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Cosmic radiation monitoring at low-Earth orbit by means of thermoluminescence and plastic nuclear track detectors

Iva Ambrožová [a,*], Kateřina Pachnerová Brabcová [a], Jan Kubančák [a], Jakub Šlegl [a], Raisa V. Tolochek [b], Olga A. Ivanova [b], Vyacheslav A. Shurshakov [b]

[a] Nuclear Physics Institute of the CAS, Prague, Czechia
[b] Institute of Biomedical Problems, Russian Academy of Sciences, Moscow, Russia

HIGHLIGHTS

- Thermoluminescent and plastic nuclear track detectors onboard ISS and BION-M1.
- Determination of LET spectra, total absorbed doses, and dose equivalents.
- Correction of LET for detectors irradiated outside the satellite BION-M1.
- Variation with shielding and orbit parameters.

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ABSTRACT

Cosmic radiation represents one of the main health issues for astronauts during space missions. To evaluate the impact of space radiation on human health and to reduce the uncertainty of related cancer risk, it is important to determine the exposure level as accurately as possible. Due to complexity of radiation environment in space and behind the shielding, accurate data cannot be obtained using only calculations; experimental measurements in real flight conditions are also necessary.

In this contribution we present results obtained during two space missions – onboard International Space Station (during 2012–2013) and onboard biosatellite BION-M1 (April–May 2013). In both cases, packages containing thermoluminescent and plastic nuclear track detectors were placed at various locations onboard ISS/BION-M1. Spectra of linear energy transfer, absorbed doses, and dose equivalents are discussed with respect to orbit parameters and shielding.

For both missions, dose characteristics can differ by a factor of about 2, depending on the location. Due to higher altitude and limited shielding, absorbed dose and dose equivalent inside BION-M1 are significantly higher than inside ISS – whereas inside ISS the maximal value of measured dose equivalent rate was about 1 mSv/day, inside BION-M1 it exceeded 3 mSv/day. Outside the capsule it was about two times higher than inside the capsule.

1. Introduction

Cosmic radiation is, together with microgravity and lack of oxygen, one of the main health issues during space missions. The exposure level in low-Earth orbit (LEO) is several hundred times higher than the one on Earth's surface. The radiation exposure can lead to circulatory diseases, damages on the central nervous systems, tumors, etc.; in some cases the exposure may be even lethal for spacecraft crew (Cucinotta et al., 2014; Hellweg and Baumstark-Khan, 2007; Kennedy, 2014).

To evaluate the impact of space radiation it is therefore important to predict and determine the exposure level as accurately as possible. This is not an easy task, since the radiation field in space is very complex and completely different from those on Earth; it is composed of primary high-energy galactic and solar particles, particles trapped in Earth's radiation belts, and also of secondary particles created in nuclear interactions of primary radiation with the surrounding material (Benton and Benton, 2001). Moreover, the exposure level depends on various parameters related to the spacecraft (like orbit parameters, material and thickness of the

* Corresponding author.
E-mail address: ambrozova@ujf.cas.cz (I. Ambrožová).

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shielding) and it also varies with the solar cycle.

Because of the complexity and variation of radiation environment in space and behind the shielding, accurate data cannot be obtained using only calculations; there is still need of experimental measurements in real flight conditions. Many experiments have been realized, especially onboard International Space Station, with various active and passive detectors (Berger, 2008; Caffrey and Hamby, 2011); however, our understanding of the radiation situation in space can still be improved.

Basically, no single detector is able to determine all required dosimetric characteristics (e.g. absorbed dose, dose equivalent, linear energy transfer (LET)) in complex radiation fields like in space; usually it is necessary to combine response from several, ideally complementary, detectors. The combination of thermoluminescent (TLD) and plastic nuclear track detectors (PNTD) is very suitable – they are small and lightweight, and they do not need neither power supply nor service. TLD are used to determine absorbed dose, particularly from low-LET particles, whereas PNTD can detect only particles with LET above its detection threshold (usually about 10 keV/μm); by their combination, LET spectra, total absorbed dose, dose equivalents and quality factors can be obtained (Doke et al., 1995).

