Chapter 4

COSMIC AND SPACE RADIATION

7/19/2018

4.1 INTRODUCTION

Even though we do not feel or see them, our bodies on Earth are bombarded every moment of the day and night by cosmic rays and their interaction products coming to us from the depth of space. These particles contribute to the natural radiation environment that living creatures on Earth are subjected to.

It is also important to study the effects of space radiation in space missions from the perspective of its effects on living organisms such as astronauts in orbiting space stations, or in bases on the moon or Mars, as well as the materials used in the space environment particularly the shielding materials and the electronic and life support equipment.

Figure 1. Astronaut Harrison H. Schmitt in the Apollo 17 mission on the moon, December 19, 1972.

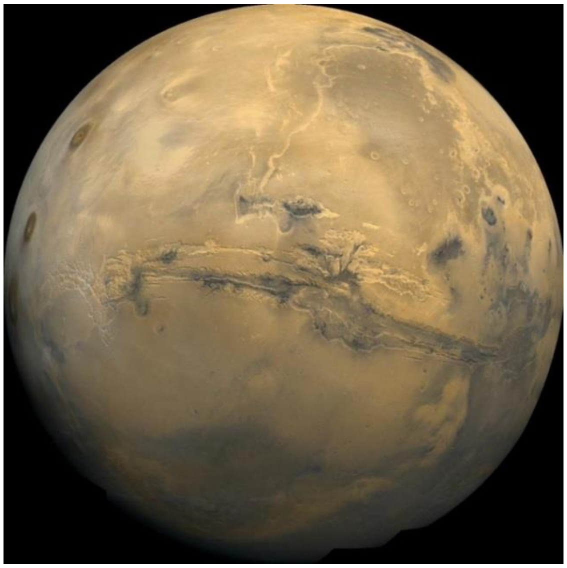

Figure 2. Mars, possible site of a future manned space mission. Source: NASA.

Two forms of radiation are encountered on space missions:

1. Galactic Cosmic Rays (GCRs) are particles caused by supernova explosions and other high-energy events outside the solar system.
2. Solar Energetic Particles (SEPs) which are are associated with the solar flares and coronal mass ejections from the sun.

Current spacecraft shield much more effectively against the SEPs than the GCRs. To protect against the low energy of typical SEPs, astronauts will need to move into shielded enclosures with extra shielding on a spacecraft or on the Martian surface. GCRs tend to be highly energetic, highly penetrating particles that can propagate unaffected through the structure or decay into secondary particles that are not stopped by the modest shielding provided by existing typical spacecraft [7].

Space is characterized by the presence of high energy particles. A typical high energy particle of radiation found in the space environment is ionized all by itself. As it passes through material such as human tissue it also disrupts the electronic clouds of the constituent molecules and leaves a path of ionization in its wake. These particles are either singly charged protons or more highly charged nuclei called "HZE" particles. Here Z is the symbol for nuclear charge and the disruption caused is proportional to Z^2. Thus a particle with <u>H</u>igh <u>Z</u> and high <u>E</u>nergy is called an HZE particle.

Particles encountered in space commonly have enough energy to disrupt the nucleus of target atoms and these collisions can cause nuclear reactions which generate new and potentially more damaging particles. The possible occurrence of nuclear reactions makes the analysis of ionizing radiation collisions difficult.

4.2 COSMIC RADIATION

Since their discovery, there has been a lot of hypotheses about the origin and the process of generation of cosmic rays. They span the two areas of astronomy on a large scale, and particle physics, on a small scale.

Most of the important knowledge in subatomic particle physics originated in the field of cosmic rays studies. In 1932, the first antimatter particle, the positron, was identified in the products of cosmic ray impacts. The muon and the pion were discovered a few years later. The cloud chamber detection device was invented in 1896 by Charles T. R. Wilson (Fig. 3).

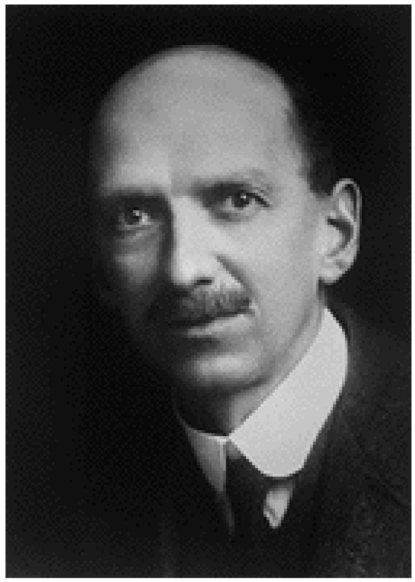

Figure 3. Charles T. R. Wilson invented the cloud chamber in 1896.

It depends on the use of a saturated vapor or liquid under its saturation pressure. Charged particles generate tracks in them similar to the condensation trails or “contrails” caused by airplanes in the atmosphere. Figure 4 shows a cloud chamber photograph of a nuclear disintegration resulting from a cosmic ray collision.

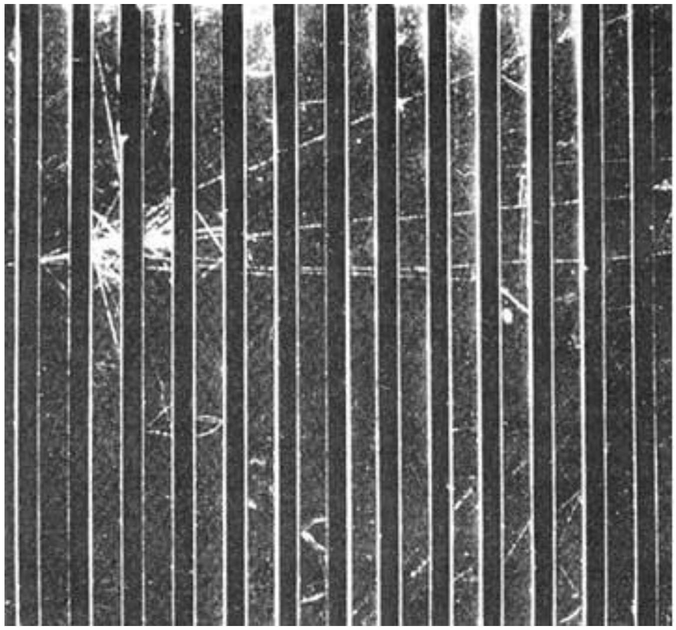

Figure 4. Cloud chamber photograph of a nuclear disintegration resulting from a cosmic ray collision.

Cosmic rays are exotic types of subatomic particles that are beyond the production capabilities of our most powerful particle accelerators. Their study elucidates crucial details about the objects and the processes that generated them, which is also beyond the capabilities of optical telescopes. Black holes neutron stars, supernovae and quasars may all have roles in their generation.

Primary cosmic ray nuclei have spent a long time in the millions of years scale reaching the Earth. During their travel, they traverse about an areal density or the product of density-thickness product of:

$$\rho.x = 3\,[\frac{gm}{cm^2}]$$

of matter. This is equivalent to a thickness of 3 cms of water with a density of 1 gm/cm^3, or a thickness of iron of 0.37 cms at a density of 8.1 gm/cm^3. They arrive at the Earth in an isotropic distribution. They appear to have existed in the same numbers for longer than a billion years.

Nowadays, cosmic radiation is thought to originate from other parts of our Milky Way Galaxy. Some of the cosmic rays come to us from the sun. These have low energies at best up to hundreds of GeVs. This radiation reaches all parts of the Earth's surface. They are more intense at higher altitudes, but are very penetrating and persist in deep caves and mines.

Figure 5. Black hole thought to exist at the center of the Milky Way Galaxy.

Active galaxies and the black holes (Fig. 5) that power them are thought to be the prime sites for the accelerating the highest energy cosmic rays. It is surmised that a black hole exists at the center of the Milky Way galaxy. These highly accelerated particles interact with some nuclei in the atmosphere to produce cosmic ray showers.

