Experimental data and GEANT4 Monte Carlo predictions of the radiation environment on board Foton-M3 satellite

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Foton-M3 is a Low Earth Orbit mission that took place from 14 to 26 September 2007. The satellite carried on board more than 40 experiments related to different scientific disciplines. Among them, three independent devices monitored the space radiation environment inside and outside the capsule, providing a wide set of dose and particle flux data.

The Liulin-Photo and R3D-B3 active spectrum-dosimeters were placed on board the spacecraft behind different shielding, inside and outside the capsule respectively. They are devices based on a silicon detector that measure in real-time the energy deposited by the incident ionizing particles and determine the energy spectrum and the absorbed dose. During Foton-M3 mission Liulin-Photo and R3D-B3 collected data with a sampling rate of 60 seconds. The comparison of their simultaneous and homologous measurements offers the very interesting opportunity to evaluate the effects of the Foton capsule shielding.

A set of passive dosimeters Bubble Detector (BDT) was also used to investigate the neutron component of the radiation field inside the capsule, testing the effectiveness of different shielding materials. Neutrons are a not avoidable component of the secondary radiation produced by the interaction of primary particles with the spacecraft shielding. They are high-LET particles and represent a main risk for both the electronics and biological organisms exposed to radiation during a space mission.

In this study we present some results from all the above mentioned experiments, providing a description of the radiation environment inside Foton-M3. Along with the analysis of the experimental data, a simulation study with GEANT4 Monte Carlo code was also performed. The transport of the free-space particles through the capsule shielding was simulated to evaluate the internal neutron and proton fluxes and the neutron doses as a function of neutron energy. Here we compare the numerical predictions obtained by GEANT4 code with the experimental results.

The overall discussion is preceded by an analysis of space weather recorded at the time of the mission, showing that Foton-M3 flight took place in a period of very low solar activity in the minimum phase of the 23rd solar cycle. This circumstance determined stable conditions in the radiation environment along the satellite orbit.

Introduction

Foton-M3 is an unmanned, Low Earth Orbit (LEO) satellite with a re-entry module launched on 14 September 2007. It flew for 12 days and its payload was composed of more than 40 experiments selected by the European and Italian Space Agencies and related to a wide range of scientific disciplines (including fluid physics, biology, crystal growth, radiation exposure and exobiology). Among them, three independent devices monitored the space radiation environment inside and outside the capsule, providing a wide set of dose and particle flux data.

In this paper some results from the active spectrum-dosimeters R3D-B3 and Liulin-Photo (L-P) and from passive neutron Bubble Detectors will be presented and discussed. The experimental data will be then compared with a simulation study of the radiation environment inside the capsule performed with the GEANT4 Monte Carlo code.

Description of the experiments

Foton-M3 mission details

Launched on 14 September 2007 at 11UT from the Baikonour Cosmodrome (Kazakhstan), Foton-M3 satellite was placed on a 63° inclined orbit with a 263 km perigee and a 302 km apogee. After completing 189 orbits the retrievable capsule landed on 26 September at 07:58UT. The orbital parameters used in this study were calculated with KADR-2 software [1].

R3D-B3 and Liulin-Photo spectrum-dosimeters

R3D-B3 and L-P are active dosimeters that monitored in real time the dose rate and flux respectively outside and inside Foton-M3 capsule, with a sampling rate of 60 seconds. The dosimeters have similar characteristics, being exemplars of the same, well-known Liulin-type dosimeters already used successfully in several LEO missions. They measure the energy deposited on a silicon detector (area 2 cm^2) by each incident ionizing particle. The energy spectrum is then digitized in 256 channels and used to determine the particle flux and to calculate the dose rate in the sampling interval.

L-P was mounted on the top of the Photo-II experiment, an automated sensor system that monitored in real-time the photosynthetic activity of several mutants of the unicellular green alga *Chlamydomonas reinhardtii* in response to the effects induced by the space ionizing radiation.

R3D-B3 was placed inside Biopan-6, a shell-like facility mounted externally to the satellite capsule. The Biopan lid was opened once Foton-M3 was in orbit exposing the experiment to free space behind ~ 0.81 g/cm^2 of shielding, and then it was closed ~ 1.5 days before the end of mission.

After the Biopan closure the shielding surrounding R3D-B3 increased to ~ 5.8 g/cm^2.

