Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 25, 2013, Sofia

PRELIMINARY RESULTS FOR THE RADIATION ENVIRONMENT OBSERVED BY RD3-B3 RADIOMETER-DOSIMETER INSIDE BION-M № 1 SPACECRAFT

***Tsvetan Dachev*[1]*, Borislav Tomov*[1]*, Yury Matviichuk*[1]*, Plamen Dimitrov*[1]**
Nikolay Bankov*[1]*, Vladisloav Petrov*[2]*, Viacheslav Shurshakov*[2]*,
Olga Ivanova*[2]*, Donat-Peter Häder*[3]*, Michael Lebert*[4]*,
***Martin Schuster*[4]*, Günter Reitz*[5]*, Gerda Horneck*[5]*, Ondrej Ploc*[6]**

[1]*Space Research and Technology Institute – Bulgarian Academy of Sciences*
[2]*State Research Center Institute of Biomedical problem – Russian Academy of Sciences*
[3]*Neue Str. 9, 91096 Möhrendorf, Germany*
[4]*Friedrich-Alexander-Universität, Institut für Botanik und Pharmazeutische Biologie, Erlangen, Germany*
[5]*DLR, Institute of Aerospace Medicine, Köln, Germany*
[6]*Nuclear Physics Institute, Czech Academy of Sciences, Praque, Czech Republic*
e-mail: tdachev@bas.bg

Abstract

Space radiation has been monitored using the РДЗ-БЗ (further is used the Latin transcription RD3-B3) spectrometer-dosimeter on board a recent space flight on the Russian recoverable satellite БИОН-М № 1 (further is used the Latin transcription BION-M № 1). The instrument was mounted inside of the satellite in pressurized volume together with biological objects and samples. RD3-B3 instrument is a battery operated version of the spare model of the R3D-B3 instrument developed and built for the ESA BIOPAN-6 facility on Foton M3 satellite flown in September 2007. Cosmic ionizing radiation has been monitored and separated in 256 deposited energy spectra, which were further used for determination of the absorbed dose rate and flux. The report summarizes the first results for the Earth radiation environment at the altitude (253–585 km) of the BION-M № 1 spacecraft.

1. Introduction

The radiation field inside the BION-M № 1 spacecraft is complex, composed of GCRs, trapped radiation of the Earth's radiation belts, possible solar energetic particles, albedo particles from Earth's atmosphere and secondary radiation produced in the shielding materials of the spacecraft and biology objects. Dose characteristics in BION-M № 1 spacecraft also depend on many other parameters such as the spacecraft orbit parameters, solar cycle phase and current helio-and geophysical parameters.

This paper analyses the first results for the radiation environment inside the BION-M № 1 spacecraft generated by different radiation sources, including: Galactic Cosmic Rays (GCRs), IRB trapped protons in the region of the South Atlantic Anomaly (SAA) and outer radiation belt (ORB) relativistic electrons. The satellite was launched on 19 April 2013 at 10:00 UT from the Cosmodrome of Baikonur (Kazakhstan). On 19th of May at 03:12 UT the Landing module of BION-M № 1 successfully touched down at Orenburg region, after 30 days in orbit. http://biosputnik.imbp.ru/eng/index.html

1.1. Earth radiation environment at BION-M № 1 spacecraft orbit

1.1.1. Galactic cosmic rays

The dominant radiation component in the ISS radiation environment consists of GCRs modulated by the altitude and geomagnetic coordinates of the space craft. GCRs are charged particles that originate from sources beyond the Solar System. They are thought be accelerated at highly energetic sources such as neutron stars, and supernovae within our Galaxy. GCRs are the most penetrating of the major types of ionizing radiation [1]. The fluxes and spectra of GCR particles show modulation that is anti-correlated with solar activity. The distribution of GCRs is believed to be isotropic throughout interstellar space. The energies of GCR particles range from several tens up to 10^{12} MeV nucleon^{-1}. The GCR spectrum consists of 98% protons and heavier ions (baryon component) and 2% electrons and positrons (lepton component). The baryon component is composed of 87% protons, 12% helium ions (alpha particles) and 1% heavy ions [2]. Highly energetic particles in the heavy ion component, typically referred to as high Z and energy (HZE) particles, play a particularly important role in space dosimetry and strongly affect humans and other biological entities in space

