Impact: Technological and biological effects of cosmic rays

Radiation affects electronics and any other exposed technological equipment, as well as the cells of living beings. Here radiation means electromagnetic waves (photons), neutral (neutrons) and electrically charged energetic particles (electrons, protons, He ions, also called alpha particles, and ions of any other chemical elements, which we refer to as heavy ions in the following). The composition of the atmosphere can be altered by interaction with the radiation. Notably the ionisation is of relevance to aircraft, because it determines conditions of electromagnetic wave propagation. The continuous cosmic ray flux from outside the solar system and the transient flux produced by the Sun therefore affect technology and life, if it is not protected by the thick atmosphere or by the magnetic field of the Earth. Varying space weather conditions create varying radiation hazards.

The natural space radiation environment can be classified into two populations: the particles trapped by planetary magnetospheres in radiation belts and extra-planetary particle populations comprising electrons, protons and heavy ions of all elements of the periodic table. The extra-planetary component consists of galactic cosmic ray (GCR) particles and solar energetic particles (SEP) associated with solar flares and coronal mass ejections (CMEs). Their impact on technology and living beings is discussed in the following. Generally available computer models and the role of neutron monitors for monitoring and prediction of extraplanetary radiation are outlined.

The technological impact

There are different types of direct damages that energetic particles can do to the equipment of spacecraft and even airplanes:

- Energetic particles can ionise atoms and displace them within their crystalline lattice. For instance solar panels on spacecraft that leave the Earth's atmosphere lose performance due to cumulative effects of displacement damages induced by energetic particles. A large solar energetic particle event can, within some days, cause the same degradation as an entire year of operation under the effect of only galactic cosmic rays. Ionisation is often the dominant mechanism by which the performance of on board electronics degrades. Mechanical and electrical insulating properties of teflon can also be changed when the material is irradiated to high levels, as well as painting used for thermal regulation. All this decreases the life time of the equipment.
- In single event effects (SEE) damage results from a single ionising particle that traverses a microelectronic device. Creation of electron-hole pairs by an impacting energetic particle can disrupt the usual response of electric circuits. Single event upsets (SEU) are produced especially by heavy ions of the primary cosmic rays or of secondaries generated in the atmosphere by a primary high-energy proton. They can generate erroneous commands in on-board computers, while latch-ups are anomalous states of electronic devices where they do no longer respond to input signals. Worst cases of SEEs are burn outs, which means a permanent and irreversible circuit damage by parasitic current flows. Increased vulnerability is caused by the miniaturisation of technologies, where single charges can deposit enough energy to cause SEE.
- Energetic electrons also create different types of damages when they penetrate into the spacecraft and deposit their energy and electric charge. At some point this may create a discharge that interferes with instruments and detectors, biases instrument readings, leads to the erosion of materials. The depth of penetration, and the region where the problems occur, depend on the particle energy.

Much of the mitigation against such events relies on engineering of the materials and devices, which must be made resistant against the different types of particle damage. The degree to which this must be done depends on the long-term evolution of particle intensity and the number of solar events, i.e. on the phase of the solar cycle, whose accurate prediction, if possible, could help specifying the requests for specific satellites.

But since space weather and especially particle fluxes are variable, there are also periods when operations should or must be avoided: for instance the launch of spacecraft or the operation of space vehicles at times of strong solar energetic particle events, especially when operations occur on orbits through the polar regions.

Aircraft operations on polar routes are also affected by energetic particles and the secondaries they create in the Earth's atmosphere, because these particles alter the state of the atmosphere - especially the polar atmosphere, which is less protected by the Earth's magnetic field. The numerous protons of relatively low energy that can penetrate down to heights of 50-70 km above the ground ionise the polar ionosphere. This effect of solar energetic particle events is called polar cap absorption (PCA), because the enhanced ionisation creates an enhanced absorption of electromagnetic waves at low frequencies, such as those used for communications with air planes. Civil airplanes have been diverted to lower altitudes during major solar energetic particle events in the past (for instance January 2005) in order to recover their ability to communicate with control stations.