Neutron Bubble Detector dosimeters

The neutron component of the radiation field inside the satellite was evaluated by using Bubble Detectors (BTI, Ontario, Canada) BDT model, placed into a little container with other dosimeters (TLDs). These neutron detectors have the following features:

- Energy sensitivity: thermal neutrons
- Dose range: 0.1÷10 mRem
- Gamma sensitivity: none
- Calibration: NCRP38

Three BDT were placed inside the satellite behind different shielding: one was shielded with Aluminum, other with Kevlar, the third was not shielded (Fig.1). A control dosimeter was used to evaluate the background neutron dose recorded during the days of the mission.

Experimental and simulation results

Space weather during Foton-M3 flight

Selected ground and space-based measurements from 14 to 26 September 2007 show very quiet conditions in space (Fig.2). The Sun was spotless for the entire period and the solar activity was very low. No solar flares or fast and wide coronal mass ejections were recorded. The geosynchronous GOES-11 satellite did not detect any Solar Proton Events and cosmic rays counts in ground-based neutron monitors do not show appreciable variations. According the Dst index, there is no evidence for geomagnetic storms. At the same time the southward B_z component of the interplanetary magnetic field and the solar wind velocity (measured by the ACE spacecraft) do not show features that could trigger intense perturbations in the Earth magnetosphere. On 20 September the Earth entered a corotating interaction region, as shown by the increase of the solar wind velocity (Fig. 2, first plot), but with no subsequent geoeffectiveness.

This results lead to the conclusion that the space radiation environment along the Foton-M3 orbit should have maintained stable its properties during the entire mission, without sharp and wide temporal changes.

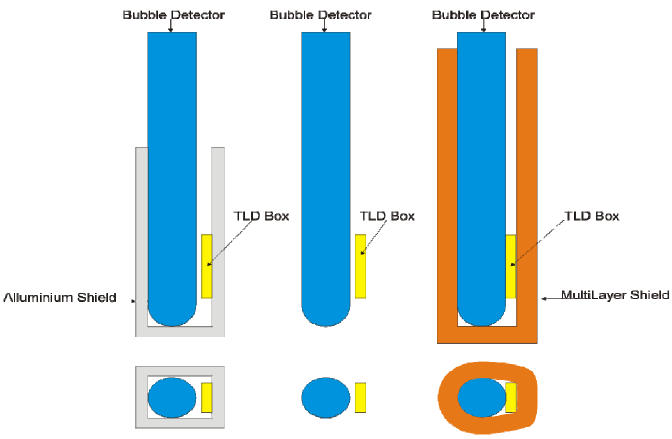

Fig. 1. The neutron Bubble Detector configuration inside Foton-M3 capsule.

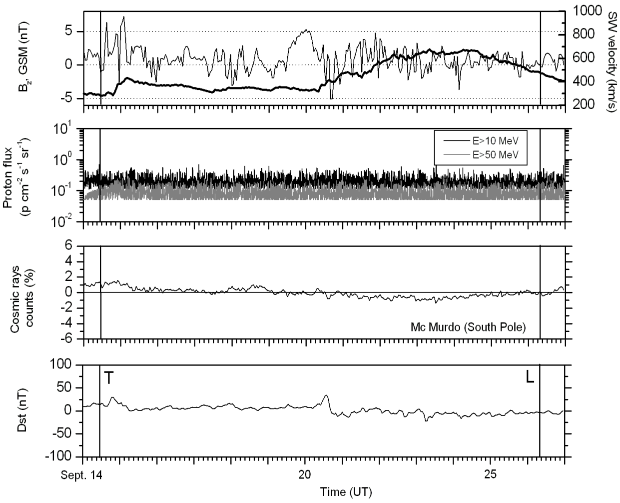

Fig. 2. Space weather during the Foton-M3 flight. The selected data were collected by ground-based stations and spacecrafts. The vertical lines T and L mark respectively the take-off and landing of Foton-M3.

R3D-B3 and Liulin-Photo measurements

Tab.1 summarizes the main dose measurements obtained by the active spectrum-dosimeters. Fig. 2 shows some experimental data. In graphs a) and b) the dose rate and particle flux distributions vs. the McIlwain's L parameter are plotted. It is possible to distinguish the various radiation components, taking into account the different shielding surrounding the devices.