[3]. HZE particles, especially iron, possess high-LET and are highly penetrating, giving them a large potential for inflicting radiobiological damage [4]. The daily average GCR absorbed dose rates measured with the R3DE instrument [5] outside of the ISS at about 360 km altitude vary in the range 77-102 μGy day^{-1} with an average of 91 μGy day^{-1}. The expected BION-M № 1 dose rates are higher because of the higher altitude.

1.1.2 Trapped radiation belts

Radiation belts are regions with high concentrations of energetic electrons and protons trapped within the Earth's magnetosphere. There are two distinct belts of toroidal shape surrounding Earth where the high energy charged particles get trapped in the Earth's magnetic field. Energetic ions and electrons within the Earth's radiation belts pose a hazard to both astronauts and spacecraft electronics. The inner radiation belt (IRB), located between about 0.1 to 2 Earth radii, consists of electrons with energies up to 10 MeV and protons with energies up to ~ 200 MeV. The South-Atlantic Anomaly (SAA) is an area where the IRB comes closer to the Earth's surface due to a displacement of the magnetic dipole axes from the Earth's center. The daily average SAA absorbed dose rates measured with the R3DE instrument [5] outside of the ISS at about 360 km altitude vary in the range 110-685 μGy day^{-1} with an average of 426 μGy day^{-1}. The maximum hourly SAA absorbed dose rates reached 1500-1600 μGy h^{-1}. It was found [6] that the docking of the US Space Shuttle with the ISS strongly decreases the SAA doses because of the additional shielding that the 78-ton body of the Shuttle provides against the IRB protons. The expected BION-M № 1 dose rates are higher because of the higher altitude.

The outer radiation belt (ORB) starts from about four Earth radii and extends to about nine to ten Earth radii in the anti-sun direction. The outer belt mostly consists of electrons whose energy is not larger than 10 MeV. Relativistic electron enhancements in the ORB are one of the major manifestations of space weather [7, 8] near Earth's orbit. These enhancements occur mainly after magnetic storms. The electron flux may cause problems for components located outside a spacecraft (e.g., solar cell degradation). ORB electrons do not have enough energy to penetrate a heavily shielded spacecraft such as the ISS wall but may deliver large additional doses to astronauts during EVA [5, 9, 10]. The average ORB dose rate measured with the R3DE [5] outside of the ISS at about 360 km altitude is 8.64 μGy day^{-1}, and ranges between 0.25 and 212 μGy day^{-1}. Rare sporadic fluxes of relativistic electrons were measured with the R3DR instrument to deliver absorbed doses as high as 20,000 μGy h^{-1}. The expected BION-M № 1 dose rates are lover because of the higher shielding inside the BION-M № 1 satellite.

1.1.3 Solar energetic particles (SEP)

The SEP are mainly produced by solar flares, sudden sporadic eruptions of the chromosphere of the Sun. High fluxes of charged particles (mostly protons, some electrons and helium and heavier ions) with energies up to several GeV are emitted by processes of acceleration outside the Sun. It is now generally understood that SEP events arise from coronal mass ejections (CME) from active regions of the solar surface. The CME propagates through interplanetary space carrying along with it the local surface magnetic field frozen into the ejected mass. There is a transition (shock) region between the normal sectored magnetic structure of interplanetary space and the fields frozen into the ejected mass, which forms a transition region (shock) where the interplanetary gas is accelerated forming the SEP. As the accelerated region passes an observation point, the flux intensity is observed to increase dramatically [11]. The time profile of a typical SEP starts off with a rapid exponential increase in flux, reaching a peak in minutes to hours. The energy emitted lies between 15 and 500 MeV $nucleon^{-1}$ and the intensity can reach 104 cm^{-2} s^{-1} sr^{-1}. Electrons with energies of 0.5 to 1 MeV arrive at the Earth, usually traveling along interplanetary field lines, within tens of minutes to tens of hours. Protons with energies of 20 to 80 MeV arrive within a few to 10 h, although some high energy protons can arrive in as early as 20min. SEP are relatively rare and occur most often during the solar maximum phase of the 11-year solar cycle. In the years of maximum solar activity up to 10 flares can occur, during the years of minimum solar activity only one event can be observed on average [12].