The magnetosphere of the Earth is not always a shield - it may also be a danger. The solar wind continually puts energy into the system, which is released in explosive events called magnetospheric substorms. The energetic electron fluxes generated during these events within the magnetosphere create spacecraft charging at communication satellites. These events occur under quiet solar conditions, when high-speed solar wind streams from coronal holes are particularly efficient for transferring energy to the Earth's magnetosphere.

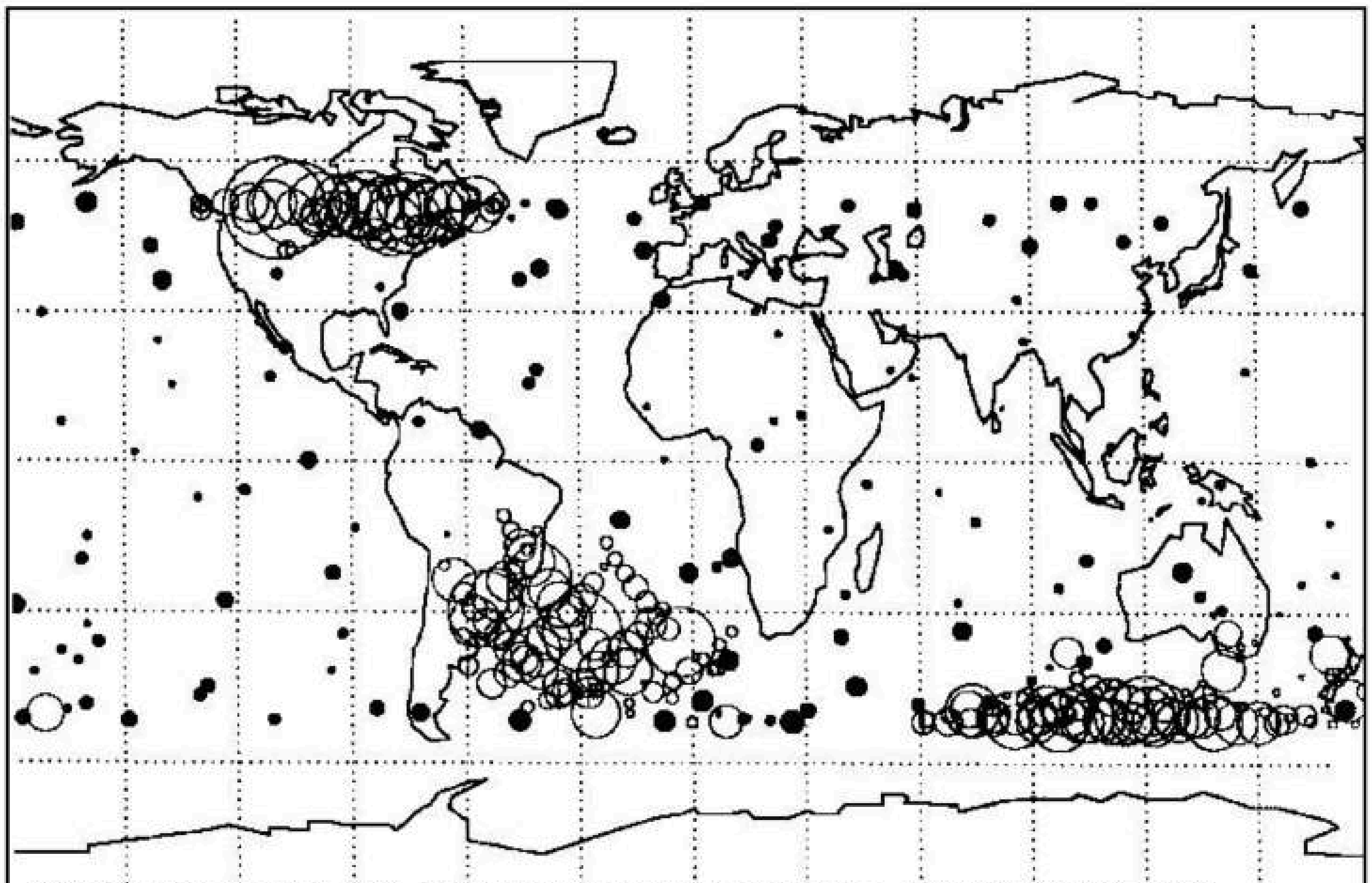
The biological impact

Energetic particles are a potential health risk, because they may damage cells: when an energetic particle impacts a cell, it will deposit part of its energy by interacting with the electrons of the molecules that build up the cell. The consequence of this interaction depends on the species and energy of the energetic particle (proton, ion, electron, neutron, photon). Any damage caused to the molecules, especially the DNA, may have consequences for the future of the cell, its ability to divide and to maintain its structure. In turn, the incorrect functioning of the cell may affect the tissue and organ of which it is the constitutive part.

- A damaged cell may repair itself. If it does not succeed, it will die. If too many cells die, the organ may cease to work correctly.
- If the repair is incomplete, the cell may succeed to divide a few times, but may transfer some damages to the daughter cells. Again, the incorrect functioning of too many daughter cells may cause a major or even definite damage of the organ. Damaged cells that survive can also become precursors of cancer cells.

Cosmic radiation therefore constitutes two types of hazard to living beings:

- High radiation doses are an immediate threat for health or even life. This is a danger for human spaceflight outside the Earth's magnetosphere. Solar energetic particle events are therefore recognised as a major threat for flights to the Moon or Mars. The major solar event of 4 August 1972 occurred during the period of the Apollo flights to the Moon. It would likely have had deadly consequences if a flight had been underway at that time. Therefore the astronaut safety is a major issue for future manned spaceflight.
