The Radiation Environment in Space

"My God, space is radioactive!"

1958…. A quote attributed to Ernie Ray, a protégé of van Allen, discoverer of the radiation belts surrounding the earth.

The problem is serious.

- Over the past 20 years, on average one to two satellites per year experience a partial or total mission loss directly attributed to radiation effects on electrical components.

- Low altitude orbits are protected by the earth's magnetic field, but higher earth orbits, or missions to the Moon or to Mars experience significant radiation environments.

- In the novel, *Space,* by James Michener, two astronauts on the Moon receive a lethal dose of radiation from a solar storm. The scenario is accurate.

- The fictional doses described by Michener are extreme, but are based on the great solar storm of August 4, 1972.

- There were Apollo lunar landings in April 1972 and in December 1972. Had this storm happened 4 months earlier or later, astronauts in the lunar module would have been exposed to a radiation dose over a 12 hour period that would have caused acute radiation sickness and possibly even death.

Current NASA research programs supporting the International Space Station (ISS) and a possible manned mission to Mars focus on two aspects involving radiation:

- Understanding the biological effects of the types of radiation present in space

- Designing adequate shielding to protect astronauts from this radiation environment.

Cosmic Radiation

Early History

- It was noted by several investigators that electroscopes would remain slightly ionized. This effect could be reduced with lead blocks (implying an external radiation source).

- The radiation was more penetrating than radium in the walls.

- Also seen atop the Eiffel tower (too high for radium effects). Lead to the assumption that the source was in the atmosphere.

- Balloon experiments showed that the radiation intensity increased with altitude (thus not a terrestrial radiation).

- Millikan coined the term "cosmic rays" in 1925. [First American-born scientist to win the Nobel prize in physics.]

- In the 1930s and 1940s correlations of global electromagnetic disturbances were made with solar activity. Simultaneous effects at both poles.

- Early astronauts reported visual phenomena ("stars" or "streaks" or "tadpoles"), usually in one eye only and only seen by one astronaut at a time.

- This was investigated by accelerating high Z particles in an accelerator and looking! Conclusion: cosmic rays interacting with the retina.

Sources of radiation in space

The two principle types of radiation are galactic cosmic rays (GCR) and radiation emanating from the Sun. The particle energies and types vary widely. The earth's magnetic field and spacecraft shielding greatly affect the energies. The biological effect is a combination of the primary particles and the secondary particles.

Galactic Cosmic Rays

- The major components are energetic protons and heavier ions with ~ 2% electrons and positrons.
- The abundance drops as the atomic number increases, but **peaks again at iron**, sharply decreasing after that.

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Figure 2.1 in [SSB-Crew Hazards]. Commission on Physical Sciences, Mathematics, and Applications, Space Studies Board (SSB). *Radiation Hazards to Crews of Interplanetary Missions: Biological Issues and Research Strategies.* Washington DC: National Academies Press, 1996.
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- The source of the GCRs is not known, but it is outside of our solar system.
- The direction is isotropic.
- There is a broad energy distribution with a peak at about 1 GeV/nucleon.
- The fluence is relatively constant over time.
- The GCR fluence can be affected by solar events, decreasing by as much as a factor of 10 due to the effects of the solar event on the interplanetary magnetic field.

The Sun

- Our Sun produces a constant flux of low energy particles, mostly protons, known as the **solar wind**.

- The major radiation hazard is not associated with the solar wind but occurs when the sun experiences magnetic storms, which cause solar flares or coronal mass ejections (CMEs).

- These solar particle events (SPEs) create primarily very high-energy protons as well as other heavier particles.

- These solar events greatly deform the earth's magnetic field, cause disruption of communications on the earth, and represent a potentially lethal radiation hazard for astronauts in space.