2. Instrumentation

In order to determine and quantify the radiation field outside the Foton M2/M3 satellites a radiation environment spectrometers-dosimeters R3D-B2/B3 were developed by the collaboration of the Bulgarian and German teams and integrated into the Biopan-5/6 facilities [13-15]. Both of them worked successfully during the Foton M2/M3 missions. The RD3-B3 spectrometer-dosimeter used at the BION-M № 1 mission is a battery operated version of the spare model of the R3D-B3 instrument developed and built for the ESA Biopan-6 facility on Foton M3 satellite in September 2007 [10, 16].

The scientific objectives of the RD3-B3 spectrometer-dosimeter were in first order connected with the quantification of the global distribution of the radiation field inside the BION-M № 1 satellite.

Also there was housed other 17 scientific equipment’s http://biosputnik.imbp.ru/eng/science_tech.html related to different scientific disciplines. For many of the experiments on board the knowledge of the space radiation properties and the dynamics of the dose accumulation is highly important for the interpretation of the data collected during the mission.

The RD3-B3 instrument is successor of the Liulin-E094 instrument, which was part of the experiment Dosimetric Mapping-E094, headed by Dr. G. Reitz, that was placed in the US Laboratory Module of the ISS as a part of the Human Research Facility of Expedition Two Mission 5A.1 in May-August, 2001 [17-20].

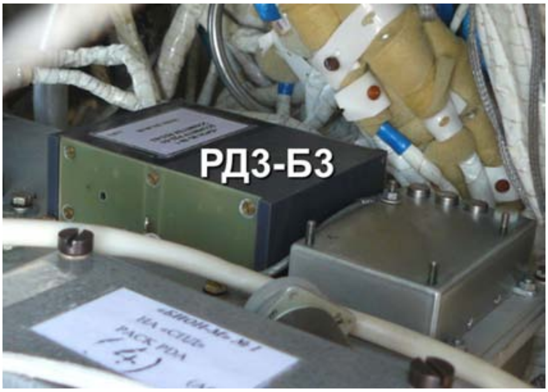


Fig. 1. External view of R3DE instrument

Figure 1 present the RD3-B3 instrument as situated inside the BION-M № 1 satellite. In the left side of the figure is seen the 2 Lithium-ion battery housing (pl. look below the label), while in the right side is the R3D-B3 instrument. The RD3-B3 instrument is low mass, small dimension automatic devices that measure solar radiation in four channels and ionizing radiation in 256 channels Liulin type energy deposition spectrometer. The four solar UV and visible radiations photodiodes are seen in the left part of the figure. They were active during the flight of BION-M № 1 satellite but because of the darkness inside the obtained values were equal to zero. The size of the aluminum box of R3D-B3 instruments is with 53x82x28 mm size of the box and 120 g weight [15, 16].

The ionizing radiation is monitored using a semiconductor detector (2 cm^2 area and 0.3 mm thick). Its signal is digitized by 12 bit fast A/D converter after passing a charge-sensitive preamplifier. The deposited energies (doses) are determined by a pulse height analysis technique and then passed to a discriminator. The amplitudes of the pulses are transformed into digital signals, which are sorted into 256 channels by multi-channel analyzer. At every exposition time interval one energy deposition spectrum is collected. The energy channel number 256 accumulates all pulses with amplitudes higher than the maximal level of the spectrometer of 20.83 MeV. The methods for characterization of the type of incoming space radiation are described by Dachev in [21].