Astronauts and aircraft crews and passengers are exposed to significantly higher amounts of radiation than people on the ground. The latter have the protection of the atmosphere to attenuate the particles resulting from the showers. At least one airline, Lufthansa, bars its female flight attendants from flying when they are pregnant to avoid the radiation effects on the growing fetuses.

4.3 COSMIC RAY PARTICLES

The major components of a cosmic ray extensive air shower includes pions (π^+, π^-, π^0) and kaons (κ^+, κ^-), that are produced in the initial interaction with an atmospheric nucleus. Protons and neutrons are also produced. Charged pions may decay to produce muons (μ) and neutrinos (ν). The electromagnetic cascade of negatrons (negative electrons) (e^-), positrons (e^+), gamma rays (γ) is initiated by the decay of a neutral pion (π^0).

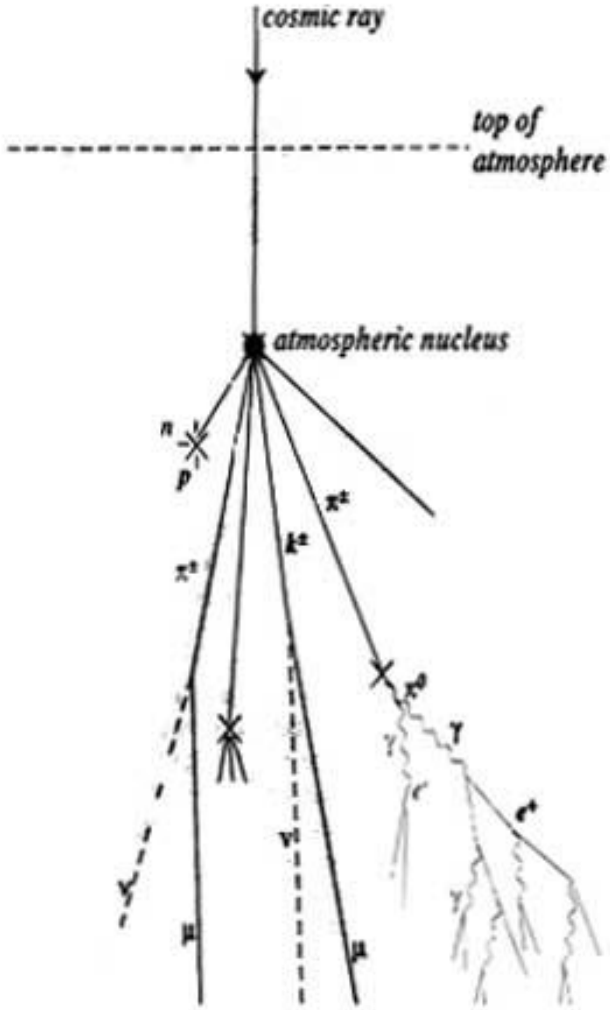

Figure 6. Components of a cosmic ray shower in the atmosphere.

Some large showers would reach the lower atmosphere with an intensity I = 1 million (10^6) particles with an energy of E = 10 MeV on the average each. These particles would have been attenuated in the atmosphere by a factor f = 100. Thus the initial energy E_0 in the particle initiating the shower would be:

$$\begin{aligned} E_0 &= I.E.f \\ &= 10^6 \text{ particles} \times 10 \left(\frac{\text{MeV}}{\text{particle}}\right) \times 100 \times 10^6 \left(\frac{\text{eV}}{\text{MeV}}\right) \\ &= 10^{15} \text{ eV} \\ &= 10^6 \text{ [GeV]}. \end{aligned} \tag{1}$$

Table 1. Table of the Subatomic Particles.

Family	Symbol	Name	Electric Charge	Mass (MeV)	Half Life (seconds)	Common Decay Products	Antiparticle
HADRONS							
Baryons (Strongly Interacting Fermions) Spin= half integral	p	proton nucleon	+e	938.26	stable		*p antiproton
	n	neutron nucleon	0	939.55	stable (in nucleus) 7x 10^2 (free state)	p, e, $^*\nu_e$	*n antineutron
	λ	lambda hyperon		1,115.6	$1.7x10^{-10}$	p, π^- p, π^0	$^*\lambda$ antilambda
	Σ^+	sigma plus hyperon	+e	1,189.4	0.6 10^{-10}	p, π^0 n, π^+	$^*\Sigma^-$ anti sigma minus
	Σ^0	sigma zero hyperon	0	1,192.5	< 10^{-14}	λ + radiation	$^*\Sigma^0$ anti sigma zero
	Σ^-	sigma minus hyperon	-e	1,197.3	$1.2x10^{-10}$	n, π^-	$^*\Sigma^+$ anti sigma plus
	Ξ^-	xi minus cascade hyperon	-e	1,321.2	$0.9x10^{-10}$	λ, π^-	$^*\Xi^+$ anti xi plus
	Ξ^0	xi zero cascade hyperon	0	1,314.7	$1.0x10^{-10}$	λ, π^0	$^*\Xi^-$ anti xi zero
Mesons (Strongly Interacting Bo Spin = 0	π^+	pion	+e	139.6	$1.8x10^{-8}$	μ^+, ν_μ	π^- pi minus
	π^-	pi minus	-e	139.6	$1.8x10^{-16}$	μ^-, $^*\nu_\mu$	π^+ pi plus
	π^0	pi zero	0	135.0	$0.7x10^{-8}$	radiation	π^0 pi zero
	κ^+	kaon	+e	493.8	$0.8x10^{-8}$	μ^+, ν_μ ,π^+, π^-	κ^- K minus
	κ^-	k minus	-e	493.8	$0.8x10^{-8}$	μ^-, $^*\nu_\mu$,π^-, π^0	κ^+ K plus
	κ^0	k zero	0	497.8	$0.7x10^{-10}$ (fast mode) $4x10^{-8}$ (slow mode)	$\pi^+\pi^-$, $2\pi^0$ 3 π^0, $\pi^+\pi^-\pi^0$ π^+ μ^- $^*\nu_\mu$, π^+ $e^*\nu$ π^- $\mu^+\nu_\mu$, π^- $e^{+*}\nu$	$^*\kappa^0$ anti K zero
	* κ^0	anti K zero	0	497.8	$0.7x10^{-10}$ (fast mode) $4x10^{-8}$ (slow mode)	$\pi^+\pi^-$, $2\pi^0$ 3 π^0, $\pi^+\pi^-\pi^0$ π^+ μ^- $^*\nu_\mu$, π^+ $e^*\nu$ π^- $\mu^+\nu_\mu$, π^- $e^{+*}\nu$	κ^0 K zero
	ω	omega	0	782.852	6.6 x 10^{-23}		ω
	J or Ψ	J particle	0	3,096.66	1.0 10^{-10}		J or Ψ
	η	eta	0	548.8	< 10^{-16}	3 π^0. $\pi^0\pi^+\pi^-$ $\pi^+\pi^+$ + radiatio radiation	η eta
ELEMENTA PARTICLES							
Massless Bosons, Classons Spin = 1 ħ	γ	photon	0	0	stable		(γ)
Spin = 2 ħ	g	graviton	0	0	stable		(g)
Leptons (Weakly Interacting Fermions) Spin=1/2 ħ	μ^-or μ^+	muon	-e	105.7	2.2 x 10^{-6}	e, ν_μ , $^*\nu_\mu$	μ^+or μ^-
	τ or τ^-	tau particles	-e		3.0 x 10^{-13}		
	ν_τ	tau neutrino		about 0	stable (?)		
	e^-	electron	-e	0.511	stable		e^+ positron
	ν_e	neutrino-electron	0	0	stable		$^*\nu_e$ antineutrino
	ν_μ	neutrino-muon	0	0	stable		$^*\nu_\mu$ mu antineutrino
	ν_τ	neutrino-tau	0	0	stable		$^*\nu_\tau$

							tau antineutrino
Quarks	u	up	+2/3 e	310.177	stable		*u
	d	down	-1/3 e	310.177	stable		*d
	c	charm	+2/3 e	1,481.9	?		*c
	s	strange	-1/3 e	504.868	?		*s
	t	top	+2/3 e	>51100	?		*t
	b	bottom	-1/3 e	5,110	?		*b
Weakons	W^-	W particle	-e	81,760	?		W^+
	Z	Z particle	0	91,980	?		Z
Wimps (Weakly Interacting Massive Parti	N	Neutralino (Dark Matter)	-	-	?		-

For comparison, the energy of photons in optical astronomy is of the order of 1 eV, or one thousand million million times less in energy. Figure 6 shows the components of a cosmic ray shower. Table 1 shows some of the cosmic ray particles.

