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CR Damages in Planetary Environments

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Abstract

Because of the increasing in space mission duration and number of space travellers the requirement of an accurate assessment of space radiation damage and the evaluation of suitable shielding is a crucial necessity. In particular it is unavoidable in planning future missions to the Moon and Mars. In this paper the method for the evaluation of the cosmic radiation dose on board of spacecraft is described. As an example experimental measurements and MonteCarlo calculation of the contribution of various components of secondary radiation inside the FOTON–M3 ESA Satellite are described, with special attention to the neutron component.

1. Introduction

The importance of the evaluation of space radiation effects on human being health and on the electronic instrumentation on board of aircraft and spacecraft is dramatically increasing. In fact it is more and more increasing the number and altitude of commercial flights as well as the number of satellites and spacecrafts. In particular, for long term manned space missions (i.e. long permanence on the ISS International Space Station and in the future mission to the Moon and Mars), the success of the project strictly depends from the evaluation and shielding of cosmic radiation [1-3], both for aircrew health and high precision instruments protection.

2. Space radiation environment

To evaluate the radiation dose inside a spacecraft, it is necessary to distinguish between primary radiation, due to primary cosmic rays in free space, and secondary radiation produced by the primary particles interacting with shielding materials of the vehicles.

2.1 Primary radiation

The primary radiation is composed mainly by Galactic Cosmic Rays (GCR) produced in supernovae explosions and accelerated by shock waves, composed of hadrons (98%) and leptons (2%). The hadron component consists of protons (87%), alpha-particles (12%) and heavy-ions (1%). Cosmic ray flux on Earth is modulated by solar activity, following the 11-years solar cycle. In addition, during solar flares, a contribution is due to Solar Particle-Events (SPE), in general large clouds of charged particles (mainly protons and helium nuclei in a wide range of energy). During the Apollo programme, between the manned missions 16 and 17, one of the largest solar particle-events occurred (August 4-9, 1972). Radiation doses to the crew inside the thinly shielded lunar module or during extravehicular activities during such an event would have been extremely serious. The main number of spacecraft and steady telecommunication satellites orbit in LEO (Low Earth Orbits) paths, between 350 and 2000 Km from the Earth, with a typical 90 min period. At these altitudes, the main contribution to the dose is due to the trapped particles in the Van Allen belts, due to the geomagnetic field shape. The geomagnetically trapped radiation consists of electrons with $E > 0.5$ MeV, protons with $E > 10$ MeV and few helium nuclei.

Over the south atlantic region, the geomagnetic field draws particles closer to the Earth. This region is known as the South Atlantic Anomaly (SAA). At an orbit below an altitude of about 550 km a considerable part of absorbed radiation dose is caused by passing the SAA (about 30%).

2.2 **Secondary radiation**

The total dose inside the spacecraft strongly depends from the shielding material composition. In fact the primary radiation interacts with the spacecraft walls, producing a complex secondary shower. Secondary radiation consists of different particles, (protons, neutrons, electrons, heavy ions) and from a radioprotection point of view, could be more dangerous that the primary radiation. The effects of the radiation, both on human cells and electronic components depend on the energy release along their tracks. The LET (Lineal Energy Transfer) expressed in keV/µm is an index of the ionization density along the particle track in a tissue: higher density corresponds to higher biological damage. In table 1 the values of LET for different radiations are shown.

PARTICLE	**LET_∞**
Electrons	0.2 – 30 keVμm^{-1}
Protons	50 – 100 keVμm^{-1}
Alfa	40 – 250 keVμm^{-1}
Heavy Ions	100 – 4000 keVμm^{-1}

Table 1: Lineal Energy Transfer value for different radiations.

Low LET radiation produces a Single Strand Break (SSB) on the DNA structure that can be repaired; high LET radiation produces a Double Strand Break (DSB) with no repair.

3. Evaluation of radiation damage

The evaluation of space radiation damage is performed both by experimental technique and MonteCarlo (MC) simulation. The measurements of the various components is quite difficult, because each kind of radiation requires a specific detector. In case of secondary neutrons, characterized by an energy range covering more that eleven magnitude orders, different detectors have to be employed for different energy range.

MC codes (GEANT4, FLUKA, MCNPX) are used for the simulation of the space radiation environment and the transport inside the aircraft.

3.1 Dosimetric quantites

The main dosimetric quantities used in radiation damage evaluation are:

- Absorbed dose D : energy of radiation R absorbed per unit mass expressed in Gy (J/Kg)

- Equivalent Dose H : sum of contributions of dose from different radiation types, each multiplied by the radiation weighting factor (w_R) expressed in Sv (J/Kg)

$$H = \Sigma_R \, w_R \, D_R$$

- Ambient Dose Equivalent H^* : is the dose equivalent related to the ICRU sphere at a d depth in millimetres expressed in Sv (J/Kg).