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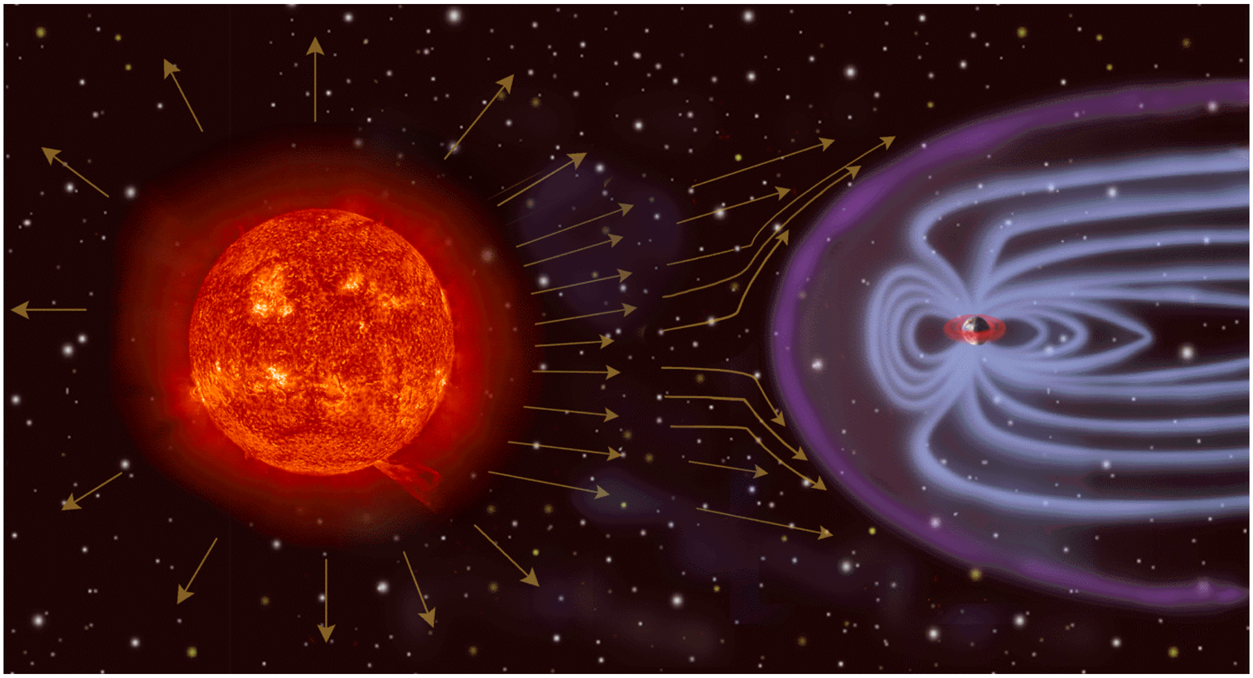
Figure 1.1 in [SSB-Space Station]. Commission on Physical Sciences, Mathematics, and Applications, Space Studies Board (SSB). *Radiation and the International Space Station: Recommendations to Reduce Risk.* Washington DC: National Academies Press, 2000. See http://books.nap.edu/books/0309068851/html/8.html#page_top.

- The earths's magnetic field interacts with the solar wind, SPEs and the GCRs.
- Charged particles are trapped in zones known as the van Allen radiation belts.
- Where the field lines are "open" at high latitudes, particles can penetrate to the upper atmosphere or to the surface.

Space weather: the solar wind



Source: NASA. “Living in the Atmosphere of the Sun.” [updated 20 Jan 2000, cited 29 March 2004.] http://www-istp.gsfc.nasa.gov/exhibit/main.html