The total external and internal shielding before the detectors of R3D-B3 instrument is not well known but very rough estimations give value of et lest 5 g cm^{-2} aluminum material. The calculated stopping energy of normally incident particles to the detector of the instrument is 8.5 MeV for electrons and 67.5 MeV for protons [22]. This means that only protons and electrons with energies higher than the above mentioned could reach the detector.

BION-M № 1 is a LEO satellite that orbited the Earth with a period of 89.9 min, an inclination of 63° with respect to the Earth’s equator (highly inclined orbit), and with an altitude above the Earth surface in the range 253-585 km. In this study the orbital parameters used were calculated by the software KADR-2 [24].

3. Data analysis and results

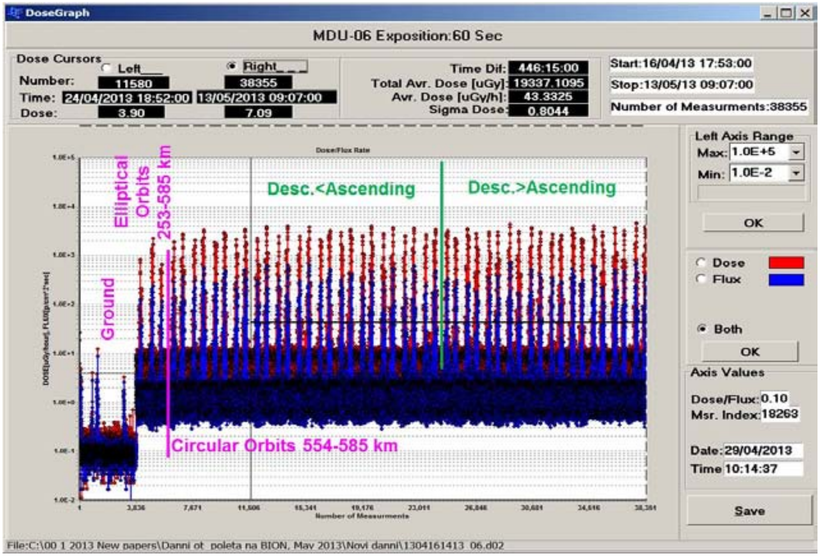
3.1. All time dose rate and flux measurements

BION-M № 1 mission took place in the decreasing phase of the 24th solar cycle, and the satellite flew during a period characterized by moderate solar activity. 2 relatively small SEP occurred during the flight of the satellite. The maximum of the first one occurred about midday on 21 April 2013. No real enhancement in the proton flux with energies above 100 MeV was observed in the GOES-13 data. The maximum of the second one http://www.swpc.noaa.gov/ftpdir/warehouse/2013/2013_plots/proton/20130426_proton.gif occurred at the early morning time on 25 April 2013. In this period BION-M № 1 was in the region of the SAA that is why R3D-B3 instrument was not able to registries it. The geomagnetic field during the period of the BION-M № 1 flight was also at moderate level with a sporadic period with Kp=5 in the interval 3:00-6:00 on 26 April 2013.

Ionizing radiation doses and fluxes during the whole monitoring period of the RD3-B3 instrument (16 April to 13 May 2013) are plotted at Fig. 2. The red curves there correspond to the dose rate values, while the blue curves shows the flux rate variations.

Fig. 2 shows two important periods recorded at 1-min resolution. The lowest doses and fluxes in the left part of the figure were obtained after 16:00 UT on 16 of April 2013 when the switching ON of RD3-B3 into the BION-M № 1 satellite occurred. These values are comparable with the natural background radiation with a mean value about 0.1 μGy h^{-1}. Few sporadic maxima, which are seen there was generated by the so called "Microphone effect" when the detector produces noise pulses in result of mechanical strikes outside the RD3-R3 instrument.