- Low radiation doses may not have any immediately noticeable consequence, but be a risk on the long run. Crews of space missions and even aircraft that travel repeatedly through those regions of the Earth's atmosphere that are exposed to enhanced radiation doses, such as the high latitude (polar) regions, are in this situation.



Bottollier-Depois et al. 1994, Life Sciences Research in Space, p. 217, ESA SP-366, 1994
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The map shows radiation doses measured aboard the Russian MIR space station by the Nausicaa experiment of the French Space Agency CNES during enhanced radiation exposure from solar energetic particle events in October 1989. The diameter of the circle gives the dose rate. The MIR orbit, at an altitude of 420 km and an inclination of 51° with respect to the Earth's equator, leads the station through the magnetic polar regions above Canada and the Pacific Ocean south of Australia. The radiation doses received there, as indicated by the diameters of the circles, are well above those at other latitudes, with the exception of the region of weak magnetic field above the southern Atlantic Ocean. There the enhanced radiation doses are not due to the solar events, but to particles circulating in the Earth's magnetic field.

Radiation doses due to cosmic rays

The health effect of exposure to radiation depends on the amount of energy that is absorbed by the tissue (the stronger the particle flux, the more energy will be deposited), but also on the particle species, their energy, and the specific organ. For instance, X-rays deposit energy in a relatively uniform way in a volume, while neutron energy deposit is more localised, depending on the nuclear interaction in the tissues. Neutrons have a greater ability to create lesions than high energy protons, electrons or gamma rays.

Radiation doses received by personnel aboard space stations and aircraft must be monitored because of the accumulation of exposures to low levels of radiation. The unit used to measure the cumulative effect of prolonged exposure to relatively low levels of radiation is the Sievert (Rolf Sievert, Swedish physicist 1896-1966). It represents the sum of the radiation doses absorbed by the different organs of a human being, weighted by (1) the particle species (highest weight for alpha particles and heavy nuclei; neutrons; protons; finally photons and electrons); (2) the exposed organ to take into account its sensitivity to ionising radiations.