An increase in the dose rate and flux with respect to the Galactic Cosmic Rays (GCR) background is observed in both R3D-B3 and L-P data starting from L=1.1. This is produced by charged particles trapped in the inner Van Allen belt and in the South Atlantic magnetic Anomaly (SAA) region in particular (protons up to 300-400 MeV). The outer borders of this region, populated by less energetic protons, are different for the two devices. As observed by R3D-B3 the inner belt terminates at L=2.5 while for L-P the belt is narrower, ending at L=2. This difference is due to the higher L-P shielding.

The contribution of the trapped relativistic electrons to dose rate and flux are observed only by R3D-B3 in the range L=3.2÷7. The shielding surrounding L-P was too high for the outer belt electrons to penetrate inside the Foton capsule. R3D-B3 recorded the maximum dose rate 2315 µGy/h at L~4.4. A small dose rate peak is visible at L=7 (35 µGy/h).

The GCR contribution is represented by the ticker part in dose and flux plots that shows a knee around L=3. GCR component is in practice equal in both instruments for all the L values. The dose values range from 10 to 15 µGy/h starting from L=3 up to L=25 (out of scale).

Plot c) in Fig.3 shows the deposited dose spectra for both instruments, corresponding to the crossovers of the SAA. They were obtained as an average over 20 spectra recorded simultaneously by the dosimeters in the L-range 1.24÷1.63, corresponding to a narrow region centered in the point of geographical coordinates S32 W41. The L-P spectra correspond to dose peaks higher than 100 µGy/h, representing the highest values for this device. All the R3D-B3 spectra were recorded before the closure of the Biopan lid.

Table 1
Summary of some dose measurements obtained by R3D-B3 and Liulin-Photo spectrum-dosimeters on board Foton-M3

	Total dose (mGy ±10%)	**Minimum hourly dose rate (µGy/hour ±10%)**	**Max. hourly dose rate (µGy/hour ±10%, geographic coordinates of the measurement location)**	**Average daily dose rate (µGy/day ±10%)**
R3D-B3	3.06	0.347	2314.85 (S63.02 W24.08) (relativistic electrons)	283.68
Liulin-Photo	1.85	0.29	292.14 (S32.98 E39.13) (Inner belt trapped protons)	155.61

The dose spectra are calculated as a function of the deposited energy (DE) and kinetic energy of the incident particles on the detector (KE). We can reasonably assume that the dose is deposited mostly by the protons trapped in the SAA. Under this hypothesis it is possible to convert DE to KE using a power law expression obtained from calibration curves and GEANT code predictions for Liulin-type instruments [2, 3]. The spectra in Fig.3 have a similar shape for both dosimeters. The R3D-B3 spectrum stands over L-P spectrum for DE<10 MeV, due to lower shielding. For the same reason, in R3D-B3 the maximum of the dose is deposited by 56 MeV protons, while it moves to higher value of 66 MeV for L-P.

GEANT4 Monte Carlo simulation: the set-up

We performed a first attempt to reconstruct some properties of the radiation environment inside Foton-M3 capsule by Monte Carlo simulations. The simulation toolkit used for this study is GEANT4, a code developed by CERN to simulate the transport of particles through the matter and used in high energy physics, medical and space sciences. In our study, taking into account the technical complexity of implementing the simulation, the Foton-M3 spacecraft structure was simplified and modeled as a sphere of radius r=1130 mm composed of 3 spherical layers made of different materials: the external heat shield (Carbon Fiber, thickness 5 cm); an equivalent Aluminum shell (Al-2219-T851, thickness 3.3 cm) to implement the satellite infrastructure; an internal equivalent Kevlar shell (C, 71%; O, 12%; N,13%; H, 4%, thickness 3.7 cm) to model the mission equipment.

As shown in Fig.3, Foton-M3 encountered 3 radiation components during the flight: GCR and Van Allen trapped particles (protons and relativistic electrons). In the simulation GCR and trapped protons were treated separately as primary particles impinging on the satellite wall (as experimentally observed, outer belt relativistic electrons do not penetrate the capsule shielding). The orbit averaged differential fluxes of proton and alpha components of GCR were modeled by OMERE suite tool (based on Nymmik model) [4]. Only protons and alpha particles were considered because of the low contribution of other particles to the total secondary neutron dose. The orbit averaged differential flux of trapped protons in the inner Van Allen belt was evaluated by the SPENVIS tool using the NASA AP8-min model [5].

