Characteristic of the radiation field in low earth orbit and in deep space

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Abstract

The radiation exposure in space by cosmic radiation can be reduced through careful mission planning and constructive measures as example the provision of a radiation shelter, but it cannot be completely avoided. The reason for that are the extreme high energies of particles in this field and the herewith connected high penetration depth in matter. For missions outside the magnetosphere ionizing radiation is recognized as the key factor through its impact on crew health and performance.

In absence of sporadic solar particle events the radiation exposure in Low Earth orbit (LEO) inside Spacecraft is determined by the galactic cosmic radiation (protons and heavier ions) and by the protons inside the South Atlantic Anomaly (SAA), an area where the radiation belt comes closer to the earth surface due to a displacement of the magnetic dipole axes from the Earth's center. In addition there is an albedo source of neutrons produced as interaction products of the primary galactic particles with the atoms of the earth atmosphere. Outside the spacecraft the dose is dominated by the electrons of the horns of the radiation belt located at about 60° latitude in Polar Regions. The radiation field has spatial and temporal variations in dependence of the Earth magnetic field and the solar cycle. The complexity of the radiation field inside a spacecraft is further increased through the interaction of the high energy components with the spacecraft shielding material and with the body of the astronauts.

In interplanetary missions the radiation belt will be crossed in a couple of minutes and therefore its contribution to their radiation exposure is quite small, but subsequently the protection by the Earth magnetic field is lost, leaving only shielding measures as exposure reduction means. The report intends to describe the

Das Strahlenfeld im nahen Erdorbit und im intergalaktischen Raum

Zusammenfassung

Die Strahlenexposition im Weltraum durch kosmische Strahlung lässt sich durch sorgfältige Missionsplanung und konstruktive Maßnahmen z. B. der Einrichtung eines Schutzraums im Raumfahrzeug zwar vermindern, verhindern lässt sie sich indes nicht. Grund hierfür ist die hohe Energie der Strahlung und der damit hohen Eindringtiefe in Materie.

Bei Abwesenheit von nur sporadisch auftretenden solaren Teilcheneruptionen wird die Strahlenexposition im nahen Erdorbit innerhalb von Raumfahrzeugen zum einen durch die galaktische Strahlung (Protonen und schwerere Ionen) und zum anderen durch die Protonen in der Südatlantischen Anomalie (SAA), einer Region in der der Strahlungsgürtel bis auf 200 km an die Erdoberfläche heranreicht, bestimmt. Hinzu kommen Neutronen, die als Wechselwirkungsprodukte der primären galaktischen Strahlung mit der Erdatmosphäre entstehen. Bei Außenbordaktivitäten wird die Hautexposition durch die Elektronen in der SAA und in Polnähe dominiert. Das Strahlenfeld variiert räumlich und zeitlich in Abhängigkeit vom Erdmagnetfeld und vom Sonnenzyklus. Durch Wechselwirkung der hochenergetischen Teilchenkomponente des Strahlungsfeldes mit den Atomkernen des Raumfahrzeuges und denen der Astronauten kommt es zur Bildung sekundärer Teilchen.

In interplanetaren Missionen wird der Strahlungsgürtel in wenigen Minuten durchquert, wodurch sein Beitrag zur Strahlenexposition sehr gering ist, allerdings fällt danach der Schutz durch das Erdmagnetfeld weg, wodurch als reduzierende Maßnahme lediglich die Hülle

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radiation field in space, the interaction of the particles with the magnetic field and shielding material and give some numbers on the radiation exposure in low earth orbits and in interplanetary missions.

Keywords: cosmic radiation, radiation measurements

des Raumschiffes und eventuell vorgesehene Schutzräume als dosisverminderte Maßnahmen verbleiben.
Der Beitrag beschreibt das Strahlenfelds, dessen Wechselwirkung mit dem Erdmagnetfeld und mit Abschirmmaterialen und zeigt Resultate einiger Messungen auf der Internationalen Raumstation und anderen Missionen und die Abschätzung von Expositionen in interplanetaren Missionen.

Schlüsselwörter: kosmische Strahlung, Messungen des Strahlenfeldes

Introduction

The radiation environment at a given point inside the solar system is a complex mixture of particles of solar and galactic origin with a huge range of energies. Radiobiological relevant are the galactic cosmic rays and particles ejected from the sun during solar energetic particle events as well as secondary radiation produced through interaction with the nuclei of the planets atmosphere and with their magnetospheres. The solar wind particles even when enhanced due to higher solar activities do not contribute to the radiation burden to man due to their relative low energy and hence their absorption in already very thin shielding thicknesses. Nevertheless the solar wind modulates the flux of galactic cosmic rays in the energy range below some GeV/n. During phases of higher solar activity the cosmic ray flux is decreased by a factor of three to four against phases during minimum solar activity. Through the earth magnetic field and an atmospheric thickness of about 1000 g/cm^2 thickness, the exposure to cosmic radiation on the earth surface is reduced to nearly zero level. Leaving Earth astronauts are shielded by the structure of the spacecraft and its interior in the mean by 20 g/cm^2, a shielding close to that one of the Martian atmosphere, but when in low earth orbit they are still protected by the earth magnetic field which limits even the exposure to solar energetic particles to exposures far below such causing early radiation effects in man.

