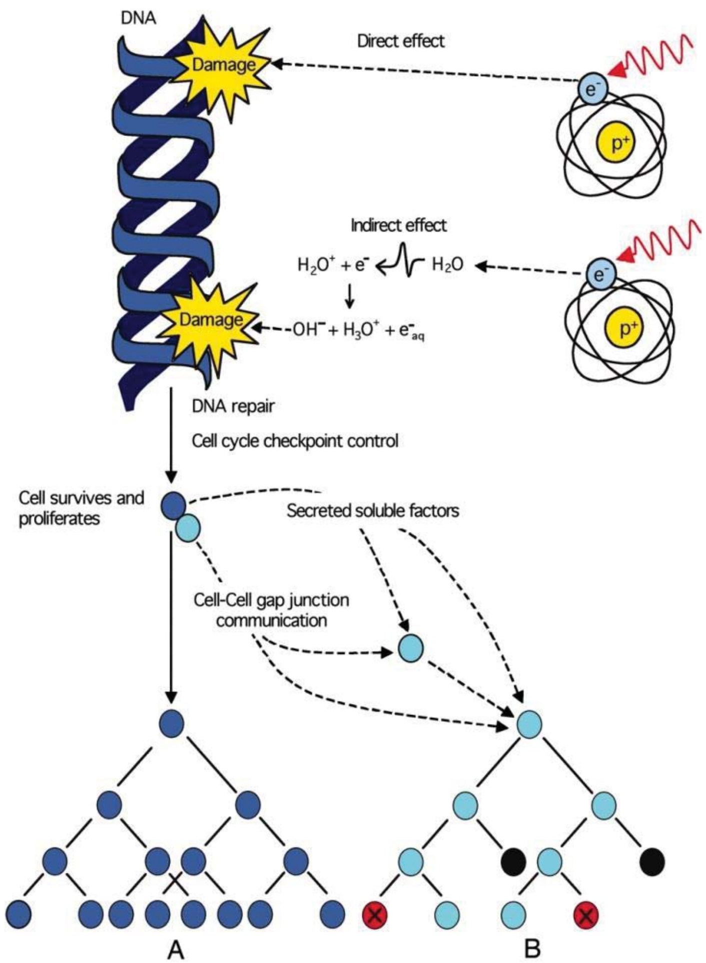




http://www.world-nuclear.org/info/inf05.html

CR effects on human health and safety

- **Exposing cells to ionizing radiation leads to lethality, mutation induction, and carcinogenesis**
- **Primary and secondary cosmic ray particles transfer energy, proportional to charged particle LET = dE/dx, to atoms and molecules in the cellular structure along the particle ionization track so as to:**
  - Produce free radicals
  - Break chemical bonds
  - Produce new chemical bonds and cross-linkage between macromolecules
  - Damage molecules and molecular assemblies that regulate vital cell processes (e.g. DNA, RNA, proteins, and membrane lipid structures)
- **Ionizing radiation induces both direct biomolecule damage and indirect biomolecule damage through the radiolysis of water.**
  - At low doses (i.e. damage rates), such as what we receive every day from background radiation, the cells repair the damaged molecules rapidly enough to survive
  - At higher doses (up to 1000 mSv), the cells might not be able to repair the damage rapidly enough , and the cells may either be changed permanently or die.
- **Cells changed permanently may go on to produce abnormal cells when they divide. In the right circumstance, these cells may become cancerous. This is the origin of our increased risk in cancer, as a result of radiation exposure.**
  - Bystander cells can also be affected via intracellular signal transduction pathways (inflammation)



http://www.pnas.org/content/102/40/14127/F1.large.jpg

Biological Effects of Cosmic Radiation – Manned Space Flight Environments

Spaceflight Radiation Examples - Human Spaceflight Mission Type Radiation Dose:

Assuming 20 to 50 g/cm^2 Al shielding and not including secondary particle shower effects internal to the human body which can increase effective dose by about 50%

Space Shuttle Mission 41-C **(8-day mission orbiting the Earth at 460 km)**	**5.59 mSv**
Apollo 14 **(9-day mission to the Moon)**	**11.4 mSv**
Skylab 4 **(87-day mission orbiting the Earth at 473 km)**	**178 mSv**
International Space Station (ISS) Mission **(up to 6 months orbiting Earth at 353 km)**	**80 mSv**
Estimated Mars mission (3 years)	**1200 mSv**

Slow accumulation of whole body dose from GCR (expressed in Effective equivalent Sv) and including secondary particle showers in the human body) presently limits the duration of manned space operations outside earth's magnetosphere to times on the order of 180 days (assuming 20 to 30 g/cm^2 shielding mass). The overall programmatic cost of the available active or passive shielding needed to extend that limit is likely prohibitive at this time (Francis A. Cucinottaa, Myung-HeeY. Kim, Lei Ren; "Evaluating shielding effectiveness for reducing space radiation cancer risks," Radiation Measurements 41 (2006) 1173 – 1185)