The energy of cosmic rays extends to at least up to 10^{20} eV. Their numbers vary inversely as an almost constant power of the energy above 10^9 eV. Below this energy, the differential intensity continues toward lower energies until the galactic cosmic rays become indistinguishable from the solar cosmic rays.

The energy density generated by cosmic rays is about 10^{-12} [ergs/cm$^{3]}$. The source must be producing individual particles with energies a billion times more energetic than that of our most powerful particle accelerators. An extremely large amount of total energy must also be generated depending upon the size of the volume over which this energy density extends.

4.4 ISOTOPES PRODUCED BY COSMIC RAYS

The neutrons generated by cosmic ray showers are slowed down in the atmosphere to the same temperature as other molecules. At this slow energy they are easily captured in the nuclei in the atmosphere leading to the generation of various isotopes. For instance they are captured by the nitrogen nuclei forming radioactive carbon^{14} , according to the reaction:

$$_7N^{14} + {_0n^1} \rightarrow {_6C^{14}} + {_1H^1} \tag{2}$$

They are also captured by deuteron nuclei to form tritium, according to the reaction:

$$_1D^2 + {_0n^1} \rightarrow {_1T^3} + \gamma \tag{3}$$

A list of other isotopes produced by cosmic rays is shown in Table 2.

4.5 ACTIVITY UNITS

The activity unit measures the rate of nuclear transformations per unit time in a radioactive sample. The activity in one gram of the isotope Radium^{226} is used to set the conventional unit of activity in the conventional system of units as the Curie (Ci) honoring Madame Marie Curie, the discoverer of radium, as:

$$1 \text{ Curie (Ci)} = 3.7\text{x}10^{10}[\frac{\text{transformations}}{\text{sec}}] \tag{4}$$

In the Système International (SI) system of units, the Becquerel (Bq), honors Henri Becquerel, the discoverer of radioactivity where:

$$1 \text{ Becquerel (Bq)} = 1\ [\frac{\text{transformation}}{\text{sec}}] \tag{5}$$

4.6 CARBON DATING

The external exposure from these isotopes is not significant since their radiations are not penetrating. In the form of a gas such as carbon dioxide, these can be inhaled or ingested and can be dangerous in large amounts.

This is the basis of the Carbon Dating methodology. The production of carbon^{14} with a half life of 5,730 years is an ongoing nuclear transformation from the cosmic rays bombardment of nitrogen^{14} in the Earth's atmosphere. The atmospheric radiocarbon exists as $C^{14}O_2$ and is inhaled by all fauna and flora. Because only living plants and animals continue to incorporate C^{14}, and stop incorporating it after death, it is possible to determine the age of organic archaeological artifacts by measuring the specific activity or activity per unit mass, of the carbon present in it $A'(t)$. The equilibrium specific activity A'_∞ of C^{14} in carbon has been constant, except for fluctuations at the times of solar events, at about 15 [disintegrations/(minute.gram)].

In the radioactive decay law:

$$\begin{aligned} A'(t) &= A'_\infty e^{-\lambda . t} \\ &= A'_\infty e^{-\frac{\ln 2}{T_{1/2}}.t} \end{aligned} \tag{6}$$

Taking the natural logarithm of both sides, and solving for the time t, we get:

$$t = -\frac{T_{1/2}}{\ln 2} \ln \frac{A'(t)}{A'_\infty} \tag{7}$$

Substituting for the known value of the half-life and the equilibrium specific activity, we get

$$\begin{aligned} t &= -\frac{5,730}{0.6931} \ln \frac{A'(t)}{15} \\ &= -\,8.267 \times 10^3 \ln \frac{A'(t)}{15} [\mathit{years}] \end{aligned} \tag{8}$$

Upon measuring the activity of the archaeological sample, A(t), and determining its weight g, one can calculate its specific activity as:

$$A^{'}(t) = \frac{A(t)}{g}\left[\frac{\text{Transformations}}{\text{min.gm}}\right] \qquad (9)$$

By substitution of the measured value of the sample's specific activity from Eqn. 9 into Eqn. 8, one can then determine its archaeological age t in years.

Table 2. Some Radioactive Isotopes produced in the atmosphere by neutrons from cosmic rays.

Isotope	Half life	Activity density in the lower troposphere, [dis / (min.m^3)]
Tritium, $_1T^3$	12.3 years	10
Beryllium^7	53 days	1
Beryllium^{10}	2.7 x 10^6 years	10^{-7}
Carbon^{14}	5,760 years	4
Sodium^{22}	2.6 years	10^{-4}
Silicon^{32}	700 years	2.0x10^{-6}
Phosphorous^{32}	14.3 days	2.0x10^{-2}
Phosphorous^{33}	25 days	1.5x10^{-2}
Sulfur^{35}	87 days	1.5x10^{-2}
Chlorine^{36}	0.3 x 10^6 years	3.0x10^{-6}

4.7 RADIATION ABSORBED DOSE UNIT

The short term effects of radiation are measured in terms of the radiation absorbed dose (rad) unit. The rad unit is used here to express the yearly dose ion the conventional system of units. It corresponds to the absorption of 100 ergs of energy per gram of absorbing material:

$$1 \text{ rad (radiation absorbed dose)} = 100 \left[\frac{\text{ergs}}{\text{gm}}\right] \qquad (10)$$

In the Système International (SI) system of units, the Gray unit is used where:

$$1 \text{ Gy (Gray)} = 100 \text{ rad} \qquad (11)$$

The Gray unit honors Louis Gray (1905-1965), a radiation pioneer. The following relationship is commonly use:

$$1 \text{ rad} = 1 \text{ cGy} = 1 \text{ centiGray} \qquad (12)$$

Figure 7. Louis Gray, radiation pioneer (1905-1965).

4.8 DOSE RATES FROM COSMIC AND ENVIRONMENTAL RADIATION

Life on earth has always been affected by radiation. It is postulated that radiation has resulted in the mutations that led the myriad of plant and animal forms on Earth. Will the genetic effects of radiation affect the future evolution of Homo Sapiens? We can say with certainty that it will in the future as it did in the past. By adding human knowledge, one hopes that the changes will be for the better.

Space travel and colonization will definitely be affected from the ability of the human race in conjunction with other forms of life to survive in the harsh space radiation environment. The dose rates from external and internal natural radiation sources are listed in Table 3.

Table 3. Dose Rates from External and Internal Sources of Natural Radiation.

Source	Yearly Dose [mrad/year]	Yearly Dose [mGy/year]
External Sources		
Cosmic Rays at sea level		
Ionizing component	28	0.28
Neutrons	0.7	0.007
Terrestrial Radiation	50	0.50
Cosmic Rays at 20,000 feet	1,500	15
Cosmic Rays near the top of the atmosphere	30	0.30
Internal Body Radiation		
Potassium^{40}	20	0.20

Rubidium^{87}	0.3	0.003
Carbon^{14}	1	0.01
Radium^{226}, Radium^{228}	1	0.01
Tritium^{3}	2	0.02
Average Total dose to body	100	1

We are continuously being bombarded with solar neutrinos. These penetrate matter so easily that their intensity on the shadow side of the Earth is still 90 percent of their intensity on the sun side.