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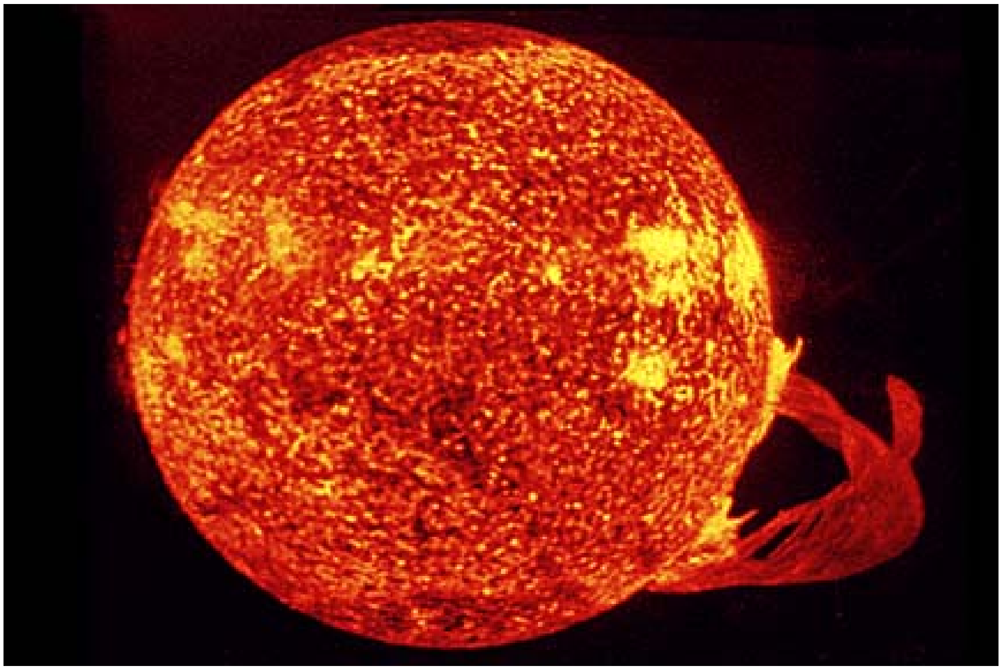
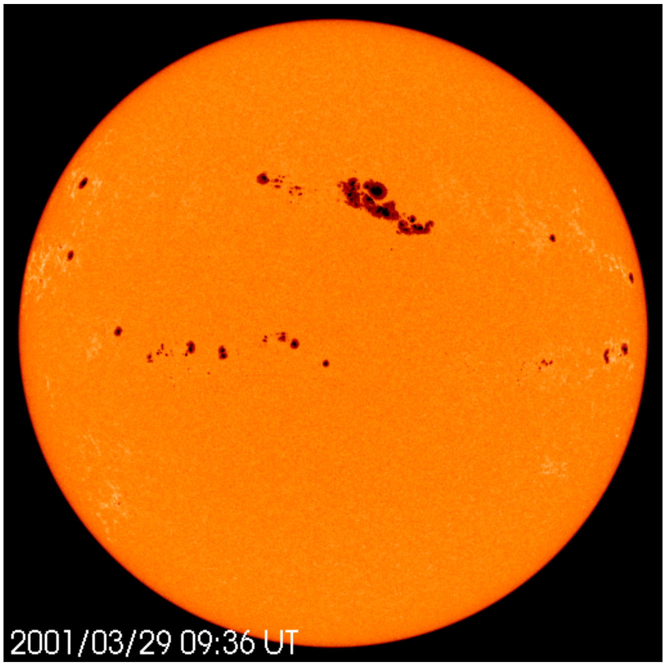


Source: 1996 Skylab photo from NASA. "Our Magnificent Sun." [cited 29 March 2004]
http://cossc.gsfc.nasa.gov/images/epo/gallery/solar/

Solar flares are associated with the production of high-energy particles, mostly protons, which pose a significant radiation risk to astronauts.



Source: NASA Goddard Space Flight Center . [updated 30 March 01, cited 29 March 2004.]
http://www.gsfc.nasa.gov/gsfc/spacesci/solarexp/sunspot.htm

Sunspots have been observed for centuries. The numbers of spots and the distribution vary greatly. Sunspot numbers have been shown to vary in an 11-year cycle.

The solar cycle

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- Temporal variations in the suns activity have been directly observed for about a century.

- Around 1830 an obscure German amateur astronomer, H. Schwabe, began observing sunspots as a hobby. In 1851 he announced a “solar cycle” – the number and positions of sunspots vary in an 11-year cycle.

- A year later it was discovered that terrestrial magnetic compass deviations followed the same cycle.

- A sunspot is a magnetically disturbed area on the surface of the sun that is cooler than its surroundings.

- It appears darker only because its gases, at 4000 - 4500º K, radiate less than the surrounding gas at 5700º K.

- The sunspot cycle occurs because the sun rotates faster at its equator than near its poles. This causes a shearing and twisting of the magnetic field that controls the motion of the solar gas.

- During years of maximum sunspot activity, there is an increased likelihood of solar flares and coronal mass ejections. The relationship between flares, CMEs and sunspots is not understood.

The van Allen Radiation Belts

- Charged particles, trapped in the magnetic field surrounding the Earth are called radiation (or van Allen) belts.