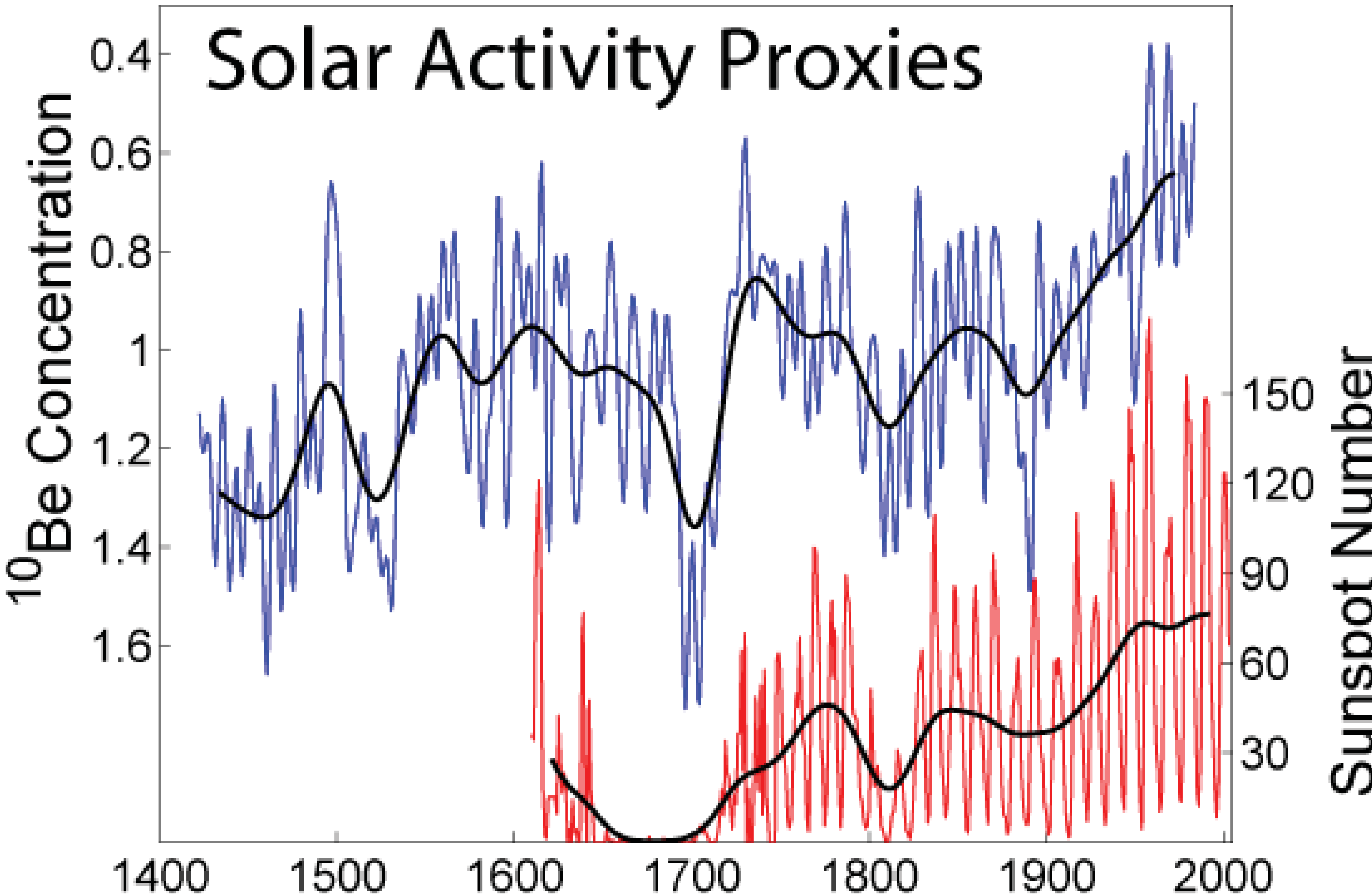
3.0 Summary & Conclusions

- The effects of energetic cosmic ray, solar particle event, and trapped radiation charged particles on contemporary electronic systems as well as human health and safety depends on:
  - The production of ionization/excitation tracks in target materials
  - Collisions with target material nuclei to initiate secondary particle showers
- CR secondary particle shower species, especially neutrons, dominate effects on electronic systems and human health at high shielding mass
  - Earth surface operating environments
  - High altitude aircraft operating environments
  - Heavily shielded manned spacecraft
  - In massive targets, like the human body, secondary particle showers can contribute on the order of 50% of the total body dose expressed in Sv
- SEE effects on electronic systems can be managed by: 1) selection of resistant parts, 2) EDAC and FDIR functions, and 3) robust/highly redundant system architectures
- Shielding mass can mitigate electronic system TID and SEE effects from SPE and trapped radiation but is largely ineffective against GCR
- Slow accumulation of whole body dose (expressed in Sv) from GCR presently limits the duration of manned space operations outside earth's magnetosphere to times on the order of 180 days. The overall programmatic cost of the available active or passive shielding needed to extend that limit is prohibitive at this time.

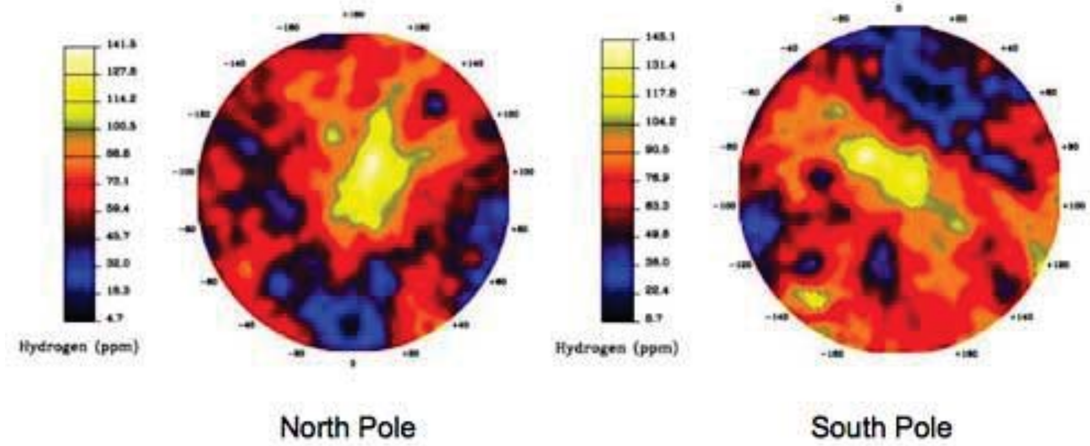
4.0: What do cosmic rays do for us?

- Useful aspects of cosmic rays are the result of GCR collisions with nuclei in solar system bodies.
  - Cosmogenic nuclide (radioisotope) production
    - E.g. ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{129}I
    - Terrestrial and planetary geochemistry and geophysics
    - Geomorphology, Paleoclimate, paleontology, and archeology
  - Secondary shower particles and radioisotope decay products
    - Neutrons and gamma rays for near surface composition and resource prospecting
    - Muons mapping of volcanos and similar large geological features on Earth and Mars
    - Muon radiography for nuclear materials and weapons detection (national security, nuclear safety, and disaster recovery)

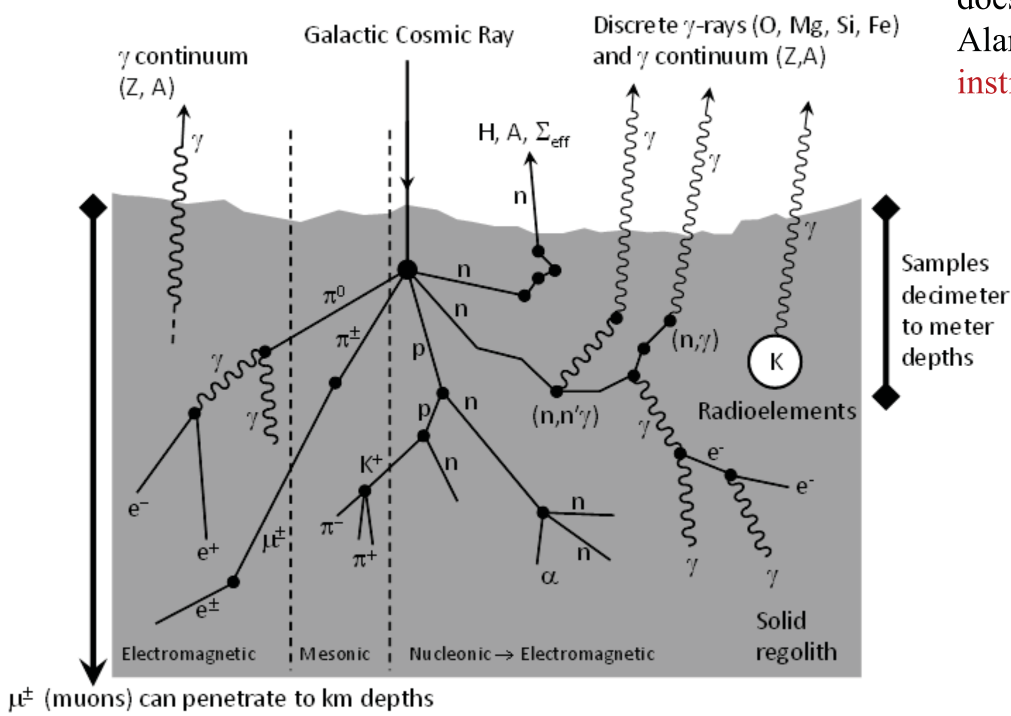
Cosmogenic Nuclides example: ^{10}Be in arctic ice and the Maunder Minimum - Solar wind modulation of GCR