The recorded maxima in the central and right side part of Fig. 1 were obtained during the crossings of the South-Atlantics magnetic anomaly (SAA) region where the inner radiation belt populated with high-energy protons is encountered. The meander of dose rates between 0.3 and 12 μGy h^{-1} is generated when the satellite crosses the geomagnetic equator



MDU-06 Exposition:60 Sec

Dose Cursors
○ Left
● Right
Number: 11580 38355
Time: 24/04/2013 18:52:00 13/05/2013 09:07:00
Dose: 3.90 7.09

Time Dif: 446:15:00
Total Avr. Dose [uGy]: 19337.1095
Avr. Dose [uGy/h]: 43.3325
Sigma Dose: 0.8044

Start:16/04/13 17:53:00
Stop:13/05/13 09:07:00
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Left Axis Range
Max: 1.0E+5
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Axis Values
Dose/Flux: 0.10
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Fig. 2. Ionizing radiation doses and fluxes during the whole monitoring period of the RD3-B3 instrument (16 April to 13 May 2013)

(0.3 μGy h^{-1}) and returns back to high latitudes in the polar regions (12 μGy h^{-1}).

Very first part of the in orbit data at figure 2 was recorded when the BION-M № 1 satellite was still in elliptical orbits at altitudes between 253 and 585 km, that is why these SAA crossings maxima are relatively lower than the main part of the data. In the circular orbits data well seen are 2 different periods. First period shows that the descending orbits SAA maxima are lower than the ascending. In the second period this is in reverse. The probable reason for these features is changing in the orientation of the satellite.

3.2. Analysis of the recorded space radiation sources

In Dachev [21] it was shown that the dose from flux and dose to flux dependencies can characterize the type of the predominant radiation source in the Liulin type instruments. The dose to flux dependence is also known as specific dose (SD). Figure 3 is prepared to confirm these features again with the RD3-B3 data and to be analyzed the recorded space radiation sources.

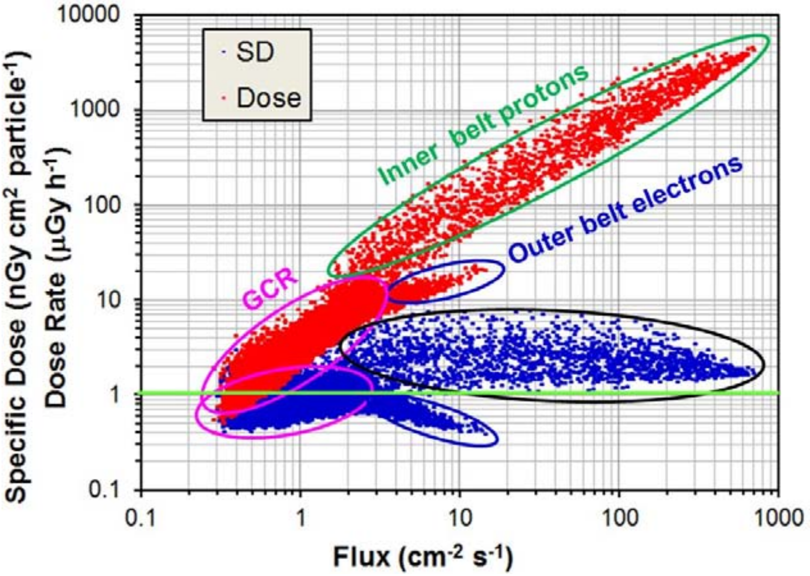

Fig. 3. Characterization of the RD3-B3 predominant radiation sources by the dose rate from flux and specific dose dependencies

The abscissa plots the measured flux in cm^{-2} s^{-1}, while the ordinate shows the dose rate in μGy h^{-1} and specific dose in nGy cm^{2} part^{-1} [21, 23] (Heffner, 1971; Dachev, 2009) for the period 23 April - 13 May 2013.

The large amount of red points in the diagonal of the figure is responsible for the dose rate values, which, as expected, are in linear dependence from the flux, while the almost horizontally plotted blue points present the SD values.