Cosmic galactic radiations

Galactic cosmic radiations (GCR) originate outside the solar system and impinge isotropically on Earth. There is no conclusive proof of the mechanisms accelerating them and of the astrophysical sites where matter becomes cosmic particle radiation. There is no information about the direction of their sources since these particles are scrambled by irregular interstellar magnetic fields on their way towards the earth. Because of their high energies up to 10^{20} eV they most probably originate from supernova explosions, neutron stars, pulsars or other sources where high energetic phenomena are involved. Detected particles consist of 98% baryons and 2% electrons. The baryonic component is composed of 85% protons (hydrogen nuclei), with the remainder being alpha particles (14%) and heavier nuclei (about 1%). Figure 1 shows the abundances of these elements up to tin relatively to silicon. The energetic ions heavier than alpha particles have been termed HZE-particles (high charge Z and high energy). Although iron ions are one-tenth as abundant as carbon or oxygen their contribution to the GCR dose is substantial, since absorbed dose is proportional to the square of the charge. This is also indicated in Figure 1 [1].

Additionally to the galactic cosmic rays the so-called anomalous component is observed. It consists of originally neutral particles coming from the interstellar gas which become single ionized by solar radiation after entering the heliosphere. These particles are then accelerated in collision regions between fast and slow moving streams of the solar wind. They are able to penetrate deeper into the magnetic field than fully ionized cosmic rays. Their

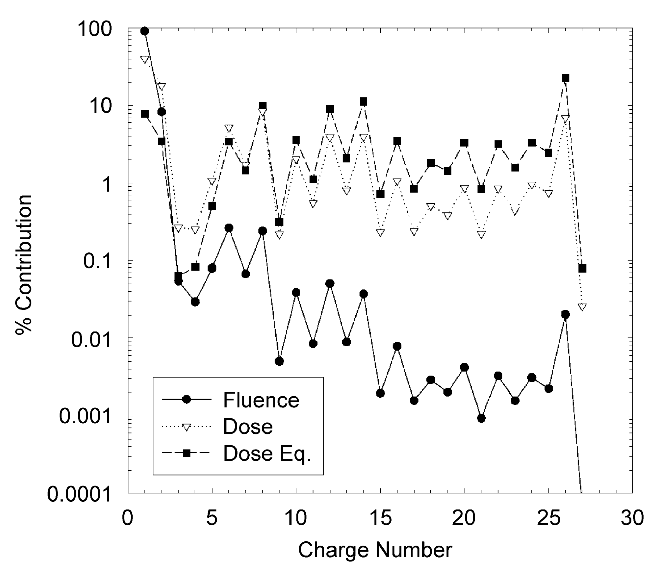

Figure 1. Elemental composition of galactic heavy ions and their contribution to absorbed and equivalent dose [1].

energies are around 20 MeV/nucleon; therefore they can only contribute to radiation effects behind small shielding.

However, it has to be considered that they lose all their electrons after penetration of a very small amount of shielding material and thus also deposit energy proportional to the square of their charge.

Energies of cosmic ray nuclei are generally presented as kinetic energy per nucleon. This has the advantage that all nuclei having the same value of energy per nucleon move with the same velocity regardless their mass. Using this energy scale many of the properties of the elemental energy spectra are identical. Differential energy spectra for hydrogen, helium, carbon and oxygen, and iron are shown in (Fig. 2). They give the particle flux per interval of energy. At energies above some GeV/nucleon they are well represented by a power law N(E)$\sim$ $E^{-\gamma}$ with $\gamma \sim 2.5$. Towards lower energies the spectra get flatter and show a maximum around some hundred MeV/nucleon.

Cosmic ray fluxes are not constant; they vary between two extremes which correspond in time with the maximum and minimum solar activity. Solar activity and cosmic ray fluxes are anticorrelated. The slope of the energy spectra in Figure 2 for energies below some GeV/nucleon is affected by this modulation of the cosmic ray flux [2]. It is caused by the solar magnetic field, which is coupled to the solar wind. The solar wind is a continuous stream of high ionized plasma emerging from the sun; its intensity depends on solar activity which can be described by the number of observed sunspots. During the minimum of the 11-year solar cycle the solar wind has a minimum strength and its effect on the energy spectra is smaller than at maximum solar activity. Cosmic rays incident on the solar system interact with the solar magnetic field and thus lose energy, which leads to flattened energy spectra at lower energies. With increasing solar

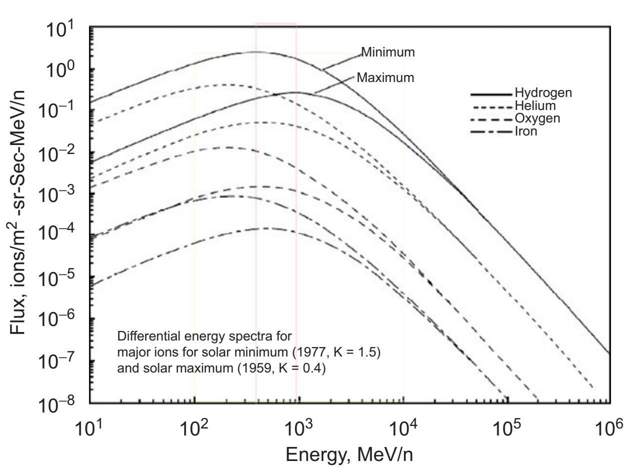

Figure 2. Galactic Cosmic Ray (GCR) particle spectra and their modification by solar activity of galactic heavy ion energy spectra at 1 AU as relevant for radiation protection [2].

activity the maximum of the energy spectrum is shifted to higher energies. At 100 MeV per nucleon the particle fluxes differ by a factor of about 10 between maximum and minimum solar activity conditions, whereas at about 4 GeV per nucleon only a variation of about 20% is observed.