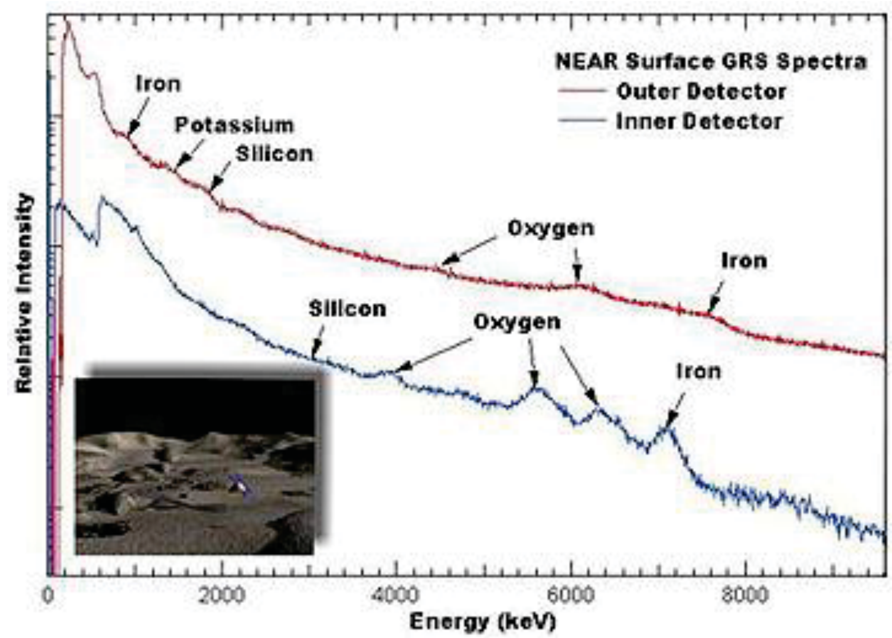


GCR induced emission of neutrons and gamma rays for solar system exploration



Lunar Prospector neutron spectrometer maps of the lunar poles. These low resolution data indicate elevated concentrations of hydrogen at both poles; it does not tell us the form of the hydrogen. Map courtesy of D. Lawrence, Los Alamos National Laboratory. http://lunar-research-institute.org/images/science/1999/98009346.pdf

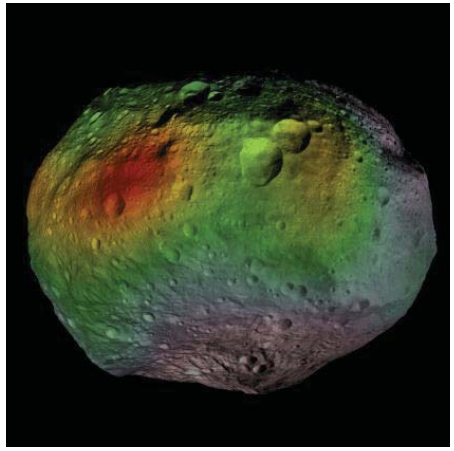


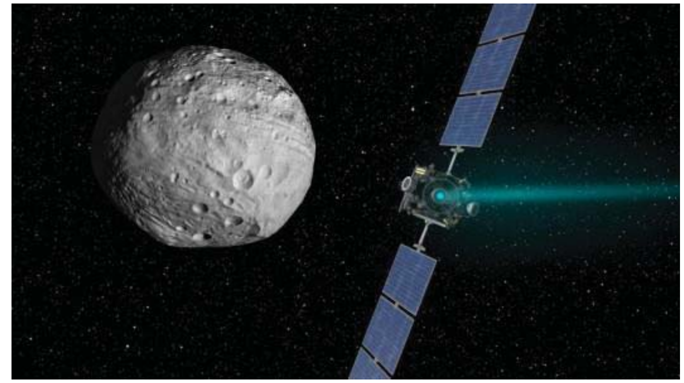


NEAR spacecraft gamma ray spectra of the surface of the asteroid Eros. http://www.jhuapl.edu/techdigest/TD/td1902/goldsten.pdf

Planetary Exploration 1 – finding water (hydrogen rice regions) with gamma ray and neutron detectors

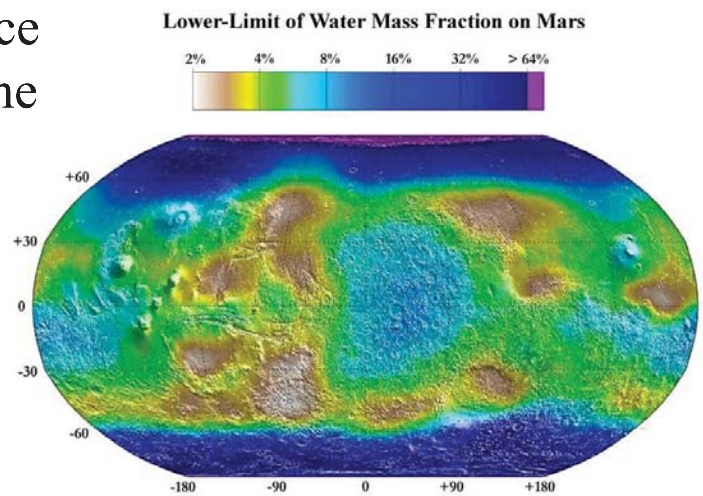
Together, gamma rays and neutrons produced by collisions of GCR particles with near surface materials reveal many of the important atomic constituents of the celestial body's surface down to a depth of one meter.