- The **inner** belt, located between about 1.1 and 3.3 Earth radii in the equatorial plane, contains primarily protons with energies exceeding 10 MeV.

- The inner belt is a fairly stable but it is subject to occasional perturbations due to geomagnetic storms, and it varies with the 11-year solar cycle.

- As a result of the offset between the Earth's geographical and magnetic axes, the inner belt reaches a minimum altitude of about 250 km above the Atlantic Ocean off the Brazilian Coast.

- This **South Atlantic Anomaly** occupies a region through which low-orbiting satellites frequently pass. Energetic particles in this region can be a source of problems for the satellites and astronauts.

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- The **outer** belt contains mainly electrons with energies up to 10 MeV. It is produced by injection and energization events following geomagnetic storms, which makes it much more dynamic than the inner belt (it is also subject to day-night variations).

- 'Horns' of the outer belt dip sharply in towards the polar caps. Radiation levels reaching the surface are increased at high latitudes.

The radiation belts are of importance primarily because of the harmful effects of high-energy particle radiation for man and electronics:

- it degrades satellite components, particularly semiconductor and optical devices
- it induces background noise in detectors
- it induces errors in digital circuits
- it induces electrostatic charge-up in insulators

- it is also a threat to the astronauts
- The largest portion of the dose to Apollo astronauts was received when they were passing through the Van Allen belts; dose can be influenced by the trajectory through the belts.

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Figure 1.2 in [SSB-Space Station].
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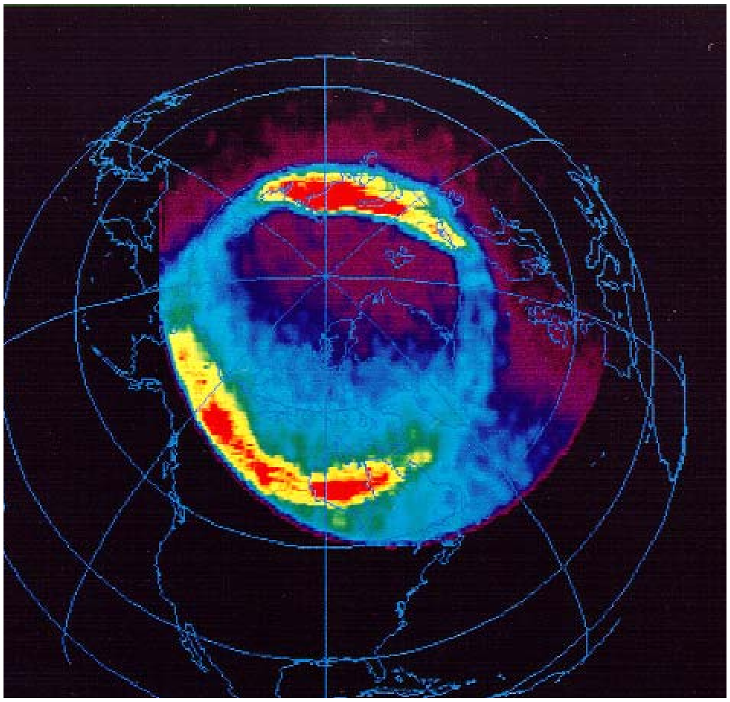
Aurora (Roman goddess of the dawn)

- The solar wind confines Earth's magnetic field to a comet-shaped cavity known as the magnetosphere.
- As the solar wind flows past the magnetosphere, it acts like a cosmic generator, producing millions of amps of electric current.
- Some of this electric current flows into Earth's upper atmosphere which can light up like a neon tube to create the aurora.
- Earth's magnetotail deflects solar wind toward Earth's polar regions.
- An aurora is produced when the energetic charged particles comprising the solar wind collide with neutral gas molecules in the upper atmosphere.
- The electrical discharge occurs about 70 miles above Earth's surface.



Source: NASA. "Space Science Photos: Prior to 1997 [cited 29 March 2004] http://www.gsfc.nasa.gov/indepth/photos_spaceearly.html

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The International Space Station

Radiation exposure will come from

- The earth's radiation belts
- The galactic cosmic rays
- Solar particle events

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Construction, and the associated space walks, taking place now are near the period of maximum solar activity.