Some examples of radiation doses

- The natural dose due to the ambient radio activity on Earth is on average 2.4 mSv (1 mSv = 1 milli Sievert) in one year, with major differences between different regions, depending on the bedrock specificity. At sea level the cosmic ray contribution is about 0.3 mSv.
- The radiation doses received during medical radiography range from 0.1 to several tens of mSv, depending on the type of radiography.
- The typical dose received during a transatlantic flight (Europe-North America) from galactic cosmic rays is 0.05 mSv. It can be enhanced significantly by a solar energetic particle event (enhancements up to factor 10 have been estimated in cases of maximum exposure to an event - but those events

are sufficiently rare and short that the annual dose will in general not be fundamentally changed). Aircrew and frequent flyers may accumulate yearly doses of a few mSv.

- The airline companies have now the legal requirement to check that the air crew members do not receive, like any worker, a dose higher than 100 mSv over 5 years with a maximum of 50 mSv for a given year. The pregnant air crew, as the foetus is more exposed, should not receive more than 1 mSv until the end of her pregnancy.
- The maximum radiation dose rates in the MIR/Nausicaa measurements, shown by the largest circles in the map above, are 2 mSv/h.
- A space flight to Mars implies a radiation dose around 1 Sv due to galactic cosmic rays. This does not include the radiation dose from major solar particle events, which can be much higher and be immediately life threatening if no adequate shield has been conceived.

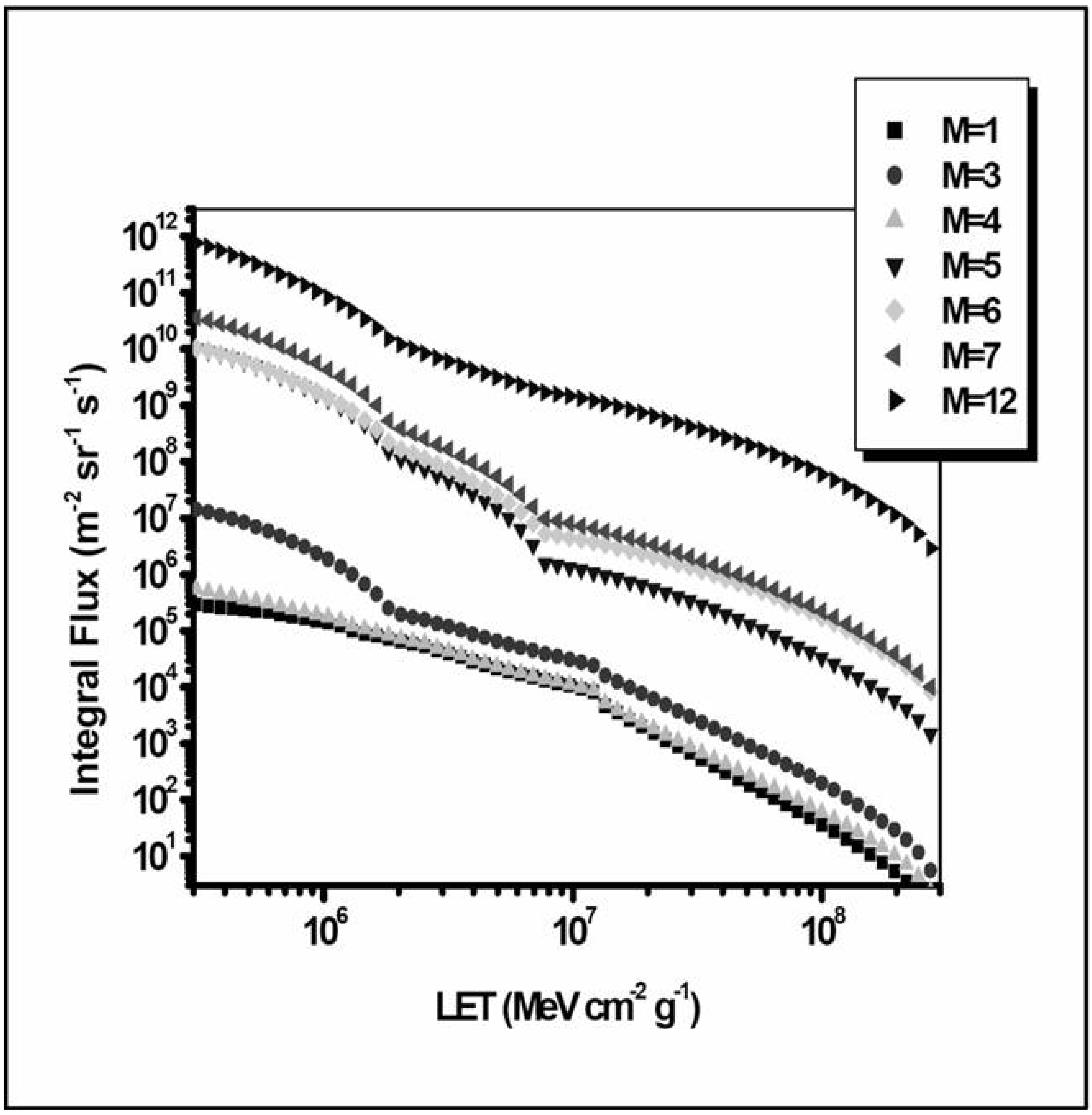
Note that due to the fact that the Sievert assesses the risk due to exposure to low levels of radiation (stochastic effects), it makes no sense to talk of values above 1 Sv.