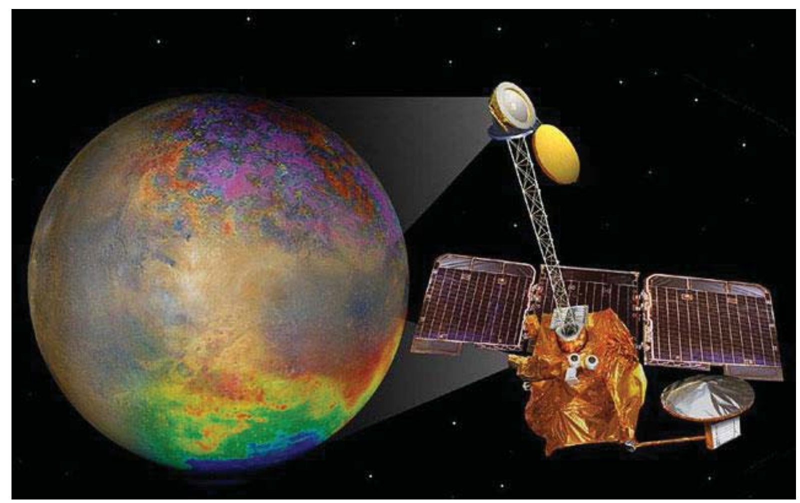




Dawn

http://onlinelibrary.wiley.com/doi/10.1111/maps.12187/pdf

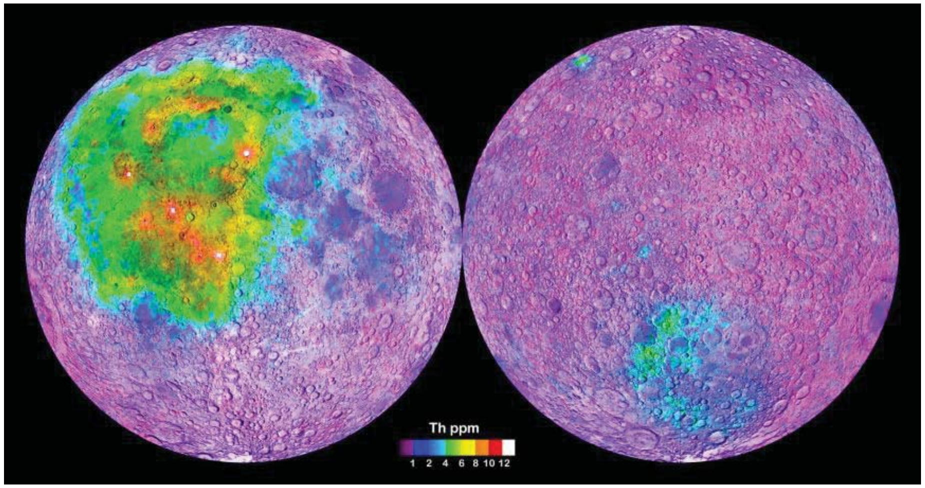




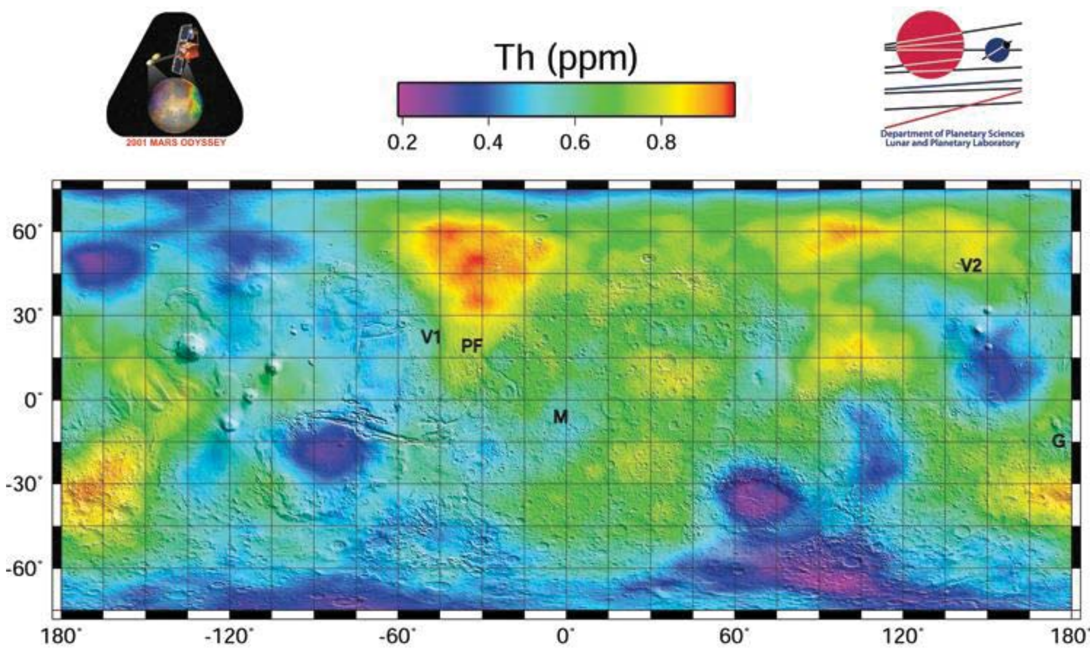
Mars Odyssey

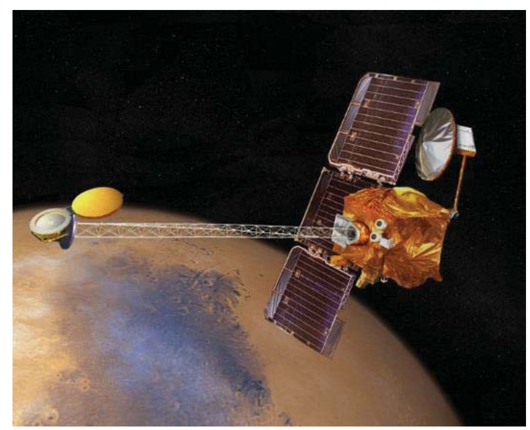
http://mars.nasa.gov/odyssey/mission/instruments/

Planetary Exploration 2: Thorium maps with GCR induced gamma ray emission



http://lunar-research-institute.org/images/science/1999/98009346.pdf

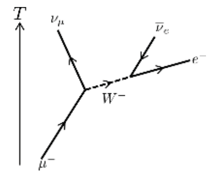




http://grs.lpl.arizona.edu/home.jsp

What are muons [$\mu(\pm)$s] and what's so special about them?