Extraterrestrial radiation has a component which consists of *strange* particles resulting from catastrophic high energy collisions. These are very short-lived particles that decay more slowly than they are formed, indicating that the production process and decay process result from different fundamental reactions. They include the k-mesons and hyperons. Radiobiologists are interested in the effects of such high energy interactions. An inventory has to be taken before estimating the exposure from them.

4.9 DAMAGE TO LIVING ORGANISMS

The basic unit of the living organism is the cell. Within the cell, the deoxyribonucleic acid (DNA) molecules contain the information required for the synthesis of intracellular proteins, for cell reproduction and for organization of the tissues and organs. The diameter of a cell is typically of the order of 1/1,000 inch. Inside the cell's nucleus, the DNA is tightly wound into a tiny double helix forming the chromosomes, thousands of times smaller than the cell.

Passage of ionizing radiation can result in direct effect on the DNA leading to Single Strand Breaks (SSB), Double Strand Breaks (DSB), associated Base Damage (BD), or clusters of these damage types.

The initial damage caused by the HZE particles at the cell level and to the tissue is unique compared to the damage caused by the terrestrial radiation such as x-rays or gamma rays. Because of their high ionization density, HZE particles can also cause clusters of damage where many molecular bonds are broken in the tissue along their trajectory.

The cell's ability to repair DNA damage becomes impaired as the severity of clustering increases leading to DNA deletions and other forms of mutations. The long range of the HZE's allows for the potential damage along a long column of cells in tissue. Since HZE particles are rare on Earth, the prediction of biological risks to humans in space must rely on fundamental knowledge gathered from continuing biological and medical space research.

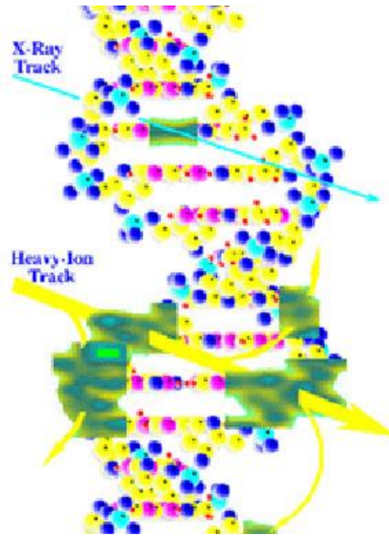

Figure 8. Comparison of effect of an x-ray photon and a heavy ion on the DNA molecule.

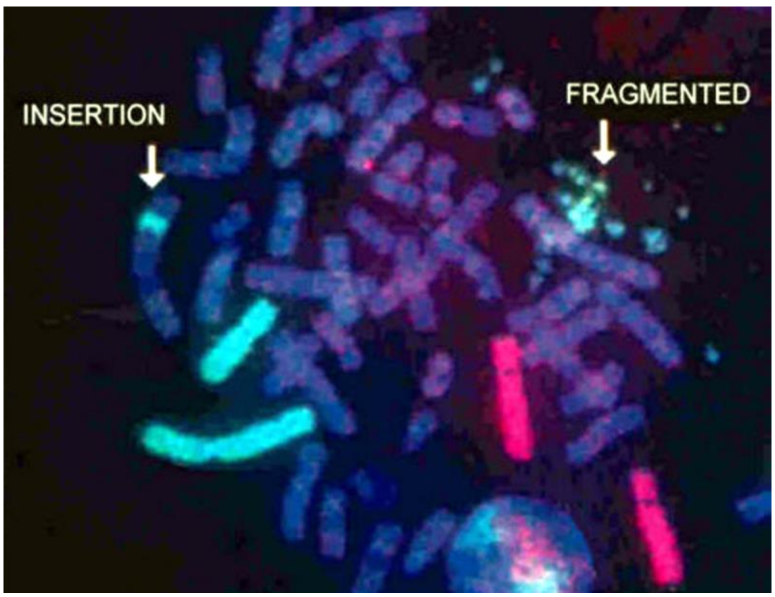

Figure 9. Damaged metaphase chromosome number 2, following a space flight.

4.10 SHIELDING AGAINST SPACE RADIATION

Space is a harsh radiation environment. Astronauts cannot be totally shielded from this potentially harmful radiation.

Shielding provided by the typically-available structural aluminum skin on a spacecraft around 5 mm in thickness, is significant, but it provides very little reduction in the number of energetic ionizing particles.

In addition, the shielding itself produces secondary particles and radiation such as neutrons and other energetic particles which pose an additional hazard. The amount of aluminum shielding required to eliminate the currently-perceived risk from these heavy ions would produce a spacecraft so heavy that it could never be launched. And, even if this were done, astronauts working outside the spacecraft would still be exposed to space radiation, especially if a solar event occurred.

The long term effects of radiation are measured in terms of the effective dose previously known as the dose equivalent unit. In the conventional system of units the effective dose unit is the radiation equivalent man or rem unit;

$$1 \text{ rem (radiation equivalent man)} = 1 \text{ Q.rad} \left[\frac{\text{ergs}}{\text{gm}}\right] \tag{13}$$

where Q : radiation quality factor.

The quality factor accounts for the long term or chronic effects of different types of radiation on living tissue.

In the Système International (SI) system of units, the Sievert unit is used for the effective dose or dose equivalent, where:

$$1 \text{ Sv (Sievert)} = 100 \text{ rem} \tag{14}$$

The following relationship is in common use:

$$1 \text{ rem} = 1 \text{ cSv} = 1 \text{ centiSievert} \tag{15}$$

The six months effective dose rate (dose equivalent rate) for astronauts in the International Space Station (ISS) is shown in Fig. 10 to be around 0.45 [mSv/day]. In a space mission to Mars, it would be three times as much at about 1.3 [mSv/day]. It is clear that special consideration must be given to the shielding and location of the dwellings of any space mission to Mars or for a lunar base.

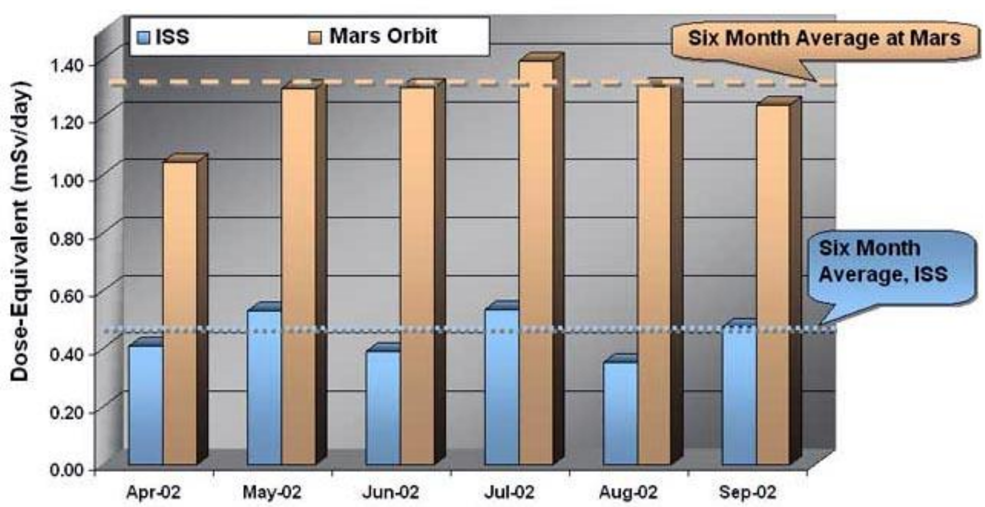

Figure 10. Comparison of effective dose rate or dose equivalent rate for a six months mission in International Space Station (ISS) and in a Mars orbit.