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The ISS orbital inclination of 51° is a compromise with the Russians having to do with launch geometries. It also increases radiation exposure.

Violent space weather

- High energy CMEs can produce "shocks".
- The most energetic particles during these events can reach earth in 10 to 100 minutes depending on the path taken along the magnetic field lines.
- Particle fluences can increase by many orders of magnitude in a very short time.
- Astronauts exposed directly risk lethal radiation doses.
- Spacecraft design must include "storm shelters" for protection during such events.
- A network of satellites and ground stations monitor the sun for signs of SPEs.

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Figure 4.1 in [SSB-Space Station].
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A CME can greatly deform the earth's magnetic field, increasing the radiation hazard in space and increasing the background radiation on the earth's surface.

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Monitoring for SPEs

The Apollo experience

- The Apollo missions occurred during solar maximum years, when more SPEs are expected.

- NASA realized that SPEs posed a real hazard, especially for astronauts on the lunar surface or in the LEM.

- A network of ground-based solar observatories was used to give real time warnings to astronauts.

- Solar Particle Alert Network (SPAN): 7 observatories around the world to give 24hr/day coverage of the sun.

- Monitor for solar flares accompanied by radio bursts, which prior research had show precede virtually all SPEs.

- While some relativistic particles could reach the earth and moon within minutes, the highest intensity was expected at 4-6 hours after the flare.

- The plan was to move the astronauts off of the lunar surface and back to the command module, with its better shielding.

- Fortunately this emergency action was never needed.

The biological effects of radiation in space

- NASA has invested considerable research effort into the radiation biology of the particles present in the space environment.

- High energy protons have a biological effectiveness close to 1. The risk from exposure is real, the biological effects are fairly well known.

- Even though the fluence is low compared to protons, the high-energy, high z, (HZE) particles represent the greatest uncertainty, and may present the greatest risk.

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Particle penetration

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Outside the earth's magnetic field, the fluence rates of the GCR at maximum (during the solar minimum) are approximately

- 4 protons/cm^2/sec
- 0.4 helium ions/cm^2/sec
- 0.04 HZE particles/cm^2/sec

For a 100 μm^2 nucleus, **each cell nucleus in the body** would be hit by

- a proton once every 3 days
- a helium ion once every month
- a HZE particle once per year (depends greatly on degree of fragmentation as the particle penetrates the spacecraft).

[Curtis and Letaw, 1989, Galactic cosmic rays and cell hit frequencies outside the magnetosphere. Adv. Space Res., 9, 293-298.]

Potentially lethal radiation doses occur during SPEs.

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Figure 2.3 in [SSB-Crew Hazards].
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- Astronauts inside a spacecraft would be shielded enough to survive.

- The real risk is to astronauts outside of the spacecraft during a spacewalk or on the lunar or Martian surface.

"*Radiation Hazards to Crews of Interplanetary Missions*"

National Academy Press, 1996

- Radiation exposure can be reduced by adding shielding.
- Shielding adds weight and cost to space missions.
- The risks must be understood.
- The uncertainties in the risk estimates need to be reduced.

As was the case with radon, the risks of exposure to low fluences of high-LET particles are unknown. The uncertainties are high.

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Biological Effects of Radiation

Early effects

- Radiation sickness
    - occurs within a few hours
    - nausea, vomiting (definitely to be avoided in a spacesuit!)
    - doses: > 1 Sv in less than 1 day
- Acute radiation syndrome
    - Occurs within 2-4 weeks
    - bone marrow suppression; doses 1.5-2.0 Sv
    - lethal doses (whole-body): 10% at 3 Sv; 90% at 4 Sv (with no countermeasures)
- Skin
    - Reddening (erythema) occurs at about 6 Gy
    - 15-20 Gy will cause moist desquamation
- Hair loss
    - (reversible) at doses of ~ 6 Gy or higher

Early effects are unlikely unless an astronaut is exposed to a SPE while in a non-shielded environment.

Late effects are the major concern following exposure to radiation during spaceflights.

- **Cancer**
- **CNS damage**
- **Cataracts**

Cancer

- Most risk estimates based on Japanese atomic bomb survivors, acute dose of low-LET radiation.
- Animal data for tumor induction following particle data is sparse.
- Human data is non-existent.