More information (dead link)

Modelling, monitoring and prediction of particle fluxes in the Earth's atmosphere

Computer codes

The analysis of the complex space environment and its impact on space systems led to the development of empirical or quasi-empirical models by different organisations, often independently of one another. Regarding cosmic rays the most well known and used operating model is the Cosmic Ray Effects on Micro-Electronics (CREME) model, developed by NASA, which is also accessible through the Space Environment Information System (SPENVIS) interlink, developed by ESA. Both are provided with user-friendly interfaces via internet.



A model of galactic cosmic rays predicts particle flux spectra for all the elements of the periodic table from Hydrogen to Uranium and for energies varying from 1 to 10,000 MeV/nucleon. The energy - particle flux spectrum is converted into a linear energy transfer (LET) spectrum, which is a crucial parameter to understand the level of space environment hazards to microelectronics. It is also an important step in order to calculate the number of SEUs.

An example of using the SPENVIS interface's utility of LET spectra to represent the space environment and a calculation of SEU rates is illustrated in the Figure for a spacecraft on a geostationary orbit in the time interval 14th - 18th of July 2005. The following cases are considered: galactic cosmic rays (GCR; M=1), 90% worst case cosmic ray level (M=3), GCR and a singly ionised anomalous component (M=4), ordinary flare flux and mean composition (M=5), ordinary flare flux and worst case composition (M=6), 10% worst case flare flux and mean composition (M=7) and worst case flare flux and worst case composition (M=12).

Monitoring and prediction of particle fluxes using neutron monitors

Neutron monitor data are key elements in monitoring and predicting extraplanetary radiation:

- They can provide useful alerts ranging from several to tens of minutes in advance of the massive arrival of particles at lower energies - tens to hundreds MeV - in the vicinity of Earth, if a network of several stations provides high-resolution data in real time.
- Neutron monitor data enable the calculation of particle radiation in the space environment and at different altitudes within the atmosphere. They provide key information about the interactions of the galactic cosmic radiation with the plasmas and magnetic fields in the heliosphere that may also reveal the approach of interplanetary disturbances. Contrary to satellites, the operation of neutron monitors is not influenced by these events.

Like personnel of nuclear power plants or working with X-ray facilities in hospitals, the radiation exposure of each aircrew member must be monitored (a European directive from 1996 that has been translated into the national laws). Neutron monitors provide the basic data for monitoring the incident cosmic ray fluxes, which are then transformed into radiation dose rates using empirical models.

PREVIOUS
Other techniques

NEXT
Neutron monitor network: fundamental research and applications

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