In this contribution, results obtained during two space missions are presented. Several detectors packages containing TLD and PNTD were exposed onboard ISS (during 2012–2013) and onboard the biosatellite BION-M1 (2013). Spectra of LET, absorbed doses, and dose equivalents are discussed with respect to orbit parameters and shielding.

2. Materials and methods

Thermoluminescent detectors are used to measure absorbed dose particularly from low-LET particles. In principle, they can detect all types of radiation, but for particles with higher values of LET their relative response decreases and thus they underestimate the dose from high-LET radiation (Berger and Hajek, 2008; Spurny, 2004).

As TLD, we used $CaSO_4$ doped with Dysprosium ($CaSO_4$:Dy powder fixed by thermostable silicon binder in aluminum dishes) manufactured by Laboratories Protecta Ltd (Guelev et al., 1994). The detectors were evaluated using TOLEDO 654 TLD Reader (heating rate 10 °C/s, preheat 150 °C (22s), annealing 380 °C (10 min)) and calibrated at ^{137}Cs. Results are expressed in terms of absorbed dose in water.

The dependence of detectors' response on LET of particles was obtained using irradiation in several heavy ion beams, mostly in the frame of experiments Proton ICCHIBAN and ICCHIBAN (Yasuda et al., 2006). The recently upgraded response (relative to photons) is shown in Fig. 1. Up to about 10 keV/μm, the relative response is around 1, then it decreases; for high-LET radiation (above 100 keV/μm) it can be less than half of that for low LET radiation.

Plastic nuclear track detectors detect heavy charged particles with sufficiently high LET (the most sensitive ones from about 5 keV/μm).

As PNTD we used HARZLAS TD-1 (Nagase Landauer Ltd, Japan; 0.9 mm thick); it is a polyallyldiglycolcarbonate, so the detectors can be considered as tissue-equivalent. After the irradiation, the detectors were etched (in 5N NaOH at 70 °C for 18 h, corresponding bulk etch was about 15 μm) and after the etching, the detectors' surface was analyzed with the microscope system HSP-1000 and software HspFit from SEIKO Precision (Yasuda et al., 2005).

From the parameters of tracks (minor and major axis) and layer removed by etching, LET of the particle can be determined, after appropriate calibration. The range of LET that can be determined

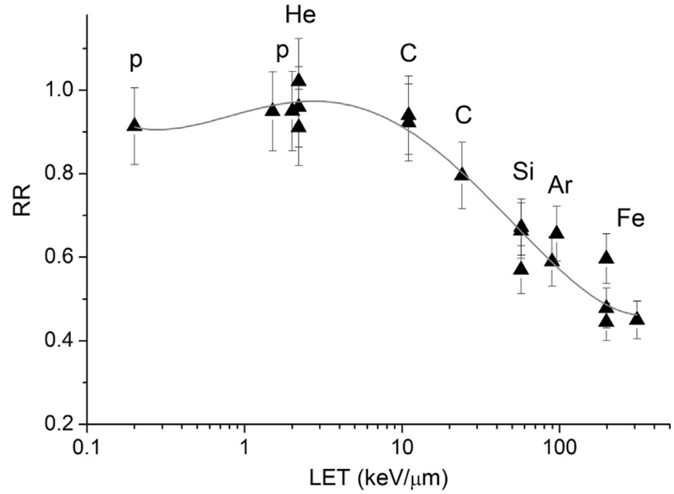

Fig. 1. Relative response of $CaSO_4$:Dy; ions corresponding to data points are indicated.

using these detectors and conditions is from 7 up to more than 1000 keV/μm (considered in water). From the LET, absorbed dose, dose equivalent, and quality factor can be then calculated (Pachnerová Brabcová et al., 2013).