Three branches in each graphic are differentiated and they look as a left hand wrist with two fingers. The wrist represents a highly populated part in the diagonal bunch of points: (1) it takes a large amount of the measured points in the range 0.3–15 μGy h^{-1}; (2) for a fixed flux a wide range of doses is observed. These two features could be explained only by the GCR particles, which, being with small statistical relevance and high LET, are able to deposit various doses for fixed flux value. The smallest dose rates (0.3–0.4 μGy h^{-1}) are observed close to the magnetic equator, while the largest are at high latitudes. In the horizontal graphic this part of the data is represented with a similar large amount of points, which in large scale overlap the dose rate diagonal points.

The “index” finger is in the dose rate range 9–23 μGy h^{-1}. Its representation in the horizontal graphic is a finger extending up to 17 cm^{-2} s^{-1}, with SD values below 1 nGy cm^{2} part^{-1} (pls. look the green horizontal line). This finger is based on low LET particles and could be formed only by the relativistic electrons [21, 25] (Dachev et al., 2009 and 2012b) in the outer radiation belt. Here because of higher shielding (more than 5 g cm^{-2} aluminum) the relativistic electrons fluxes measured with RD3-R3 instrument are much lower than the presented in the referenced above papers.

The “big” finger in the diagonal graphic has a different source compared to the previous two because it is characterized by a high range of doses for fixed flux but the dose rates are in the range 20–4300 μGy h^{-1}. This amount of points could be formed only by protons from the IRB (The region of South Atlantic Anomaly (SAA)) whose dose depositions depend on the energy. The lower energy protons are depositing higher doses. In the horizontal graphic this finger has a similar form and is situated in the range 1.2–8.5 nGy cm^{2} part^{-1}. Both IRB and ORB fingers can be approximated by straight lines. From these approximations we obtain that 1 proton in IRB produces in the Silicon detector on average a dose of 1.4 nGy, while 1 electron in ORB produces a dose of 0.33 nGy, which is in good agreement with Heffner’s formula [23].

Table 1 summarizes the observations presented in figure 3 and gives the statistics of the measured values. In the last 2 columns of table 1 the selecting requirements is presented. The values was obtained in reference with the points distribution presented at figure 3 but the data period is larger and cover the following time interval - 19/04/2013 10:08:59 - 13/05/2013 08:59:39. Also the daily average and total accumulated values are calculated and presented. In 3 columns the averaged coordinates: longitude, latitude and altitude where the values are obtained are presented.

The comparison of the values presented in table 1 with analogical values obtained at International space station (ISS) and reported by Dachev [5] reveal the following results: 1) The obtained at the BION-M № 1 GCR average daily dose rate values (120 μGy day^{-1}) is higher than the measured at ISS (91.1 μGy day^{-1}) because the BION-M № 1 altitude and inclination of the orbit is higher than respectively ISS parameters (360 km altitude and 52° inclination); 2) Same is applicable for the inner radiation belt average daily dose rate values. The ISS value is 426 μGy day^{-1}. The BION-M № 1 dose rate increase is more than 2 times and reach 876 μGy day^{-1}; 3) As already mentioned the outer radiation belt relativistic electrons dose rate on BION-M № 1 satellite are very small because of large shielding and

Table 1. Statistical data obtained with the RD3-B3 instrument in the period
19/04/2013 10:08:59 - 13/05/2013 08:59:39