Hydrogen rich compounds such as polyethelyne and water are much more effective than aluminum as shielding materials and are being considered for spacecraft use. In fact, water, which must be on board for consumption anyway may have a secondary use as shielding in the future.

Estimating the risk in any given situation including orbital inclination and altitude if in Earth orbit, and the type of shielding, current state of the solar wind is the real challenge. NASA's plan is reduce the uncertainty of long-term risk to 300 percent.

The overall uncertainty in the risk to humans due to ionizing radiation in space can be attributed to three broad categories:

1. Uncertainty in the characterization of the radiation itself in terms of energy and types and possible interactions.
2. Uncertainty in the effects of shielding which would produce a great variety of secondary particles which are in themselves a hazard too.
3. The most significant uncertainty in estimating the risk lies in the response of cells and tissues to the radiation environment that they encounter.

Electromagnetic waves exist as photons and vary according to their energy which is proportional to their frequency, ranging from low frequency, non-ionizing radio waves, up through the visible light frequencies, and then even higher to x-rays and gamma rays.

It is interesting that the energy of light photons is just below that required to ionize molecules. At energies just above the visible part of the electromagnetic spectrum, ultraviolet photons are able to remove electrons from some of the most easily ionized types of molecules such as those found in and around human cells. Fortunately, these "electromagnetic" types of ionizing radiation are not a great threat to humans in space. This is true because they can either be stopped with thin shields or, as in the case of x-rays and gamma rays, their intensity is fairly low in most volumes of space where humans desire to explore. Some have claimed that low frequency electromagnetic fields from power lines are responsible for increased cancer risk but this has not been proved. This leaves the highly energetic particles which can pass through shielding materials as the most obvious threat to humans in space.

4.11 SPACE RADIATION SOURCES

The primary radiation sources in the outer space are the Galactic Cosmic Rays (GCR), protons and electrons trapped in the earth’s magnetic field, and the Solar Particle Events (SPE). The background radiation of the GCR permeates inter planetary space and is composed of 85 percent protons, 14 percent helium and about 1 percent from HZE particles. Although the HZE particles are less abundant, they posses significantly higher ionizing power with a greater potential for radiation-induced damage and greater penetration power.

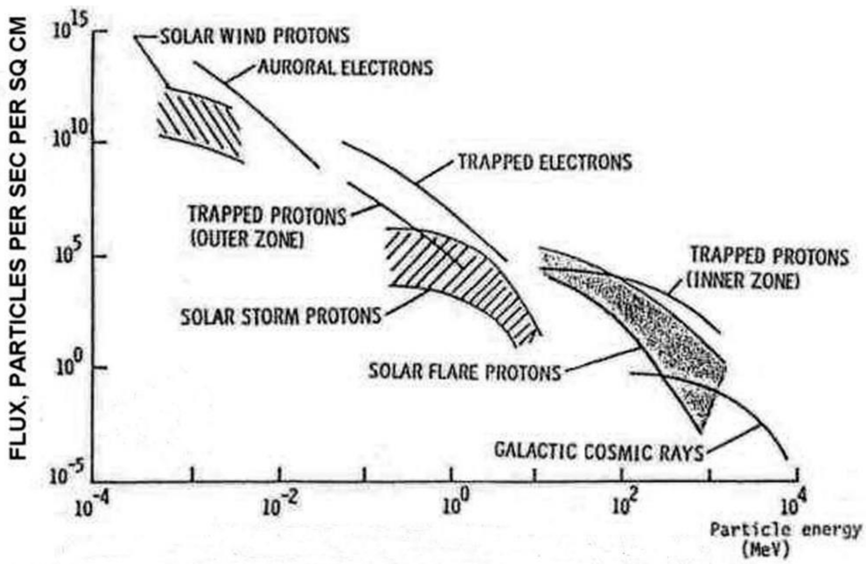

Figure 11. Types of space radiation and their fluxes.

The graph in Fig. 11 shows the flux of particles seen near the Earth. The flux covers an extremely wide range of particle energies. This is an "integral" distribution, that is, it shows the flux of particles with energies above the energy shown on the horizontal axis. Note that only those particles at the higher end of the energy scale or towards the right hand side, can penetrate the aluminum skin of a spacecraft which has an areal density or density (ρ) by thickness (x) product (ρx) typically around 1 [gm/cm^2].

4.12 GALACTIC COSMIC RAYS

Galactic Cosmic Rays (GCRs) originate from outside the solar system but generally from within the Milky Way Galaxy. GCRs are atomic nuclei from which all of the surrounding electrons have been stripped away during their high-speed passage through the galaxy, hence they are ionized. They have probably been accelerated within the last few million years, and have traveled many times across the galaxy, trapped by the galactic magnetic field.

Galactic cosmic rays have been accelerated to close to the speed of light c, probably by supernova remnants or zero point magnetic field configurations. As they travel through the very thin gas of interstellar space, some of the GCRs interact and emit gamma rays, which is how we know that they pass through the Milky Way and other galaxies.

The elemental composition of GCRs has been studied in detail, and is very similar to the composition of the Earth and solar system. Studies of the composition of the isotopes in GCRs may indicate that the seed population for GCRs is neither the interstellar gas nor the remains of giant stars that went supernova. This is an area of current investigation.

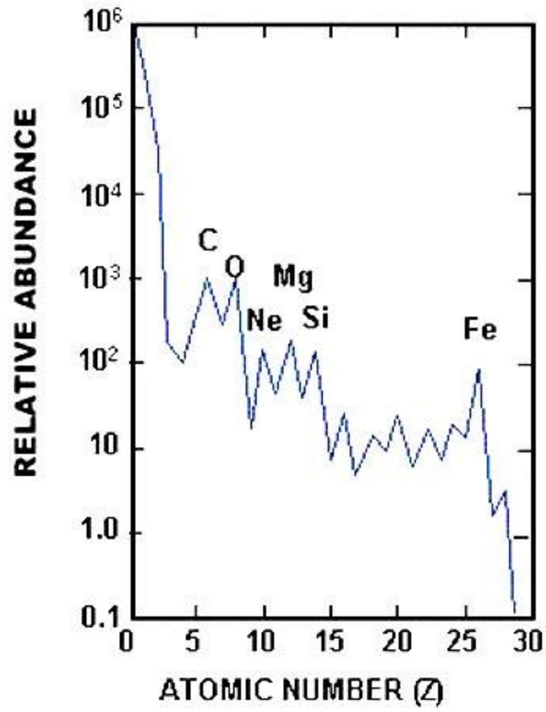

Figure 12. Logarithmic relative abundances of space particles.

Included in the cosmic rays are a number of radioactive nuclei whose numbers decrease over time. As in the carbon^{14} dating technique, measurements of these nuclei can be used to determine how long it has been since cosmic ray material was synthesized in the galactic magnetic field before leaking out into the vast void between the galaxies. These nuclei are designated as "cosmic ray clocks".

Galactic Cosmic Rays are composed of many elements but the lighter nuclei dominate. The hydrogen abundance (H) peak is about 10 times higher then the helium (He) peak and almost 10,000 times higher than the Fe peak.

Galactic cosmic rays are called galactic because their source is clearly outside the solar system, and thus are assumed to be generated somewhere in our Milky Way galaxy. Typically, these particles are highly charged and very energetic. They pass practically unimpeded through the skin of a typical spacecraft and the body of the astronauts. GCR is the dominant radiation to be dealt with on the International Space Station and on Mars missions.