Monitoring of solar modulation is possible based on the flux of secondary particles produced in the Earth's atmosphere by interacting galactic cosmic rays. This flux has been measured over longer periods by different ground based stations using neutron monitors. Figure 3 shows an example of data taken over several years with the neutron monitor at Kiel University. It can be seen from this figure that details of the modulation seem to be unpredictable statistical fluctuations. However, maxima and minima clearly appear anticorrelated to the 11-year solar cycle with a roughly sinusoidal form around an average particle flux. But the magnitude of the extremes again undergoes fluctuations. Predictions for future satellite missions are limited in accuracy within a factor of two or even larger based on unpredictable fluctuations.

Solar cosmic radiation

Besides electromagnetic radiation, the sun emits continuously particle radiation, consisting mainly of protons and electrons, the so called solar wind. The intensities of these low energy particles vary by 2 orders of magnitude between around some 10^{10} and 10^{12} particles cm^{-2} s^{-1} sr^{-1}. In terms of velocities, this particle stream is characterised by velocities between about 300 km s^{-1} and 800 km s^{-1} and more. The related energies are so low (for a proton between 100 eV and 3.5 keV), that the particles will be stopped within the first few hundred Angstrom of skin. They are therefore not of concern for radiation effects in man (Fig. 4).

Occasionally, the surface of the sun releases large amounts of energy in sudden local outbursts of gamma rays, hard and soft X-rays and radio waves in a wide frequency band. In these solar particle events (SPEs) large currents and moving magnetic fields in the solar corona accelerate solar matter. Coronal particles with energies up to several GeV escape into the interplanetary space. They spiral around the interplanetary magnetic field lines. Within the ecliptic plane field lines expand from the sun into the interplanetary medium like the beam of a rotating garden hose. They connect the earth with a certain spot on the western part of the Sun. The number and energy spectrum of particles observed in solar particle events at Earth depends on this connection. SPEs show an enormous variability in particle flux and energy spectra and have the potential to expose space crew to life threatening doses.

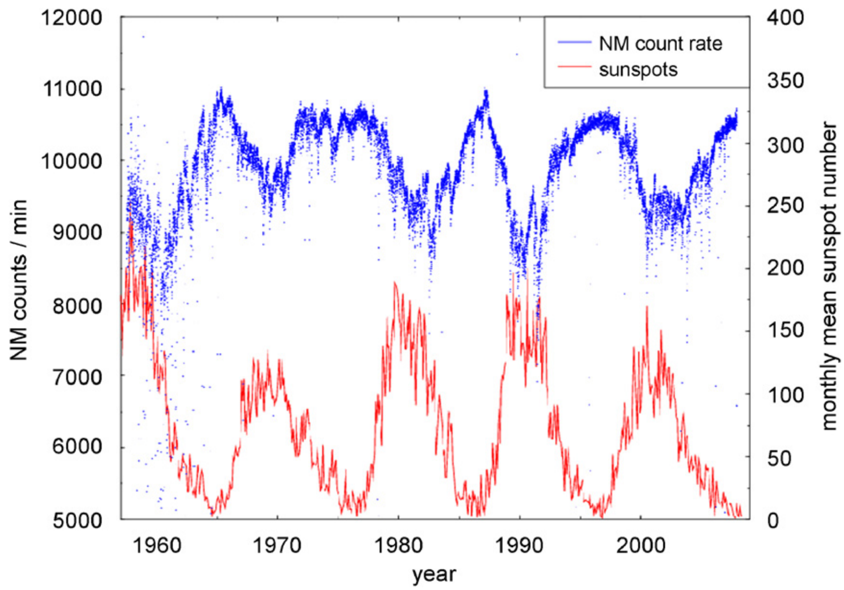

Figure 3. Cosmic ray variation with the solar cycle measured by the Neutron Monitor (NM) in Kiel (http://134.245.132.179/Kiel/Main.html). The cosmic rays show an inverse relationship to the sunspot numbers because Sun's magnetic field is stronger during sunspot maximum.

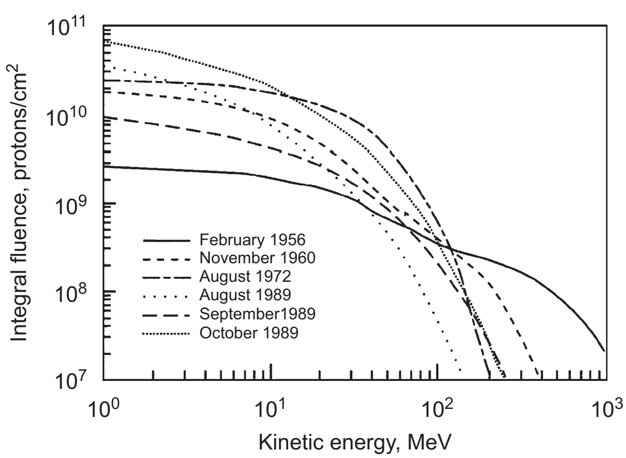

Figure 4. Integral energy spectra of historical 'worst-case' solar particle events [3].

A well connected SPE with high particle fluxes observed at earth is a rare event which is likely to be observed during the period of increasing and decreasing maximum solar activity. Therefore major SPEs are observed at Earth as random events with a low frequency, typically one per month. They last for several hours or days. Events with significant fluxes of protons with higher energies can be observed as "ground-level events" (GLE) by neutron monitors. Figure 5 shows the number of GLEs observed over the last solar cycles. Long gaps with no events can be seen during solar minimum activity. Between the last GLE in cycle 21 and the first one in cycle 22 there was a 65 month quiet period which was followed by a sequence of 11 GLEs within one year with approaching maximum of the present solar cycle.