- Muons μ are heavy leptons – sort of a heavy version of an electron
  - $e^{\pm}$ rest frame mass/energy = 0.511 MeV/c^2
  - $\mu^{\pm}$ rest frame mass/energy = 105.7 MeV/c^2
  - Muons are unstable with a half life of 2.19698 microseconds in the rest frame
    - $\mu^- \rightarrow e^- + \underline{\nu}(e) + \nu(\mu)$
    - $\mu^+ \rightarrow e^+ + \nu(e) + \underline{\nu}(\mu)$

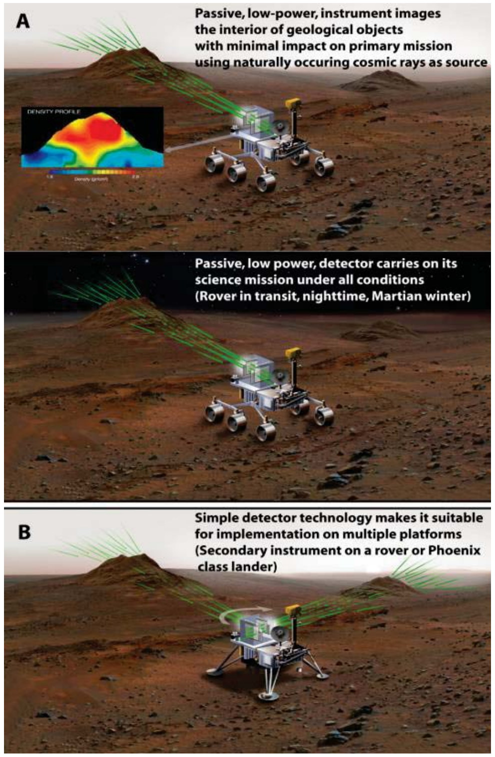


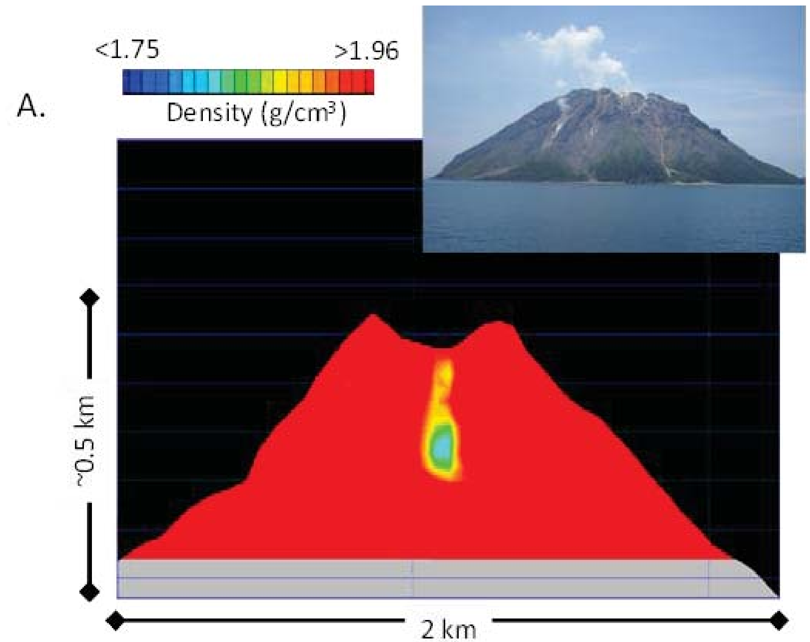
- $\mu^{\pm}$ rest frame mass/energy is so high that $\mu^{\pm}$ cannot form in natural radioisotope decay or nuclear fusion/fission reactions - only in relativistic heavy ion collisions
  - $\mu^{\pm}$s only form as a result of relativistic nuclear collisions in accelerators or in the natural cosmic ray environment.
  - Pions (composed of 2 quarks instead of 3 like protons and neutrons) are the primary collision products and relativistic collisions make a lot of them
  - Pions($\pi^{\pm}$, π^0) decay to muons ($\pi^{\pm}$) or gamma rays (π^0) if they don't collide with something else first
  - So lots of muons are formed in planetary atmospheres while a many fewer form solid or liquid targets because of the increased density.
- And $\mu^{\pm}$ are useful for Imaging really big structures and detecting very heavy elements
  - Highly penetrating – relativistic $\mu^{\pm}$ can penetrate kilometers of solid rock and thousands of kilometers of atmosphere (relativistic time dilation effect allows this in spite of short half life) to image big thin
    - High particle mass (compared to electron)
    - No nuclear reactions so not limited by nuclear collision length
  - Not easily deflected except by very high atomic number elements like uranium and plutonium

Muon imaging

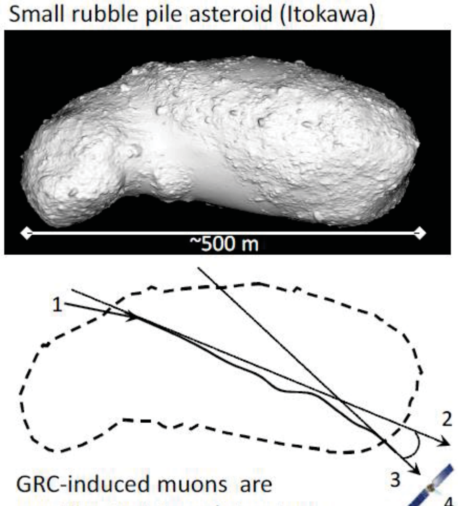
www.univearths.fr

Muon Radiography 1 – Terrestrial, Martian, and Asteroid Geology



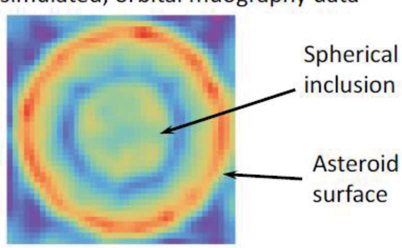


Small rubble pile asteroid (Itokawa)



GRC-induced muons are sensitive to internal structure

Tomograph of a small asteroid reconstructed from simulated, orbital muography data



Key (left):

1. Incident Galactic Cosmic Ray (GCR)
2. Initial direction of secondary muon
3. Final direction of muon as it exits the asteroid (deviation is exaggerated)
4. Orbiting spacecraft with muon telescope

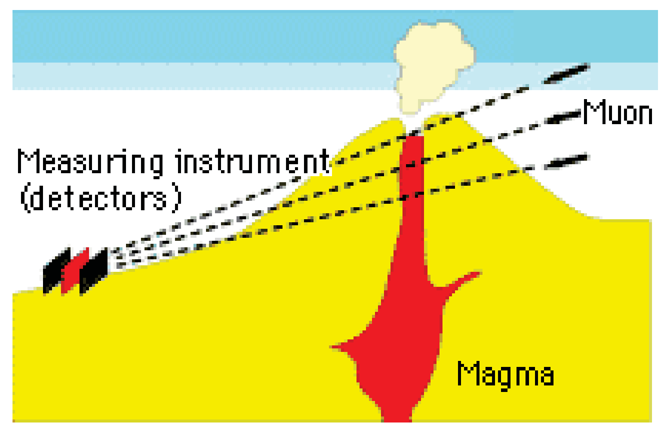
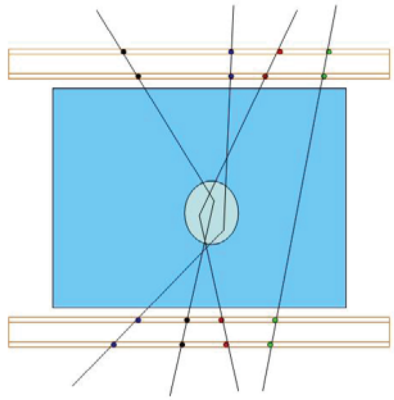
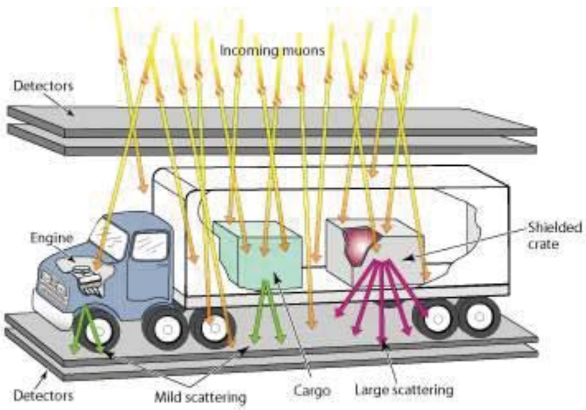