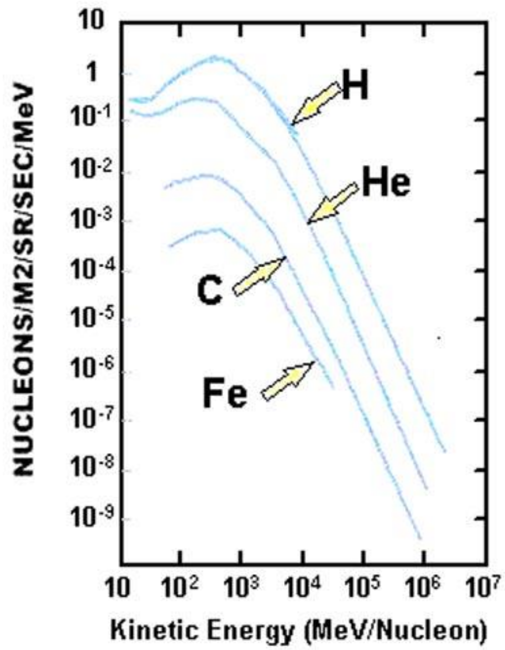

Figure 13. Logarithmic energy distribution of HZE particles.

These particles are affected by the Earth's magnetic field and their average intensity is highest during the period of minimum sun spots when the solar magnetic field is weakest and thus is less able to deflect them. The sun's magnetic field increases as we move towards solar maximum which last occurred around the year 2000 then around 2013. As the sun's field increases, GCR particles are more easily deflected and less of them are seen near the Earth. One favorable aspect is that the GCR component of space radiation is relatively predictable especially when compared to Solar Particle Events over the short term.

4.13 SOLAR PARTICLE EVENTS (SPEs)

Solar particle events are of special interest to those concerned with space radiation health because the particle flux from the sun can change quickly and dramatically with very little notice. The particles normally streaming into the solar system along the sun's magnetic field lines or solar wind are mostly fairly low energy protons and normally this presents an acceptable radiation level to humans, even in rather thin-walled space suits.

Energetic particles from the sun, mostly protons and helium nuclei, present a significant danger to men and equipment during solar storm activity. The flux of particles with energies above a specified energy is called the integral distribution. In a 1972 event over 10,000 [protons/(cm^2.sec.steradian)] with energies above 10 MeV were produced.

SUN SPOTS

Sunspots are dark-appearing splotches on the surface of the sun and have been observed since early human history. The ancient Chinese recorded the largest sunspots on the setting sun when they could be observed with the naked eye without harm. These areas are slightly lower in temperature than the normal surface of the sun and are the result of local disruptions in the magnetic field.

Figure 14. Sun magnetic prominences caused by local magnetic fields disruptions. Source: NOAA.

Eruptions which can be dangerous to astronauts are typically associated with the areas around these unsettled sunspots. Observing sunspot counts over many decades reveals that the number of spots varies widely over a period of approximately 11 years, known as the sun spots cycle. Recent studies are showing that the sun's magnetic field reverses direction every 11 years and that the actual period of the solar cycle is 22 years.

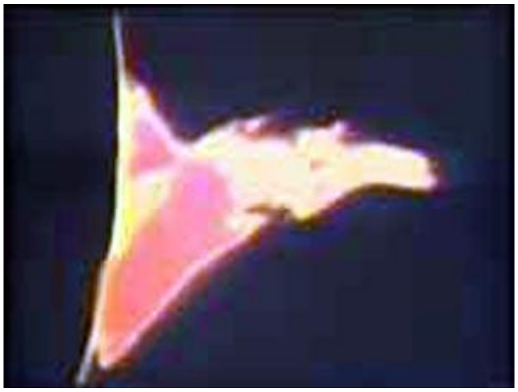

Figure 15. Solar flare prominence.

CORONAL MASS EJECTIONS (CMEs)

Coronal mass ejections (CMEs) are huge bubbles of gas threaded with magnetic field lines that are ejected from the Sun over the course of several hours. Although the sun's corona has been observed during total eclipses of the un for thousands of years, the existence of coronal mass ejections was unrealized until the space age. The earliest evidence of these dynamical events came from observations made with a coronagraph on the 7th Orbiting Solar Observatory (OSO 7) from 1971 to 1973. A coronagraph produces an artificial eclipse of the sun by placing an "occulting disk" over the image of the sun. During a natural eclipse of the sun the corona is only visible for a few minutes at most, too short a period of time to notice any changes in coronal features. With ground based coronagraphs only the innermost corona is visible above the brightness of the sky. From space the corona is visible out to large distances from the sun and can be viewed continuously.

Sometimes, with very little warning, an eruption sometimes seen as a flare near the sun's surface spews out particles which can reach the vicinity of the Earth in less than an hour. The severity of this radiation field can easily increase by factor of 10, damaging communication satellites. They generate spurious electric discharges in electrical transmission lines, triggering circuit breakers and causing massive blackouts.

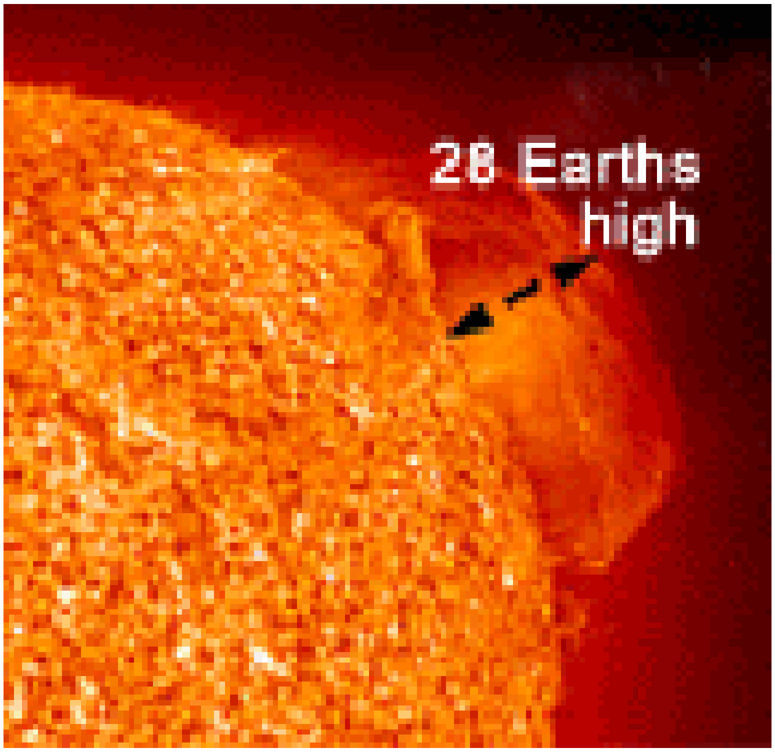

Figure 16. Coronal Mass Ejection recorded in 1997 by the SOHO satellite. Source: NOAA.

Coronal Mass Ejections disrupt the flow of the solar wind and produce disturbances that strike the Earth with sometimes catastrophic results. The Large Angle and Spectrometric Coronagraph, LASCO on the Solar and Heliospheric Observatory (SOHO) has observed a large number of CMEs.

The event of April 7th, 1997 produced a "halo event" in which the entire sun appeared to be surrounded by the CME. Halo events are produced by CMEs that are directed toward the Earth. As they loom larger and larger they appear to envelope the sun itself.

Coronal mass ejections are often associated with solar flares and prominence eruptions but they can also occur in the absence of either of these processes. The frequency of CMEs varies with the sunspot cycle. At solar minimum one CME is observed per week. Near the solar maximum we observe an average of 2 to 3 CMEs per day.

Great danger to the astronauts can ensue unless the spacecraft is kept in a low orbit inclination keeping it under the Earth's protective magnetic field. A mission at high latitudes would make such an event more serious.