Since high energetic particles are arriving first and followed by particles of lower energies the energy spectrum of SPE particles observed at earth depends on time after onset of the event. Differential energy spectra of solar particle events have the form of a power law $I(E) = I_0\ E^{-\gamma}$. After the onset of the event γ decreases with time. That means the contribution by high energetic particles decreases with time development of the event. The constant I_0, describing the absolute number of particles, shows a great deal of structure during the event caused by field irregularities and shock structures in the interplanetary medium.

The earth receives a small flux of solar particles with low energies also from SPEs at other positions of the sun which are only badly connected to earth. Local magnetic field lines are redefined in coronal mass ejections; thus particles are not bound by the interplanetary magnetic field. The fluxes of the SEPs sum up to a solar component which dominates over the galactic component in measured energy spectra at particle energies below 30 MeV/nucleon. Depending on the conditions of the interplanetary medium this component undergoes fluctuations which are highly variable and unpredictable. During periods of maximum solar activity, when the flux of galactic cosmic rays is depressed and SPEs are more frequent, the contribution of the solar component is more significant.

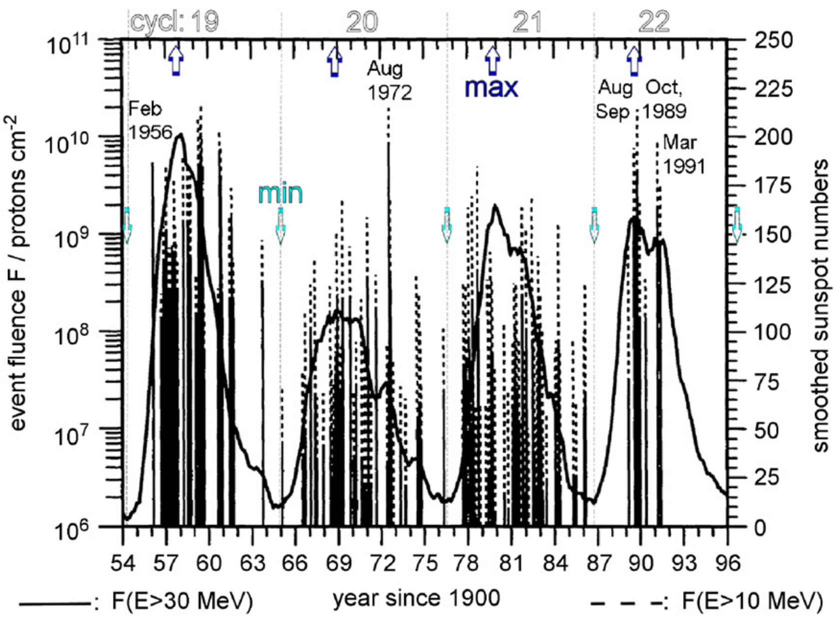

Figure 5. Occurrence of major and extreme solar particle events in solar cycles No. 19 to 22 (adapted from [4]).

Trapped radiation

The radiation field around the Earth comprises a third radiation source. The particles trapped in the radiation belts discovered by van Allen, are a result of the interaction of GCR and SCR with the Earth's magnetic field and the atmosphere. The radiation belts consist of electrons and protons, and some heavier ions. Electrons reach energies of up to 7 MeV and protons up to 600 MeV. The energy of heavy ions is less than 50 MeV/nucleon, and because of their limited penetration capacity, they are of no consequence for satellite electronics or humans. Charged particles with this energies moving into a dipole field can never enter into inner areas of this field. However, if they are put into this field for any reason, they are restricted to certain positions and cannot escape. They move in spirals along the geomagnetic field lines and are reflected back between the magnetic poles, acting as mirrors. Different processes contribute to fill in particles into the radiation belt and two main zones of captured particles are observed. The inner belt is mainly formed by decaying neutrons, coming from the atmosphere in which they are produced in cosmic particle interactions, and producing protons and electrons. The outer belt consists mainly of trapped solar particles, and is populated mainly by electrons. During disturbances of the magnetosphere by magnetic storms related to solar flares where the geomagnetic cut-off is usually depressed particles of lower energies can penetrate from outside towards the inner regions and fill them up. The radiation belts extend over a region from 200 km to about 75000 km around the geomagnetic equator (Fig. 6).

The trapped radiation is modulated by the solar cycle: proton intensity decreases with high solar activity, while electron intensity increases, and vice versa. Diurnal variations by a factor of between 6 and 16 are observed in the outer electron belt, and short term variations due to magnetic storms may raise the average flux by two or three orders of magnitude. The centre of the inner belt is quite stable, especially with respect to protons. However, at the lower edge of the belt, electron and proton intensity may vary by up to a factor of 5. For the majority of space missions in Low Earth Orbit (LEO), protons deliver the dominant contribution to the radiation exposure inside space vehicles. Because of their higher energies and correspondingly longer range, their total dose surpasses that of electrons at mass shielding above about 0.3 g/cm^2 aluminum. At lower shielding (e.g. in case of extravehicular activities (EVA)) the absorbed dose in the skin is dominated by the electron contribution and may reach up to 10 mSv per day.