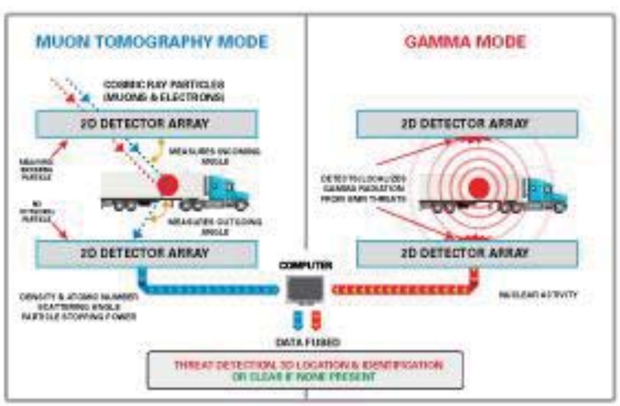
Figure 4: Analyzing the internal structure of a volcanic zone using muons

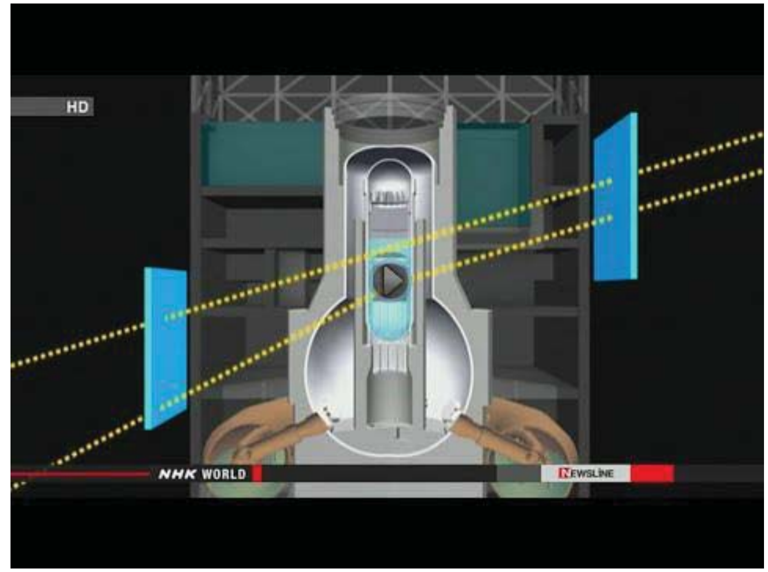
Muon Radiography 3: Nuclear Materials – Muon deflection by heavy elements



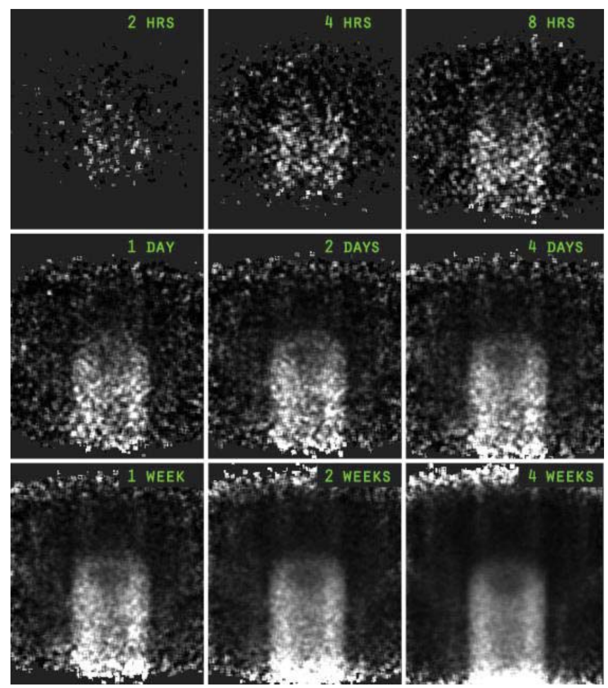
Finding nuclear materials and contraband







Kagoshima disaster recovery - Where is the nuclear fuel after the core meltdown?



A test run at a small, working reactor in Kawasaki, Japan, successfully revealed the location of nuclear fuel. These images, compiled from muon data taken over the course of four weeks, show how the picture improves over time, as more muons pass through.