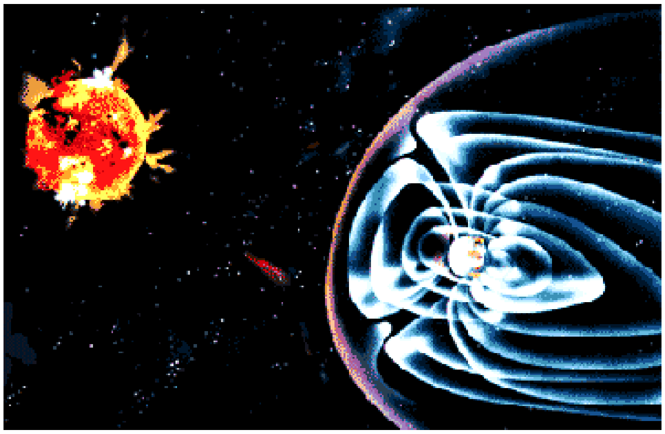

Figure 17. The Earth’s magnetic field interacts with the solar wind and with coronal mass ejections, trapping the generated particles.

The NOAA Space Environment Center provides short term “space weather forecasts.” One to three day estimates of the solar flare probability are generated, mostly based on human forecasters’ judgment. A component of the prediction is related to several indices of solar activity, a principal one being the intensity of a common x-ray band in the range of 1-8 angstroms, constantly monitored on the Earth and by satellites. Another major consideration is how well the Earth is connected magnetically to the unsettled area of the sun mostly responsible for the x-radiation. This is detected with optical telescopes specially designed to monitor the sun.

4.14 THE SOUTH ATLANTIC ANOMALY (SAA)

Early in the space age it was found that the Earth's magnetic field acts as a trap to contain energetic charged particles from reaching the surface of the Earth. The regions where these particles are trapped are called the Van Allen Belts. When the trapped particles leak to the Earth surface in the northern hemisphere emitting synchrotron radiation and ionizing the nitrogen and oxygen in the atmosphere, this is associated with the emission of the northern lights or Aurora Borealis. In the southern hemisphere it is designated as Aurora Australis.

Some of the particles originate from the solar wind but most are produced by the decay products of the galactic cosmic rays. Spacecraft traveling to points far from the Earth must pass through these areas but, in this case, the hazard for humans is low because the passage time through these radiation belts is short.

The passage time is not necessarily short for spacecraft in Low Earth Orbit (LEO). It is fairly well-known that the earth's magnetic field axis is significantly out of line with its rotation axis. Although the north magnetic pole is still in the north it is not very close to the geographical North Pole. Strictly speaking, a little noticed fact is that at the Earth's geographical north, the Earth magnetic pole is in fact a south pole of a magnet since it attracts the north pole of a compass.

Another not so commonly known fact is that the rotation and magnetic axes of the Earth are also displaced, meaning that the Earth's magnetic field has a significant asymmetry as seen on its surface. The result of this is that there is an area off the coast of Brazil above which particles trapped in the Earth's magnetic field exist at a much lower altitudes. This area is designated as the South Atlantic Anomaly (SAA). At a typical Low Earth Orbit (LEO) altitude of 300- 500 km, the radiation intensity in the SAA is much higher than that found anywhere else in orbit.

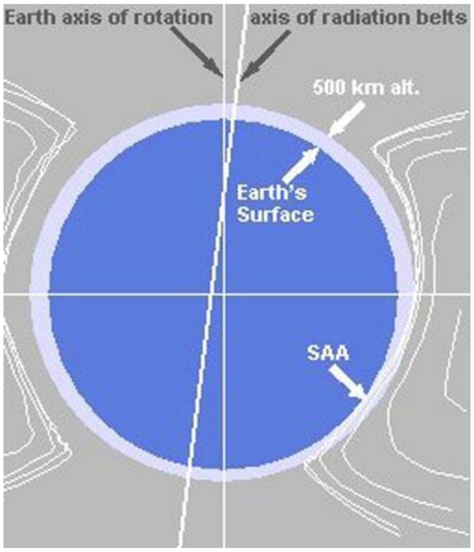

Figure 18. The South Atlantic Anomaly (SAA) occurs because of the asymmetry of the axis of rotation of the Earth and its magnetic field axis.

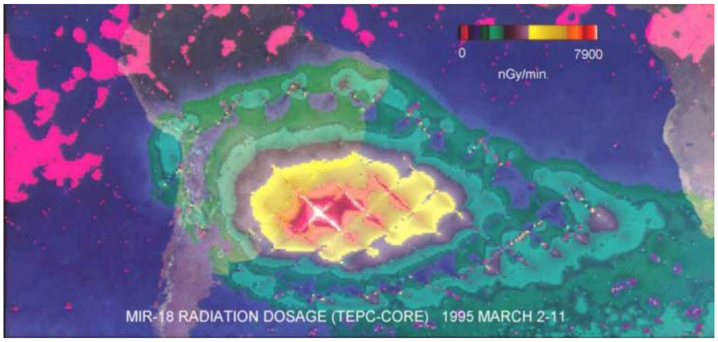

Figure 19. Dose rate to the MIR-18 Space Station showing the South Atlantic Anomaly just east of the Brazilian coastline.

A color map of the South Atalantic Anomaly shows that the hottest spot is off the east coast of Brazil. In Space Shuttle operations, Extra Vehicular Activities (EVA) are prohibited on orbits near any passages through the SAA to avoid this extra radiation risk. Also, during passage through the SAA, electronic equipment is often turned off to minimize the probability of damage due to the ionizing trails of particles through the electrically charged components.

4.15 INTERSTELLAR SPACE RADIATION SOURCES

Interstellar space is not devoid of matter; it contains various particles with different densities. A space vehicle crossing such regions will be subject to bombardment by such particles. A space vehicle will be subjected to an erosion process and material loss due to high speed impact of interstellar matter. At relativistic velocities, the heating and drag effects of this bombardment exceed the effects of erosion.

In space, a large number of gas clouds exist which consist of atoms in both the neutral and ionized states. These are mainly in the form of neutral HI and ionized HII, electrons, and concentrated matter in the form of grains and particulate dust. Table 4 shows the particle environment in space.

Table 4. Particles in space.

Particle type	Concentration
Interstellar gas	
Clouds	10^7-10^9 [particles/m^3]
Intercloud regions	2-3x10^5 [particles/m^3]
Solar neighbourhood	10^6 [particles/m^3]
Matter density of gas in solar neighborhood	1.67x10^{-21} [kg/m^3]
Kinetic temperature of gas	
Protons HI region (neutral)	50 K
Protons HII region (ionized)	10^4 K
Matter density of grains	
Mean interstellar density	1.4x10^{-23} [kg/m^3]
Intercloud regions	10^{-25} [kg/m^3]
Solar neighbourhood	10^{24} [kg/m^3]
Mean mass of grains	10^{-16} [kg]
Temperature of grains	
ProtonsHI region (neutral) as dirty ice	10-20 K
Protons HII region (ionized)	30-60 K

ELECTRONS BOMBARDMENT

Electrons impinging on a space vehicle will lose their kinetic energy and will be decelerated by their close passage to a nucleus with the emission of electromagnetic radiation. This will be absorbed by the photoelectric effect, Compton scattering and the pair production process. The Compton Effect becomes important at a speed of about (v/c) = 0.8, and pair formation becomes important only at high speeds of (v/c) = 0.8.

The matter density of electrons is much lower than the density of protons in interstellar space due to the lower mass of the electron. The bombarding electrons will also interact with the electrons in the materials of the space vehicle with the emission of bremsstrahlung radiation in the form of soft x-rays. This radiation can be easily absorbed by low atomic mass materials requiring at most a few millimeters of material.