Of special importance for low Earth orbits is the so called 'South Atlantic Anomaly' (SAA), a region over the coast of Brazil, where the radiation belt extends down to altitudes of 200 km. This behavior is due to an 11° inclination of the Earth's geomagnetic dipole axis from its axis of rotation towards Northern America and a 500 km displacement of the dipole center towards the Western Pacific, with corresponding significant reduced field strength values. Almost all radiation received in LEO at low inclinations is due to passages through the SAA. At an orbit with 28.5° inclination, six orbital rotations per day pass through the anomaly, while nine per day do not. Although traversing the anomaly takes less than about 15 min and

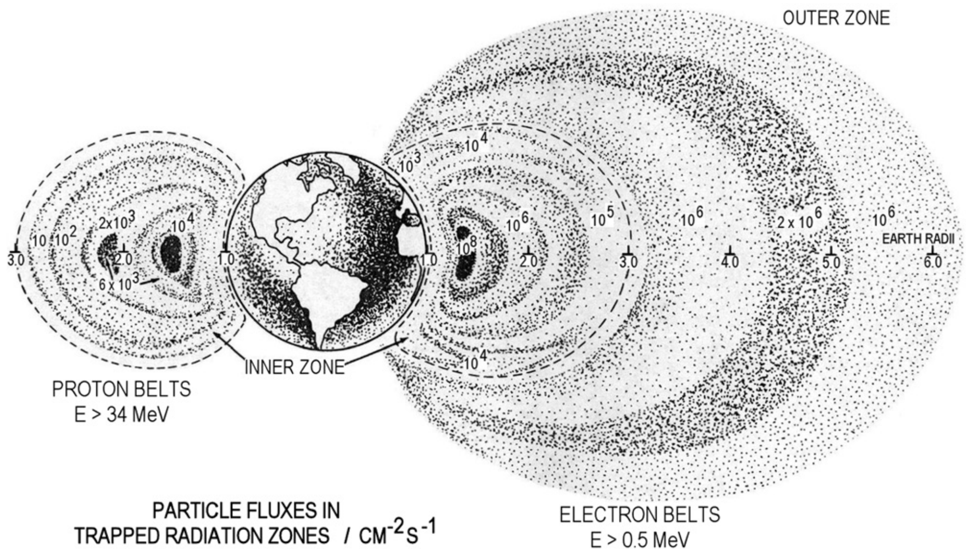

Figure 6. Integral flux densities in inner and outer terrestrial radiation belts for trapped protons and electrons in particles cm^{-2} s^{-1}.

occupies less than 10% of the time in orbit, this region accounts for the dominant fraction of total exposure.

Effects of interactions with materials

There are two fundamental mechanisms of interaction for a cosmic ray nucleus moving through matter. By Coulomb interactions the moving ion transfers energy to the electrons and nuclei of the target material. The amount of energy transferred to the nuclei is negligible small in comparison to that transferred to electrons due to their difference in mass. In collisions with target nuclei a nucleus-nucleus interaction takes place which is governed by the strong interaction force.

Thus target atoms are ionized or excited along the path of the ion. The energy loss per unit of path length dE/dx, which in radiation biology is called linear energy transfer (LET), is a function of energy and charge of the nucleus. LET varies with the square of the ion's charge. It has a minimum at relativistic energies of some GeV/nucleon and rises at lower energies, going through a maximum around some MeV/nucleon. By this energy loss a cosmic ray nucleus moving through material is slowed down until it finally stops.

Since the range of the strong force is restricted to the geometrical dimensions of the nucleus nuclear collisions can be described in an approximation by the picture of colliding bowls. In these interactions only a small amount of the kinetic energy is transferred to the colliding nuclei, but this energy is large in comparison to the binding energy of nucleons. Therefore the nuclei disintegrate more or less completely depending on the amount of overlap between them. As a result of nuclear collisions fast nuclear

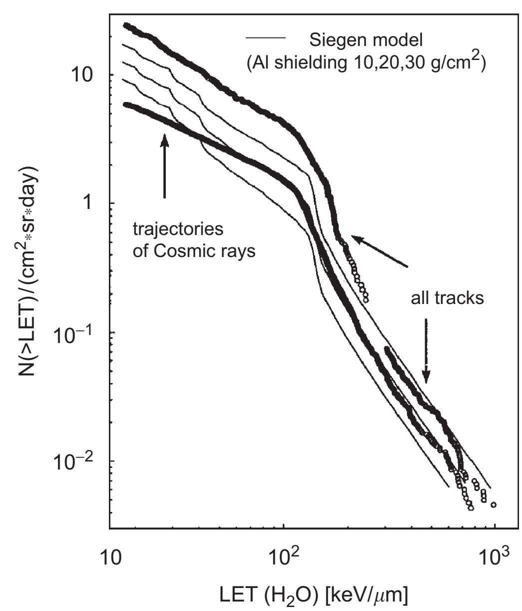

Figure 7. Measured LET spectra compared to model calculations. Spectrum normalized to a solid angle of 0.67 × 4 Π steradian to account for effect of earth shadow [5].

fragments of the projectile are produced which move with approximately the same velocity (i.e. kinetic energy per nucleon) and direction as the incoming primary nucleus. Additionally low energetic short range fragments are produced from the target nuclei which deposit their energy close to the interaction point. Figure 7 shows measured LET spectra compared to model predictions. Good agreement of measurements and calculations is demonstrated for LET > 60 keV/μm for a shielding of 20 g/cm^2 for the cosmic ray trajectories. For lower LET the detection efficiency drops down; for an accurate correction a larger number of particle tracks would be needed. The spectrum for all tracks includes target fragments, caused by interactions of the primary cosmic rays with the detector material, which caused an increase in particles by a factor of two.