5.0 Supporting Data: Modeling and Calculation Methods

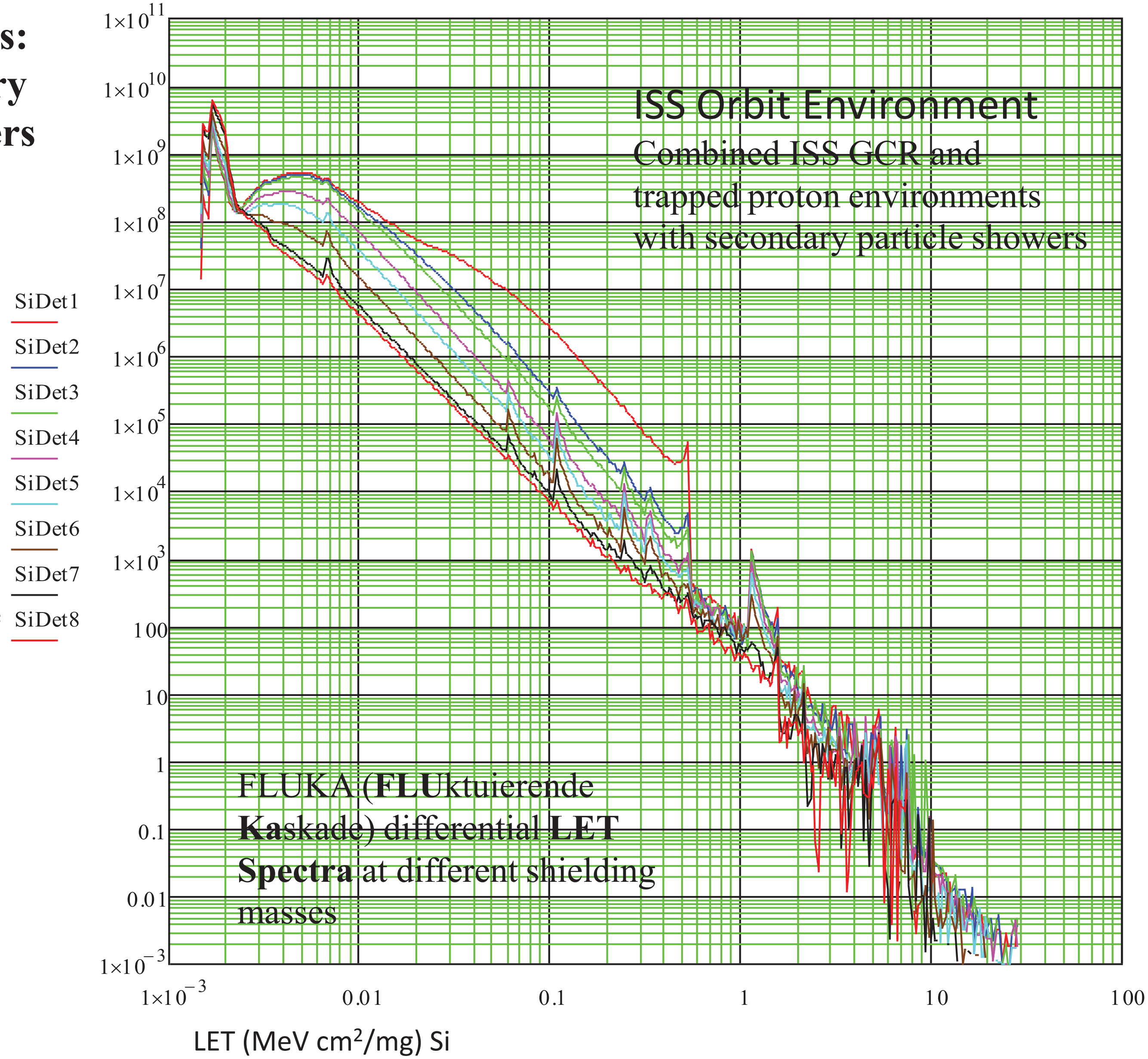
Energetic Particle Interactions with Materials

1.2: GCR Exposure Environments: Low Earth Orbit (LEO) – Primary CR and secondary particle showers

The differential LET spectra [#/(cm^2 week LET)] at various shielding depths in a concentric spherical shell model spacecraft is shown to the right.

LET spectra are calculated, using the FLUKA (1) 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 full shielding mass distribution function for each Si shell is utilized in a fully three dimensional calculation. Total ionizing dose and nuclear reactions "star" density is also calculated but not reported here.



Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011

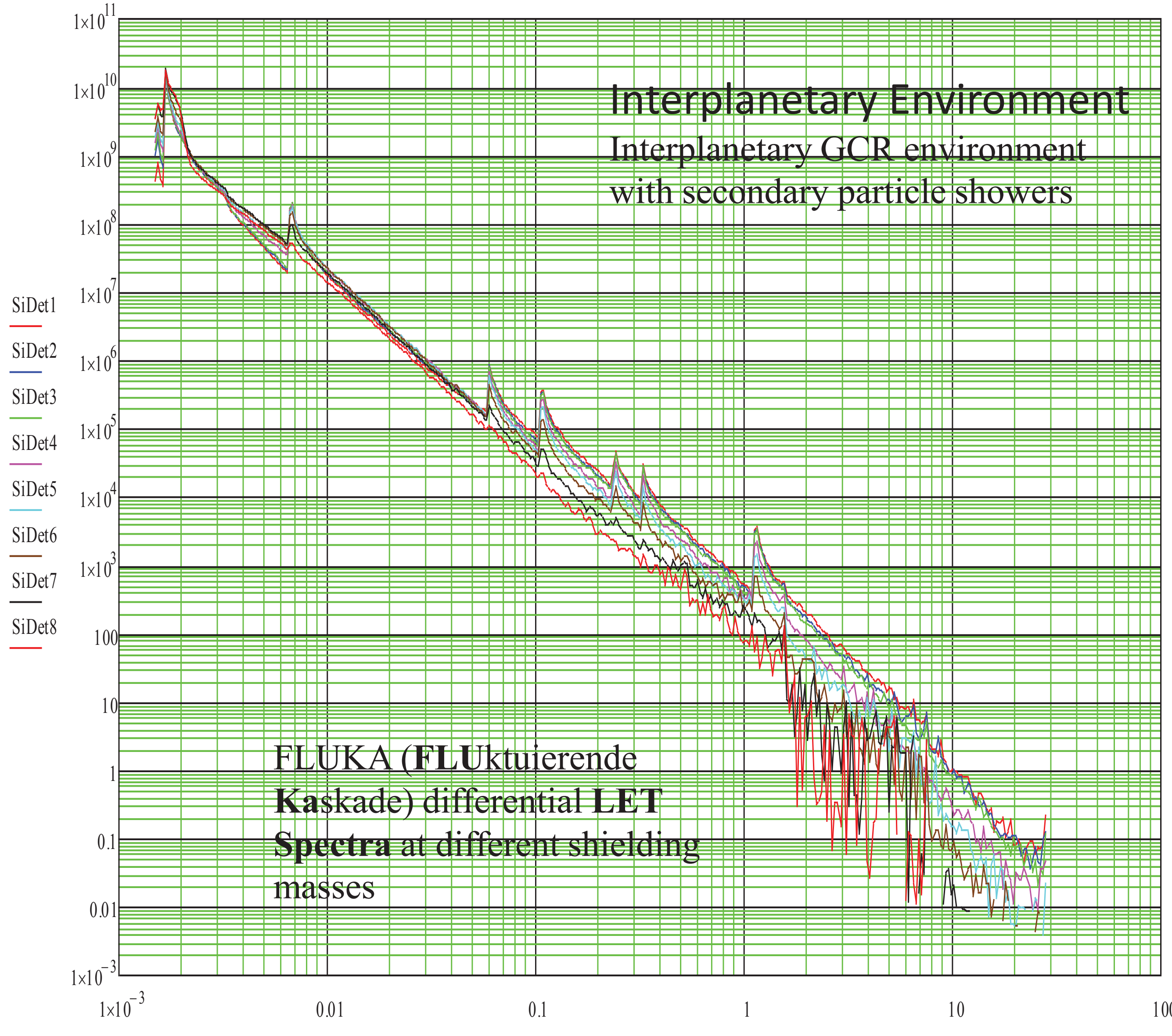
Detector Si Shell	SiDet1	SiDet2	SiDet3	SiDet4	SiDet5	SiDet6	SiDet7	SiDet8
Detector Shell Radius (cm)	5037.4	5037.3	5037.1	5035.6	5033.7	5030.0	5018.9	5000.0
Si Detector Median Al Shielding Mass in g/cm^2	0.15	0.81	1.6	7.9	15.6	31.1	77.5	156.2

1.3 GCR Exposure Environments: Interplanetary Environment – Primary CR and secondary particle showers

The differential LET spectra [#/(cm^2 week LET)] at various shielding depths in a concentric spherical shell model spacecraft is shown to the right.