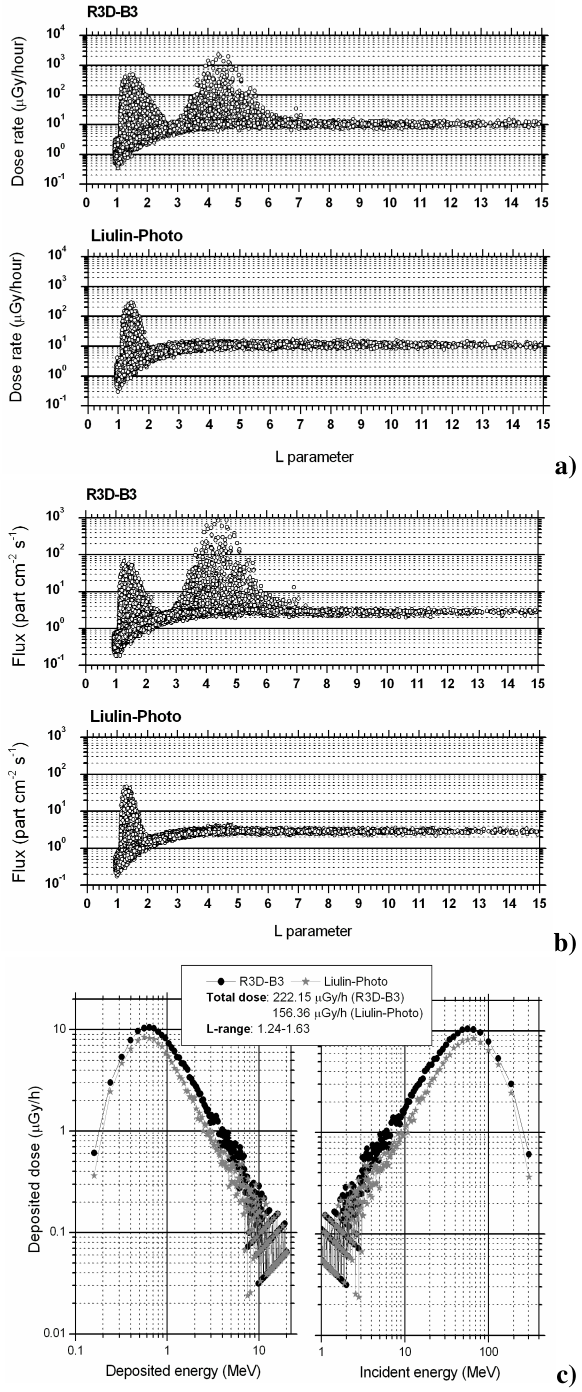

Fig. 3. Some experimental data from R3D-B3 and Liulin-Photo. Panels a) and b) show respectively the dose rate and particle flux distributions vs. McIlwain's L-parameter. Panel c) show the average deposited dose spectra for crossovers of the South Atlantic Anomaly as function of the particle deposited energy (left side plot) and of the kinetic energy (right side plot). The right plot was derived under the hypothesis that the main contribution to the deposited dose in all the energy channels is due to trapped protons.

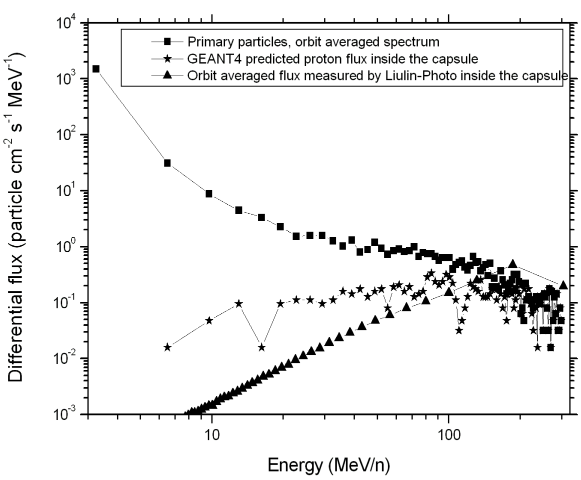

Fig. 4. Comparison between the orbit averaged proton spectrum measured by Liulin-Photo inside Foton-M3 capsule (▲) and the one predicted by GEANT4 Monte Carlo code (□). The free-space, trapped proton spectrum obtained with the NASA AP8-min model and used as input for the simulation is also showed (■).