Interaction with magnetic fields

A cosmic ray particle has to penetrate the Earth's magnetic field in order to reach spacecrafts in Low Earth Orbits (LEO). This penetrating ability is related to the ions magnetic rigidity which is given by its momentum divided by its charge. All particles with the same rigidity follow a track with the same curvature in a given magnetic field. For each point inside the magnetosphere and each direction from that point there exist a rigidity threshold below which the cosmic rays are not able to reach this point. This rigidity is called the geomagnetic cut-off rigidity. It is proportional to the magnetic field component perpendicular to the direction of particle motion, i.e. for a particle moving towards the center of Earth the cut-off rigidity has a maximum value at the equator, since the particle moves perpendicular to the field lines and the cut-off rigidity vanishes at the pole, since the particle moves in the direction of the field lines. Therefore geomagnetic shielding is less effective for high inclination orbits than for low inclination orbits. This means that in low inclination orbits only particles of high energy have access. Towards higher inclinations additionally particles of lower energies are observed. For a geomagnetic latitude λ the vertical cut-off rigidity R_c in GigaVolt (GV) can be calculated approximately by $R_c = 14.9 \cos^4\lambda/(r/r_e)^2$, where r is the distance from the dipole center in Earth radii (r_e). The rigidity for particles arriving from other directions than vertical is dependent from the angle of incidence. Due to the latitude dependant shielding the number of particles incident in the altitude of orbiting spacecrafts increases from lower inclinations towards higher inclinations.

Specific aspects of the space radiation field

Radiation exposures in space will not result in uniform whole-body dose distribution. Dose distribution will be non uniform both with respect to depth and with respect to area or region of the body involved. The absorbed dose decreases rapidly with the depth in tissue due to the spectral characteristics of the primary sources. This holds especially for solar energetic particle ejections. The fluxes in space except for SEP events are lower by orders of magnitude which usually are applied to reference experiment on earth. Basically, in space the irradiation of the body is chronically. However, in low Earth orbits there are variations due to geomagnetic shielding and solar cycle variations. Both are regular and predictable. Time scales range from minutes for the first and years for the latter variation. Secondly, there are solar particle events, which are irregular and unpredictable with time scales in the order of hours to days. Even in geomagnetically well shielded low inclination orbits there are influences of solar particle events due to magnetic storms in the Earth magnetic field, and by that changes in the trapped particle environment. Traveling in interplanetary space or being on the Moon or Mars adequate shielding has to be provided to prevent earlier radiation effects which may significantly decrease mission success.

Radiation of a huge range of energies impinge on the body and becomes scattered, fragmented and degraded in energy as it penetrates to the deeper organs. The linear energy transfer (LET) as well as dose and dose rate change with depth. All three are factors that influence the biological effectiveness, but not necessarily in the same direction. Fragmentation leads to an enhancement (build up) of low LET components on the costs of high LET components. On the other hand low LET protons of high energy produce target fragments with higher LETs. Of particular importance for dose modifications towards higher quality factors is the increase of the number of nuclear disintegration stars with higher multiplicities near the bone marrow in osseous structures.

Besides radiation during spaceflight man is exposed to several stressors: (a) flight dynamic factors, such as, above all microgravity, acceleration and vibration, (b) work environment factors, such as hypoxia, hyperoxia, hypo- and hyperthermia and noise, (c) internal body factors, such as exercises, trauma, infection, altered biorhythms and psychological. The interrelationship between the pathologies of radiation syndrome and the influence of external and internal factors, so far, is merely understood at the level of two factor combinations. Up to now, only a few data on the interaction of the first three factors with radiation for humans are available. Most of the investigations are done using cellular systems, plant seeds and animal systems, like insect eggs, larvae pupae and adults as well as rat and mice and dogs. Irradiation was performed with gamma sources before or after spaceflight or with an onboard source. The combination of microgravity and radiation yields, mostly an additive interaction by use of pre- or postflight irradiation, whereas in experiments with onboard irradiation synergistic effects (greater than the sum of the effects of each factor) dominate [6,7].

Regarding the important question of a modification of the radiation response to heavy ions by microgravity, one important result has been obtained by the use of the Biostack concept [8] in combination with the 1-g centrifuge of BIORACK. For the investigation eggs of the stick insect *Carausius morosus* were exposed in the D1 mission and allowed to continue their development during spaceflight. After retrieval, hatching rates, growth kinetics and anomaly frequency were determined. A synergistic action of heavy ions and microgravity was established in the unexpectedly high frequency of anomal larvae. Neither cosmic radiation nor microgravity alone produced an effect of similar extent nor was this extremely high anomaly rate reached by adding up the effects of the two parameters [9]. Although suggestive, this result requires further elaboration and additional experiments until answers can be given with some confidence. The hypothesis that repair is gravity dependent could not be confirmed in experiments using pre-irradiated bacteria (*E. coli, B. subtilis* and *D. radiodurans*), human fibroblast and yeast cells and irradiated yeast cells using an onboard beta source [10,11]

The combined influence of different spaceflight factors is one of the key problems in space medicine; it is of particular interest to understand the mechanisms underlying the interaction of radiation and microgravity [12].

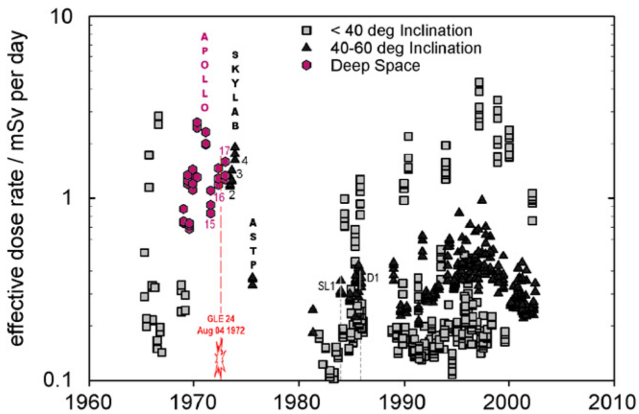

Figure 8. Compilation of mission dose rates experienced by US astronauts. Until the NASA-MIR and ISS missions the only long term missions were the Skylab, the only missions outside the terrestrial magnetosphere were the Apollo missions (ASTP: Apollo-Soyuz Test Project) [adapted from 20].