3.2 Experimental measurements

In this work special attention is paid to the secondary neutron dose evaluation because of their high RBE (Relative Biological Effectiveness). Passive detectors are chosen to avoid interference with on board electronics. Typical neutron detectors are bubble dosimeters, CR39 foils and Bismuth stack tracks detectors.

Bubble dosimeters (BTI, Ontario Canada), calibrated against an AmBe source in terms of NCRP38 [4], are suitable for neutron integral dose measurements in the range of thermal energy (BDT model 0.025 eV) and fast neutron energy (BD-PND model 100 keV – 20 MeV) [5] (with suitable conversion factor ambient dose equivalent H^* could be obtained). CR39 (20 MeV -200 MeV) is a polymeric solid-state nuclear track detector which is widely used for neutron dosimetry. CR39 detects neutrons by the damage tracks produced by secondary particle subsequently revealed by a suitable chemical etching process [6]. Bismuth stack detector, for relativistic neutrons (E > 200 MeV), consists in a stack of ^{209}Bi layers and Mylar foils: the fission fragments coming form the neutron interaction with bismuth layer produce tracks on the Mylar foils [7].

To elaborate the reading of various detectors, unfolding codes are required. The special code BUNTO has been written at INFN Torino to be used with passive detector systems, characterized by high relative errors [8]. The code is based on the random sampling of unfolding data from a normal distribution, whose parameters (mean value and standard deviation) are the average experimental reading and the associated statistic uncertainty. The BUNTO final spectrum is calculated as a mean of possible solutions of the unfolding procedure, weighted on the mean standard deviation.

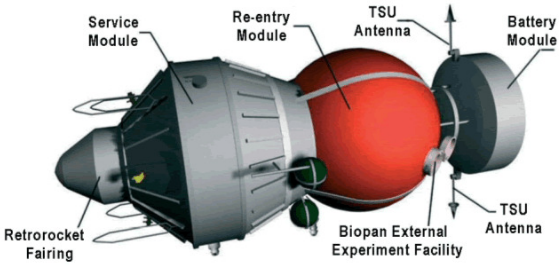
3.3 MC simulation

To compare and verify the experimental data different MC codes can be used (MCNPX, GEANT4 and FLUKA). The first step consists in the calculation of external radiation environment on the base of spacecraft orbit parameters with the support of NASA database. As second step the energy spectra of primary particles (protons and alpha) are used as input data for the MC codes for particle transport; a geometry representation of the vehicle and the composition of shielding materials is also used in the simulation code. Finally the external radiation is transported inside the aircraft and the interaction of cosmic particles with the shielding is calculated to obtain the energy and composition of secondary shower components.

In this paper as an example the dose evaluation inside and outside of the FOTON–M3 ESA satellite is described.

4 FOTON–M3 ESA Mission

FOTON–M3 is an un-manned satellite with a re-entry module who carried in Low-Earth-Orbit (inclination orbit 63°, mean altitude ~280 km) more than 40 experiments selected by the European and Italian Space Agencies and related to a big range of scientific disciplines (including fluid physics, biology, crystal growth, radiation exposure and exobiology). During a mission, FOTON–M (Fig. 1) orbits at a maximum altitude of about 304 km and a minimum altitude of about 262 Km, inclined at 63º. Outside the satellite the Biopan module is installed: it is a special container that is open when the satellite is on the orbit, in way that the biological experiments inside are directly exposed to the external radiation (Fig. 2).



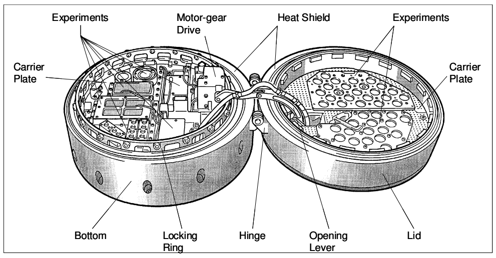


Fig. 1: Scheme of Foton-M satellite

Fig. 2 Scheme of Biopan module

The dose evaluation has been performed both by experimental measurements and by MC simulation. During its flight, FOTON–M3 encountered mainly two radiation components: Galactic Cosmic Rays and particles trapped in the Van Allen belts. To model the radiation environment during the flight the orbital parameters were obtained from public NORAD-NASA database [9]. The differential fluxes of proton and alpha components are obtained separately for GCR and Van Allen Belts. For GCR, the tool OMERE (a standalone freeware tool computing the space environment and the radiation effects on a orbit user defined) [10] is used; for Van Allen Belts particles SPENVIS (Space Environment Information System, a web interface to model of the space radiation environment about a defined satellite orbit) is used [11]. Finally these data are employed as input in the simulation with GEANT4 MC code [12].

The geometry (Fig.3) of re-entry module is represented by a sphere r = 1130 mm , the external shield is composed of Carbon fibres, with two internal layers of Al alloy (93 % Al , 7 % Cu, Fe and Mg) and Kevlar (C 71%; O 12%; N 13%; H 4%)

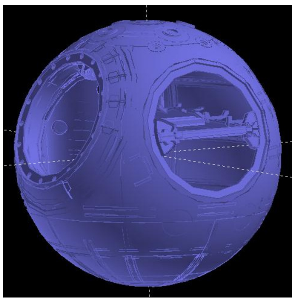


Fig. 3 Screen shoot of the FOTON–M capsule geometry imported into simulation code (Geant4) using Fastrad tool [13]. (Image kindly provided by ESA).