LET spectra are calculated, using the FLUKA (1) 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 utilized in a fully three dimensional calculation. Total ionizing dose and nuclear reactions "star" density is also calculated but not reported here.



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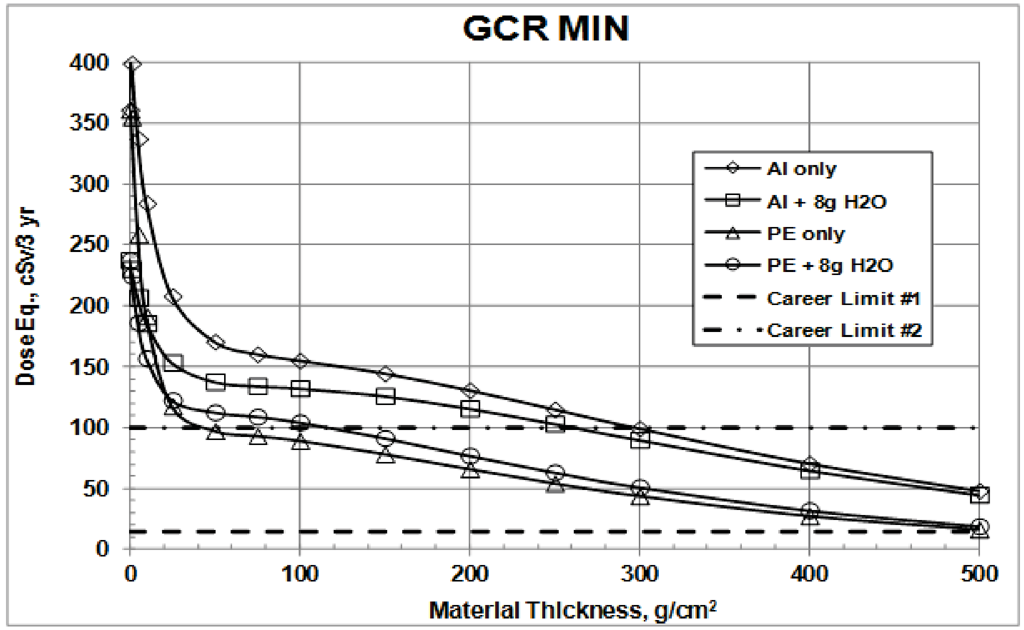
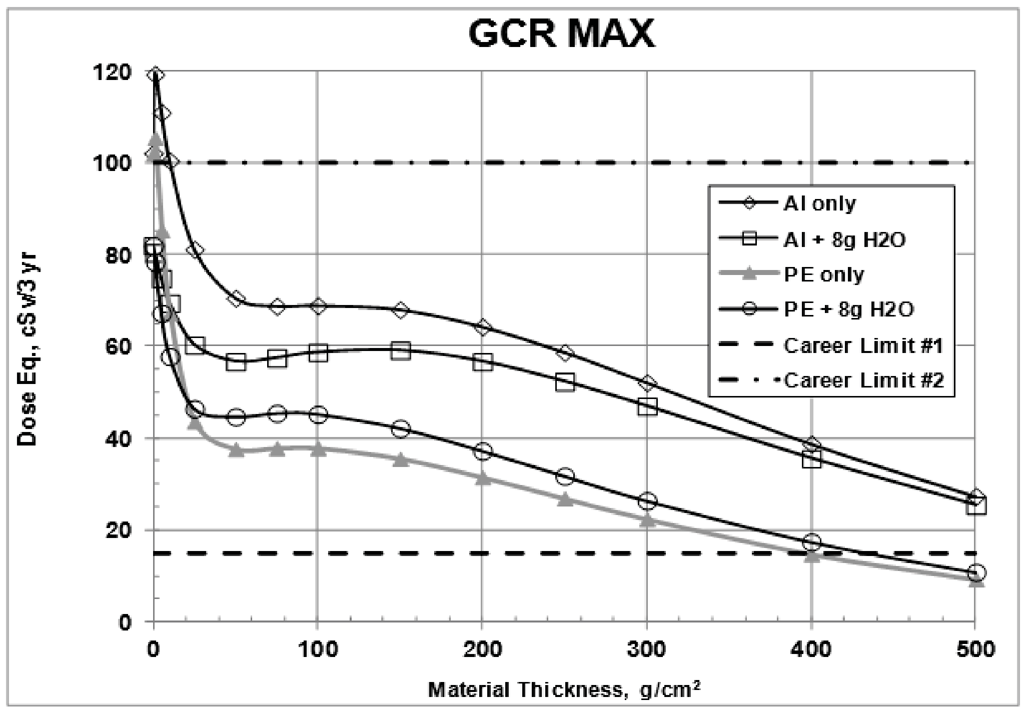
Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011

NASA HZETRN 2010 estimates of crew dose vs. shielding mass for a 3 year interplanetary mission assuming solar Maximum and solar minimum GCR environments and no SEP event contributions and both the 10 and 100 cSv career dose limits.





Biological Effects of Cosmic Radiation – Manned Space Flight Environments

GUIDELINES

- **Code of Federal Regulations**
- **Crew & Area Dosimetry**
- **ALARA – "As Low As Reasonably Achievable"**
- **NASA Flight Rules, e.g., No EVAs in South Atlantic Anomaly**
- **Crew annual and career dose limits**

CREW DOSE LIMITS

Dose limits (cGy-Eq.) for short-term or career non-cancer effects*

Organ	30-Day Limit	1-Year Limit	Career
Eye (Lens)	100	200	400
Skin	150	300	600
BFO	25	50	---
Heart	25	50	100
CNS	50	100	150

BFO – BLOOD-FORMING ORGAN
CNS – CENTRAL NERVOUS SYSTEM
cGy-Eq. (centi Gray-Equivalent ≅ cSv (centi Sievert)

*NASA STD 3000 (1994) & NCRP Report No. 132 (2000)

-Based on a limit of 3% radiation exposure induced (premature) death (REID) with 95 % confidence level (Code of Federal Regulations)
-Also, the new Crew Exploration Vehicle (CEV) design objective is 150 mSv per year, down from historical 500 mSv per year as driven by uncertainty in the dose-REID relationship in the primary CR dominated space radiation environment