Doses and Fluxes for low earth orbits and interplanetary missions

For the simulation of the radiation environment on ground information on the absorbed dose, the LET-spectra and the fluence and type of particles needs to be known for each scenario. Measurements have been performed by using active and passive devices during all manned missions so far [13–19].

Figure 8 gives a summary of the effective doses received during various shuttle flights, on Apollo, Skylab, MIR and ISS [20]. The effective doses vary with altitude and inclination for each flight. Highest values were observed during the high altitude shuttle flights at low inclinations with up to 4 mSv/day and during the Apollo Program with about 3 mSv/day (as comparison the mean daily dose on earth is 0.0066 mSv). The radiation fields responsible for

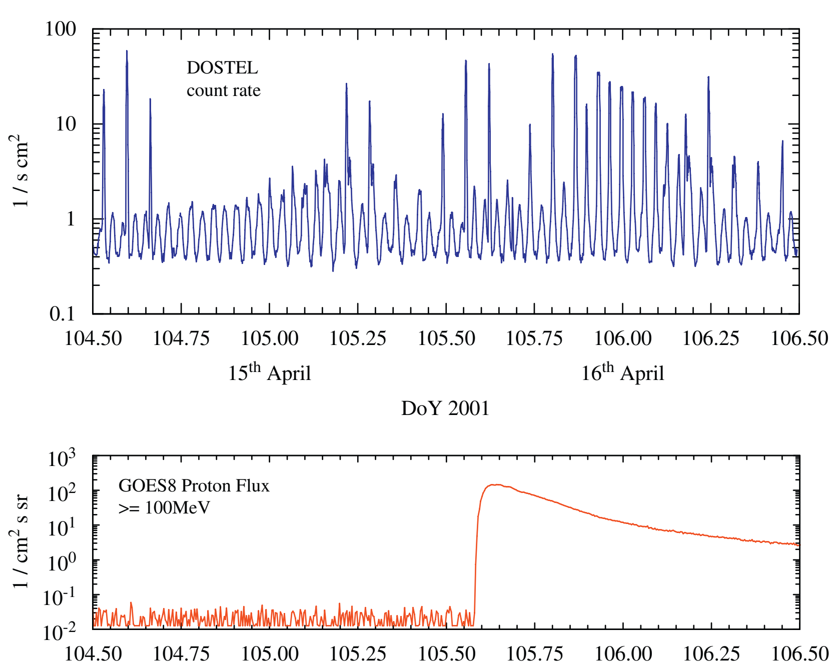

Figure 9. DOSTEL particle count rate for quiet solar conditions and during the April 16 solar particle event (top panel). At the x-axes the day of year (DoY) of 2001 is plotted. The lower panel gives the particle fluxes monitored by the GOES satellite. The strong increase of particles on day 105 indicates the solar particle event.

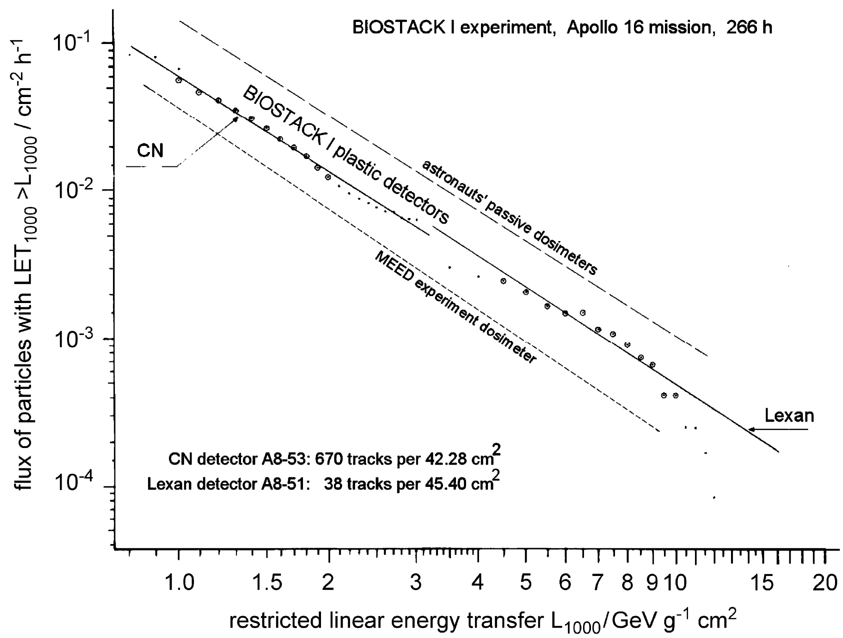

Figure 10. LET spectra of heavy ions in the Apollo 16 lunar mission.