GEANT4 Monte Carlo simulation: results

In Fig. 4 the comparison between the orbit averaged proton energy spectrum obtained by L-P and the spectrum predicted by the Monte Carlo code is showed. The L-P proton spectrum as function of the KE of the particles was obtained from the spectrum as a function of the DE (the one L-P can actually determine), under the hypothesis previously explained.

In order to calculate the neutron dose rate, the GEANT4 simulations are carried out considering separately the Inner Van Allen belt protons, protons and alpha particles of the GCR component. For all these particle population, the relative neutron flux inside the Foton-M3 capsule is first evaluated. The neutron dose rate was then computed using the NCRP38 coefficients [6] to convert the particle flux in Equivalent dose rate in order to make a comparison with the experimental data (Tab. 2). The equivalent dose rate (NCRP38) determined by the no-shielded BDT is 78±23 µSv/day. GEANT4 simulation predicts 93±10 µSv/day, in good agreement with the experimental data.

Table 2
Summary of the GEANT4 predictions for the neutron component inside Foton-M3 capsule

Primary	Averaged particle integral flux (part/ cm^2 s)	Neutron dose rate per primary (mSv/day prim)	Neutron dose rate (mSv/day)
GCR protons	0.6671	12	8
GCR alphas	0.02	61	1
Van Allen protons	1591	0.053	84
TOTAL			93

Conclusions

In this work we presented and discussed some measurements collected from 3 different dosimeters on board Foton-M3 spacecraft, which flew in Low Earth Orbit in September 2007 during the minimum phase of the 23rd solar cycle. The devices -two active dosimeters, R3D-B3 and Liulin-Photo (L-P), and a set of neutron Bubble Detectors- were placed behind different shielding. The experimental results provide information about different components of the radiation field on board the satellite and contribute to a better characterization of the radiation environment in Low Earth Orbit [7]. The analysis of space weather data showed that the entire flight took place during a period of very low solar activity which determined stable conditions in the radiation environment along the satellite orbit. Concerning the active dosimeters, the crossovers of the inner Van Allen radiation belt were characterized by dose and flux peaks in both the devices, up to 481 µGy/h for R3D-B3 and as high as 292 µGy/h for L-P (19% less due to higher shielding). Peaks are due to trapped protons with energy up to 300-400 MeV. In correspondence of the satellite passages above the central part of the inner Van Allen belt, we found that the maximum dose was deposited on average by 56 MeV protons in the case of R3D-B3, and by 66 MeV protons for L-P. Relativistic electrons in the outer Van Allen belt were recorded only by R3D-B3, with dose rates as high as 2314 µGy/h. L-P was behind a too high shielding to reveal the trapped electrons. We also performed a comparison between experimental data and predictions obtained by a preliminary simulation study with GEANT4 Monte Carlo code finalized to reconstruct some components of the radiation field inside Foton capsule. Results from this comparison show an encouraging good agreement for both the proton and the neutron components.

REFERENCES

[1] Galperin, Yu.I., Ponamarev, Yu.N., Sinizin, V.M., 1980. Some algorithms for calculation of geophysical information along the orbit of near Earth satellites. Report No 544, Space Res. Inst., Moscow (in Russian).

[2] Dachev, T., Tomov, B., Matviichuk , Yu. N., Dimitrov, P., Lemaire, J., Gregoire, Gh., Cyamukungu, M., Schrnitz, H., Fujitaka, K., Uchihori, Y., Kitamura, H., Reitz, G., Beaujean, R., Petrov, V., Shurshakov, V., Benghin, V., Spumy, F., 2002. Calibration results obtained with Liulin-4 type dosimeters. Adv. Sp. Res. 30, 4, 917-925.

[3] Dachev, T., Atwell, W., Semones, E., Tomov, B., Reddell, B., 2006. Observations of the SAA radiation distribution by Liulin-E094 instrument on ISS. Adv. Sp. Res. 37, 1672-1677.

[4] OMERE, a toolkit for space environment modelling available on-line at http://www.fastrad.net/index/main.html

[5] SPENVIS. a toolkit for space environment modelling available on-line at http://www.spenvis.oma.be

[6] NCRP38. Home Page: http://www.ncrp.org/

[7] Benton, E.R., & Benton, E.V., 2001. Space radiation dosimetry in low-Earth orbit and beyond. Nucl. Instr. and Meth. in Phys. Res. B 184, 255-294.

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