PROTON BOMBARDMENT

At velocities (v/c) <0.9, the penetration effects are not significant. Most of the energy of the particles is dissipated by interaction with the protons in the structure of the vehicle. The interaction will lead to processes of electron excitation and atomic ionization, together with de-excitation and recombination, leading to the emission of electromagnetic radiation giving rise to heating. The protons eventually collide with the nuclei of the material and are totally stopped. By this time they have lost a large fraction of their initial energy, but the collision will lead to a region of high temperature around 10^3 ^{0}K, referred to as a temperature spike. This heat will dissipate over the surrounding region causing a rise in the temperature of the vehicle material.

At high vehicle velocity, the energy of a particle upon collision with a nucleus could cause the displacement of an atom in the material to occur. This can lead to plastic deformation and local melting. If the energy transferred by the proton to the nucleus is large enough above a few MeV, nuclear transmutations and disintegration could occur. The kinetic energy for a proton for (v/c) = 0.15 is about 10 MeV. Most of this energy will be dissipated by proton-electron interaction and nuclear reactions may be considered to be rare. There would be an important consideration for (v/c) >0.9 where the proton energy would be around 1,000 MeV.

DUST GRAINS BOMBARDMENT

Dust grains impact on a vehicle's structure has a larger and more severe effect than electrons or protons. When the particles speed is greater than the local speed of sound in the material, the energy transfer from the impacting particle to the material cannot travel through the material as an elastic deformation at a velocity in excess of this speed of sound. Thus, the initial energy transfer will be restricted to a volume bounded by the shock wave front. Once the particle's speed is reduced to subsonic speed, the energy that remains is small, but the kinetic energy which has been deposited in the material will be distributed in a region with a volume only a few times that of the particle. Hence, the energy density and the temperature in this region will be very high at about 10^{12} ^{0}K at the impact point. This is high enough to melt and vaporize local areas of the material and a mass loss due to the ablation of the material will occur.

For typical grains with a mass of 10^{-16} kg, the impact energy at (v/c) = 0.15 the impact energies are of the order of 10^{11}-10^{12} MeV. The energy transfer during any collisions between the nuclei of the vehicle material and the nuclei of the particles of which the grains are constituted will lead to permanent damage to the vehicle through nuclear disintegrations, vaporization and ablation, and atomic displacements. The defect caused by displacements and vaporization could be annealed depending on the temperature of area under bombardment.

RESULTS OF BOMBARDMENT

1. **Heating:** Heating can occur without permanent changes in the materials. This is caused by the deposition of energy from the electrons and the protons. Energy deposition could be direct kinetic energy and through the absorption of radiation.
2. **Permanent damage:** These include mass loss through ablation heating caused by the bombardment of dust grains at velocities of interest.
3. **Ionization:** Without significant heating effect the mere breakage of DNA molecules in living matter becomes an important consideration in manned vehicles.

RADIATION LEVELS ON MARS

The RAD detector on NASA's Mars Curiosity rover revealed that radiation levels on the way to Mars are several hundred times higher than the dose humans receive on Earth [7]. Accumulated exposure of an effective dose of 100 cSv or rem, can increase the risk of fatal cancer by 5 percent. This is equivalent a whole-body CT scan once every 5-6 days. If current propulsion systems are used, this would exceed the radiation exposure for human astronauts NASA career limits, and requires alternate radiation shielding configurations.

A 3 percent increased risk of fatal cancer is considered by NASA as an acceptable career limit for its astronauts currently operating in low-Earth orbit. The RAD data showed that the Curiosity rover received an average dose equivalent of of 1.8 milliSieverts of GCR per day on its journey to Mars. Three percent of the radiation dose was associated with solar particles because of a relatively quiet solar cycle and the shielding provided by the spacecraft.

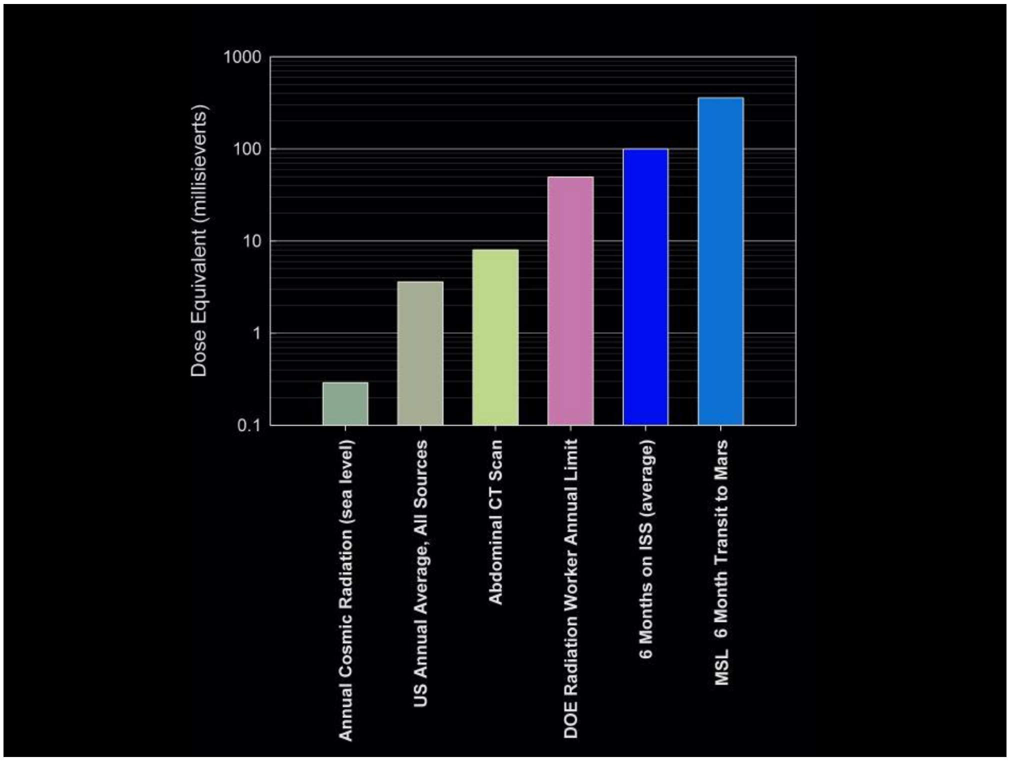

Figure 20. Logarithmic scale dose equivalent comparison in mSv for a 6 months transit to Mars from the Radiation Assessment Detector (RAD) instrument in the Mars Science Laboratory spacecraft during its flight from Earth to Mars, 2011-2012. Source: NASA/JPL-Caltech/SwRI.

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8.

EXERCISES

1. Consider the isotope Ra^{226}. Using Avogadro’s law:

$$N = \frac{g}{M} A_v ,$$

calculate its specific activity or the activity of 1 gram of material, and discuss its relationship to the Curie unit of activity. You can obtain the half life of the radium^{226} isotope from the Table of the Nuclides. You may wish to use the links on the class’ web page to data mine for information about radium^{226}.

2. Compare the average *yearly* dose of radiation under the following conditions:

a) Natural radiation to human body on Earth at about 100 [mrem/year].
b) To the astronauts on the International space station(ISS).
c) To occupants of a future base on the planet Mars.
Give recommendations for the Mars pioneers about the emplacement and design of their dwellings.

3. Deduce the cosmic rays neutrons nuclear reactions generating the cosmic rays isotopes in the Earth’s atmosphere.

4. The production of carbon^{14} with a half life of 5730 years is an ongoing nuclear transformation from the cosmic rays bombardment of nitrogen^{14} in the earth’s atmosphere. The atmospheric radiocarbon exists as $C^{14}O_2$ and is inhaled by all fauna and flora. Because only living plants continue to incorporate C^{14}, and stop incorporating it after death, it is possible to determine the age of organic archaeological artifacts by measuring the specific activity of the carbon present. Two grams of carbon from a piece of wood found in an ancient temple are analyzed and found to have an activity of 20 disintegrations per minute.

Estimate the approximate age of the wood, if it is assumed that the current specific activity of C^{14} in carbon has been constant at 15 disintegrations per minute per gram.