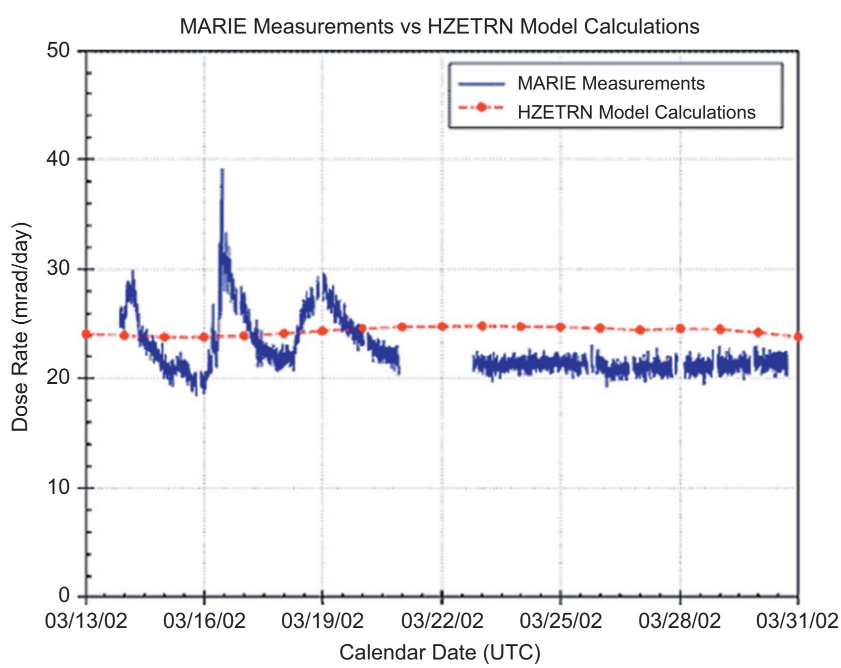

Figure 11. Comparison of measurements of the MARIE Experiment with Model calculations.

this exposure are quite different. Whereas the exposure in this shuttle flights is dominated by the protons of the radiation belt, during Apollo mainly the nuclei of the GCR providing the exposure.

The number of ionizing particles and their LET spectra inside spacecrafts in low earth orbit have been measured frequently, an example is given in (Fig. 9) for ISS increment 2 [21].

Radiation data inside spacecrafts from interplanetary flights are available only from the Apollo Moon missions in the early 80ies. The number of heavy ions having a Let $>100\,\mathrm{keV}/\mu\mathrm{m}$ were measured during the Apollo 16 mission (Fig. 10) in the Biostack experiments [8]. This information is quite important since heavy ions are extremely densely ionizing and are able to kill cells by its traversal, which is a serious fact in the case of tissues with non replaceable cells like the brain.

It took more than 30 years until the NASA experiment MARIE provides flux and dose measurements in the Mars orbit (http://marie.jsc.nasa.gov/) (Fig. 11). The dose rate measured by MARIE was around 240 μGy/day in March 2002. There are some fluctuations due to solar activities, but the measurements are not far away from the calculations of the HZETRN model. Table 1 presents model calculations to give an indication how many particle hits a cell of about 5.6 μm diameter exposed during a stay on Mars at different altitudes during one year http://marie.jsc.nasa.gov/).

There are no measurements of the radiation environment on planetary surfaces like Moon and Mars. Estimates of the environment are provided by calculations [22]. Based on calculations from Wilson [23] the absorbed dose in specific missions is given in (Fig. 12). For a long term Mars mission equivalent doses of up to 1 Sv are approached due to GCR during solar minimum. For solar maximum less than 400 mSv are calculated, but during solar maximum there is a higher probability to catch a SPE which may expose the astronauts during the transfer period to an instantaneous dose of more than 1 Sv or on Moon to half this dose. Due to its atmosphere on Mars only an exposure of about 0.3 Sv occurs in this case.

Table 1
Model calculations of probable particle hits per cell (100 μm^2) at average skin depth in one year near solar minimum.

	Particle Hits per cell year (near solar minimum)				
Altitude (km)	$Z = 1$	$Z = 2$	$3 \geqslant Z \leqslant 10$	$11 \geqslant Z \leqslant 20$	$21 \geqslant Z \leqslant 28$
0	88.4	2.76	0.13	0.95×10^{-2}	1.32×10^{-3}
2	91.2	3.24	0.17	1.37×10^{-2}	2.07×10^{-3}
4	93.8	3.84	0.23	2.03×10^{-2}	3.34×10^{-3}
6	95.9	4.65	0.31	3.14×10^{-2}	5.68×10^{-3}
8	96.8	5.54	0.41	4.72×10^{-2}	9.44×10^{-3}

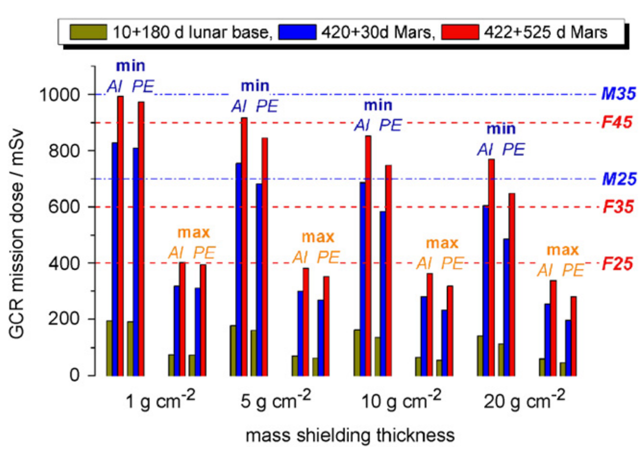

Figure 12. Estimated BFO mission doses from galactic cosmic rays for long term missions outside the magnetospheric shield during solar minimum (min) and maximum (max) phases. Shields are either Aluminium (Al) or polyethylene (PE) as a Hydrogen-rich material. Horizontal lines specify radiation protection career limits established for low earth orbits for male (M-) or female (F-) crew members of age 25, 35, or 45 at mission begin.

Conclusions

This article presents a brief review of the main sources of space radiation and its modification by magnetic fields and mass shielding, thereby describing the biological characteristics of the space radiation field and the exposure levels caused by it. There is a good understanding of the GCR environment, while trapped belt models still are inadequate and require substantial improvements. SPEs are not yet predictable. The development of accurate and reliable forecast models is one of the top priorities for long term mission planning and risk mitigation. Another high-ranking task is the radiobiology of heavy ions, which needs to be understood before humans are sent to Mars. Monitoring of all radiation sources is a mandatory task to further improve our knowledge on the environment and to provide for accurate risk estimates in future manned missions.

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