In figures 4 and 5 secondary neutron spectra in the energy interval up to 20 MeV are shown (obtained by using MC code GEANT4). In figure 4 the neutron dose rate due to GCR (proton component) is 8 μSv/day. In figure 5 the neutron dose rate due to GCR (alpha component) is 1 μSv/day.

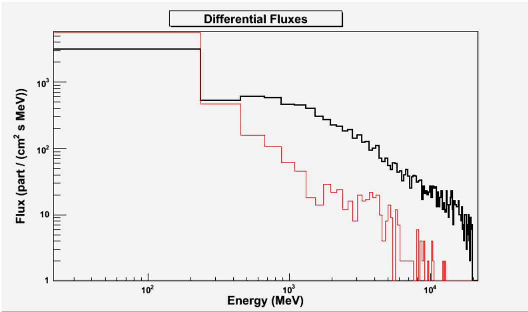


Fig. 4: GCR primary flux (proton component – black line) and the secondary neutron flux inside the satellite (red line).

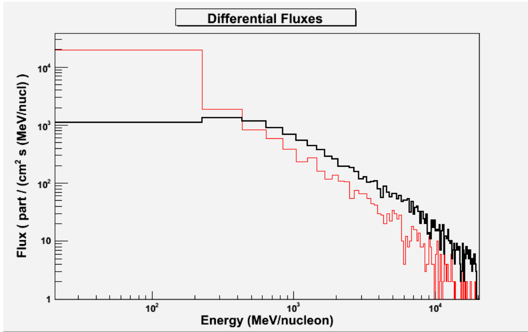
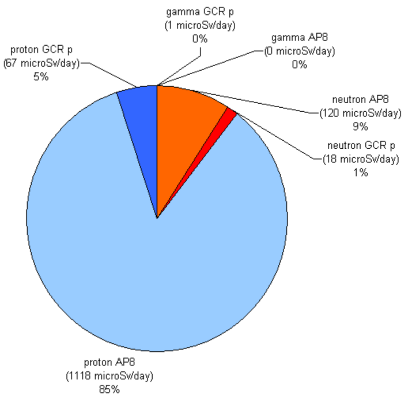


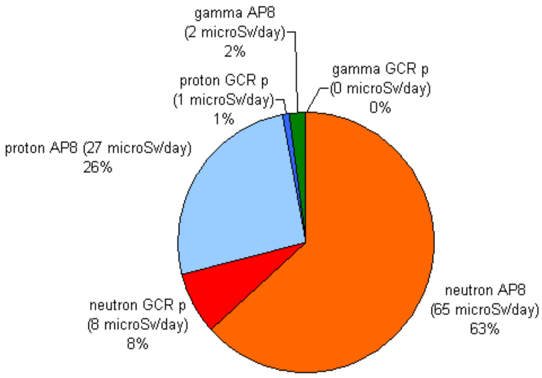
Fig. 5: GCR primary flux (alpha component – black line) and the secondary neutron flux inside the satellite (red line).

The relative percentage of secondary particles inside the satellite has also been calculated in two different energy intervals (figs. 6 and 7).



Proton AP8 (1118 µSv/day) 85%
Proton GCR p (67 µSv/day) 5%
Neutron AP8 (120 µSv/day) 9%
Neutron GCR p (18 µSv/day) 1%

Fig. 6 Ambient Dose Equivalent Rate (0-20 GeV)



Proton AP8 (27 µSv/day) 26%
Proton GCR p (1 µSv/day) 1%
Neutron AP8 (65 µSv/day) 63%
Neutron GCR p (8 µSv/day) 8%
Gamma AP8 (2 µSv/day) 2%

Fig. 7 Ambient Dose Equivalent Rate (0-20 MeV)

From the comparison, it is possible to note that the secondary neutron equivalent dose rate strongly depends from the neutron energy range. Finally, the neutron component in the energy interval from 100 keV up to 20 MeV obtained with BD-PND detector (70±23) µSv/day is compared with the simulation result (73±10) µSv/day in the same energy range.

Conclusion

The importance of accurate evaluation of damage due to CR interactions with aircraft shielding is more and more increasing because of the long term manned space missions planned in the next future and the high number of spacecraft for planetary exploration.
As an example, in this paper is described the evaluation of the neutron component of the radiation environment in a particular Low Earth Orbit, the one followed by the FOTON–M3 satellite. Secondary neutrons are high LET radiation and their energy cover more than eleven order of magnitude and they can produce dramatic damages to the astronauts' health and the instrumentations. The method here described based on both experimental measurements with passive detector and MC simulation could contribute to a better assessment of the radiation environment in Low Earth Orbit.

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