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- High LET radiation is more effective in tumor induction in the rat skin.

- For most endpoints (mostly not tumor induction), the RBE reaches a maximum at around 100 keV/µm, then decreases.

- One study on Harderian gland tumors in mice showed high RBE values for tumor induction (30-40) that remained at this level at all LETs studied. [This is troubling to NASA]

Damage to the CNS

- Hits to the nucleus depend on the nuclear diameter

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- Damage from protons can probably be repaired
- HZE effects in the CNS could include
  - Cellular effects, biochemical changes (little data available)
  - Functional effects: **premature aging** has been suggested by irradiation of rats with ^{56}Fe particles.
  - Late effects: breakdown of DNA has been demonstrated in the retina of rabbits. The effect occurred earlier with heavy ions.

Cataract formation

- Threshold dose of 1.5 - 2 Gy for low-LET radiation at high dose rate.
- Data in monkeys irradiated with protons are similar to low-LET radiation.

Radiation Doses

NCRP (1989) Limits for organ dose equivalents (Sv) for low earth orbit exposures

	Blood Forming Organs	Skin	Lens of the eye
Career	**1-4**	**6**	**4**
Annual	**0.5**	**3**	**2**
30 days	**0.25**	**1.5**	**1**

[Average annual background dose to general population is 0.0036 Sv (360 mrem).]

- The Apollo missions lasted from 5-12 days and resulted in crew doses of 160 – 1140 mrad. The largest portion of the dose was received when passing through the van Allen radiation belts.

- Skylab missions lasted from 20 – 90 days and resulted in crew doses of 1.6 – 7.7 rad.

- Doses would be much higher in the event of a solar flare. It has been estimated that the dose from a flare that occurred in July 1959 could have been between 40 – 360 rad.

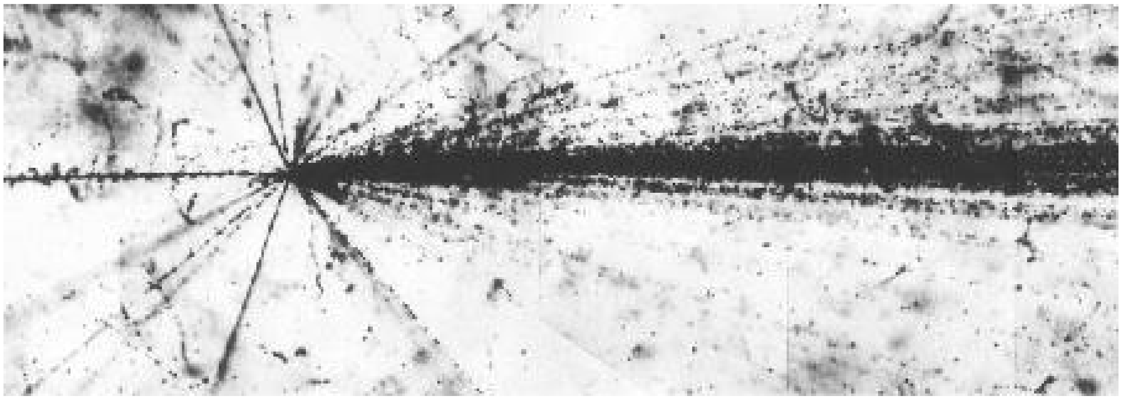
- The highest dose from a Shuttle flight (Hubble repair) was 3.2 cGy (3,221µGy/day).

- MIR cosmonaut exposures ranged from 2.4 to 8.7 cGy (144 to 468 µGy/day).

- The International Space Station has an orbit similar to that of MIR: 51^0 inclination, 400 km altitude (range 370-470 km). The estimated does rate on the ISS ranges from ~0.5 – 2.5 mGy/day.

- For a "fast transit" mission to Mars (6 months out, 1.5 years on the surface, 6 months back) the estimated cumulative dose to the bone marrow ranges from ~60-130 cSv. These doses can exceed the current limit for LEO bone marrow dose of 50cSv/year.

Shielding can actually make matters worse



Source: NASA. "Cosmic Rays." [updated 25 Nov 2001, cited 29 March 2004]
http://www-istp.gsfc.nasa.gov/Education/wcosray.html

Track structure of a cosmic ray collision in a nuclear emulsion

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