Re-gion	Meas. [No] [Day]	Aver. Dose Rate/Flux [Gy h^{-1}]/ [cm^{-2} s^{-1}] [Gy day^{-1}]	Min. Dose Rate/Flux [Gy h^{-1}]/ [cm^{-2} s^{-1}] [Gy day^{-1}]	Max. Dose Rate/Flux [Gy h^{-1}] / [cm^{-2} s^{-1}] [Gy day^{-1}]	Total Dose Rate/Fluen. [mGy]/ [No part.]	Aver. Alt. [km]	Aver. Lat. [Deg.]	Aver. Long. [Deg.]	Selecting requirements	
									Dose/Flux [Gy h^{-1}] [cm^{-2} s^{-1}]	SD [nGy cm^{2} part^{-1}]
All data	34391 23.883 34401	41.03 6.05 985	0.4 0.26 495	4530.12 699.8 1139	23.523 4159420	561	-0.06	0.08	No	No
GCR	32407 22.505	5.34 1.57 120	0.4 0.26 108	14.99 10.12 124	2.887 1015420	561	1.49	2.62	<15	<2
IRB (SAA)	1768 1.228	698.3 88.44 876	20.04 1.63 387	4530.12 699.8 1017	20.58 3127360	566	-24.9	-44.6	>20	>1
ORB	226 0.157	13.61 6.77 38	20.04 5.0 0.0	22.61 14.53 241	0.051 30580	583	-36.7	17.2	10<D<30 F>5	<0.8

practically is not comparable with data obtained outside ISS.

3.3. Latitudinal distributions of the data

Figure 4 summarizes the distribution of the obtained dose and flux data and of the calculated SD value in nGy cm^2 part^{-1} against the L value [25]. The dose and flux data show two obvious maxima – one at L values of about 1.3 and another at about 4. The lower L value maximum corresponds to the inner (proton) radiation belt, which is populated mainly by protons with energies from few tens to few hundred MeV. The higher L value maximum corresponds to the outer (electron) radiation belt, which is populated mainly by electrons with energies from hundreds of keV to a few MeV. The large amount of points with low doses and fluxes are obtained at low and mid magnetic latitudes outside of the radiation belts and is generated mainly by Galactic cosmic ray (GCR) particles. This radiation shows a ‘‘knee” at L value about 2.5–3. The large amount of points close to 1 nGy cm^2 part^{-1} is produced by GCR, which being high LET particles are able to delivery different doses with same flux values. Also the GCR did have very small fluxes and the Heffner’s formula [23] is not applicable for them.

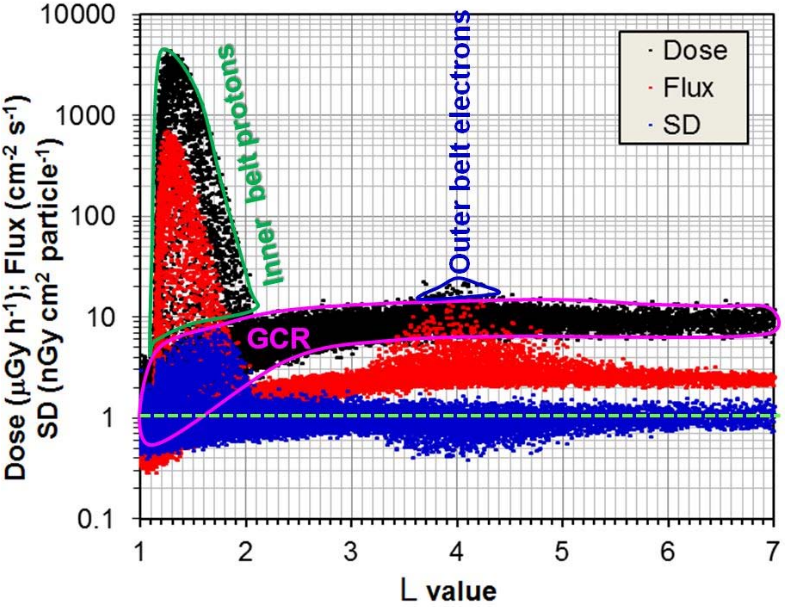

Fig. 4. Distribution of dose and flux and SD data against the L value

The specific dose value is provisionally divided into two parts – below and above 1 nGy cm^{2} part^{-1}. According to this value divides the range of doses delivered by electrons below of about 0.7 nGy cm^{2} part^{-1} and by protons above 1.12 nGy cm^{2} part^{-1}. Some more features are seen also in the SD distribution. Points with specific doses at about 1–2 nGy cm^{2} part^{-1} at L = 1.2 are generated by protons with energies of a few hundred MeV. Points with specific doses at about 2–5 nGy cm^{2} part^{-1} around L = 1.7 are generated by protons with energies below 100 MeV.

Generally the SD variations at BION-M № 1 satellite are with small dynamics in comparison with analogical distributions obtained on Foton-M2/M3 satellites and on ISS [14, 16, 21, 26] with instruments outside the pressurized volume.

Conclusions

This paper analyses the first results for the radiation environment inside the BION-M № 1 spacecraft generated by different radiation sources, including: Galactic Cosmic Rays (GCRs), IRB trapped protons in the region of the South Atlantic Anomaly (SAA) and outer radiation belt (ORB) relativistic electrons. The satellite was launched on 19 April 2013 at 10:00 UT from the Cosmodrome of Baikonur (Kazakhstan).

On 19th of May at 03:12 UT the Landing module of BION-M № 1 successfully touched down at Orenburg region, after 30 days in orbit. http://biosputnik.imbp.ru/eng/index.html

The RD3-R3 low mass, dimension and price instrument proved it ability to characterize the radiation environment inside the BION-M № 1 satellite, including the relativistic electron precipitations. This was achieved mainly with the analysis of the deposited energy spectra, obtained at each measurement cycle of 60 s.

The comparison of the values obtained with RD3-R3 instrument with analogical values obtained at International space station (ISS) and reported by Dachev [5] reveal the following results: 1) The obtained at the BION-M № 1 GCR average daily dose rate values (120 μGy day^{-1}) is higher than the measured at ISS (91.1 μGy day^{-1}) because the BION-M № 1 altitude and inclination of the orbit is higher than respectively ISS parameters (360 km altitude and 52° inclination); 2) Same is applicable for the inner radiation belt average daily dose rate values. The average ISS value is about 250 μGy day^{-1}. The BION-M № 1 dose rate increase is more than 3 times and reach 876 μGy day^{-1}; 3) As already mentioned the outer radiation belt relativistic electrons dose rate on BION-M № 1 satellite are very small because of large shielding and practically is not comparable with data obtained outside ISS.

The obtained first results with the RD3-R3 instrument on BION-M № 1 encouraged us to perform further more comprehensive analysis of the dose rate and flux data.

Acknowledgements

This work was supported financially by the Bulgarian science fund (DID-02). The authors gratefully acknowledge the discussion performed with Victor Benghin.

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ПРЕДВАРИТЕЛНИ РЕЗУЛТАТИ ЗА РАДИАЦИОННАТА ОБСТАНОВКА НАБЛЮДАВАНА С ДОЗИМЕТЪРА-РАДИОМЕТЪР RD3-B3 НА СПЪТНИКА BION-M № 1

Ц. Дачев, Б. Томов, Ю. Матвийчук, П. Димитров, Н. Банков,
В. Петров, В. Шуршаков, О. Иванова, Д.-П. Хедър, М. Леберт,
М. Шустер, Г. Райтц, Г. Хорнек, О. Плоц

Резюме

Космическата радиация е измерена със спектрометъра-дозиметъра РДЗ-БЗ (в статията се използва латинската транскрипция RD3-B3) на борда руския възвращаем спътник БИОН-М № 1 (в статията се използва латинската транскрипция BION-M № 1). Уредът е монтиран във вътрешната част на спътника, заедно с биологични обекти и проби. Приборът RD3-B3 е работеща на батерии версия на резервния модел на прибора R3D-B3, разработен и изработен за платформата на ESA BIOPAN-6 летяла на спътника Foton M3 през септември 2007 година. Космическото йонизиращо лъчение е наблюдавано с 256 канални спектри на погълнатата енергия, които по-нататък се използват за определяне на погълнатата доза и поток. Докладът представя първите резултати за радиационната обстановка на височина (253-585 km) на спътника БИОН-М № 1.