The sensitivities of TLD and PNTD are largely complementary and by combining results from these two types of detectors, values of total absorbed dose and total dose equivalent can be obtained. Using the TLD efficiency function and LET spectrum measured with PNTD, high-LET part of the dose is subtracted from the measured TLD dose. The remaining low-LET dose fraction is then added to the high-LET dose measured with PNTD to obtain total absorbed dose. Similarly, the TLD low-LET dose fraction is added to the dose equivalent measured with PNTD to obtain the total dose equivalent (Doke et al., 1995). In the results – when combining the response of TLD and PNTD – the value 10 keV/μm was used as the high/low-LET threshold.

3. Exposure at low-Earth orbit

The detectors (several packages containing TLD and PNTD) were exposed at low Earth orbit during two space missions – one was onboard the biological satellite BION-M1, another onboard International Space Station. In both experiments, our detectors were placed inside several Aluminum boxes (of dimensions 12 × 6 × 4 cm and thickness 0.3 g/cm^2) together with biological samples and other detectors.

BION-M1 was free space flyer mission, containing the animal-carrying space capsule (Sychev et al., 2014). It was launched into orbit on April 19, 2013 and it flew for 30 days, encircling Earth in almost circular orbit at 575 km. Biological samples and detector instruments were installed inside the capsule (which was pressurized and had controlled temperature) in 4 boxes and also outside (unpressurized and uncontrolled temperature) in 2 boxes.

Onboard ISS, the detectors were irradiated from May 2012 for 1 year in the frame of one of the Matroshka-R experiments. Average ISS altitude was 409 km (variation 398–417 km). In total, 6 boxes were placed at different compartments inside the Russian part of the ISS – box 1 was in Piers 1 module, box 2 was in Small Research Module 2, and boxes 3–6 were in Service Module (Jadrnickova et al., 2009).

Both missions took place in the middle of the 24th solar cycle, during a period characterized by moderate solar activity.

4. Results

The spectra of LET were determined by means of track detectors; registered tracks corresponded to ions of primary galactic cosmic radiation and to secondary particles created in nuclear interactions of high-energy protons, neutrons, and heavy ions.

In Fig. 2, differential particle flux spectra obtained inside and outside of BION-M1 satellite are shown.

One can see some differences in LET spectra. Outside the capsule there is clearly higher contribution of particles with LET below 100 keV/μm. There is also variation for internal LET spectra – for the box 2, which was placed at the most shielded location inside BION-M1, the flux is the lowest, whereas for box 1, at the less shielded location, the flux is the highest. The uncertainties are relatively large for high-LET region because of poorer statistics.

In Table 1, there are summarized dose characteristics obtained using TLD and PNTD for BION-M1. Average inside total absorbed dose rate is 1 mGy/day, dose equivalent rate is 2.5 mSv/day. Outside doses are about twice higher. However, it should be noted that these are measured data without any corrections to environmental conditions outside the capsule (uncontrolled temperature, lack of oxygen etc.). It is known that if the environmental oxygen and temperature is not favorable, the ionization produced in PNTD by the incident particles can decay or partly recombine (Csige et al., 1988; Keane et al., 1999). The effects of various environmental treatments like temperature and oxygen conditions (before, during, and after the exposure) were studied for different PADC and it was observed that track diameters and sensitivity of the detectors were reduced for exposures in vacuum and at higher temperatures (Kodaira et al., 2009; Dörschel et al., 2005; Abou El-Khier et al., 1995).

However, the temperature and oxygen conditions outside the capsule were uncontrolled and unknown, so for the correction, we used the method described in (Zhou et al., 2007). The sensitivity fading of PNTD exposed in space can be corrected using galactic cosmic radiation iron peak at about 1 GeV/n.

To find the tracks that could possibly correspond to iron ions, the detectors were etched several times and carefully analyzed. The tracks of primary galactic cosmic particles can be distinguished from tracks created in nuclear interactions (mostly of high-energy protons) based on the assumption that secondary particles have short range and cannot penetrate too deep into the detector. So by analyzing and comparing the same area in different depths of the detector, primary high-energy long-range heavy ions were identified.

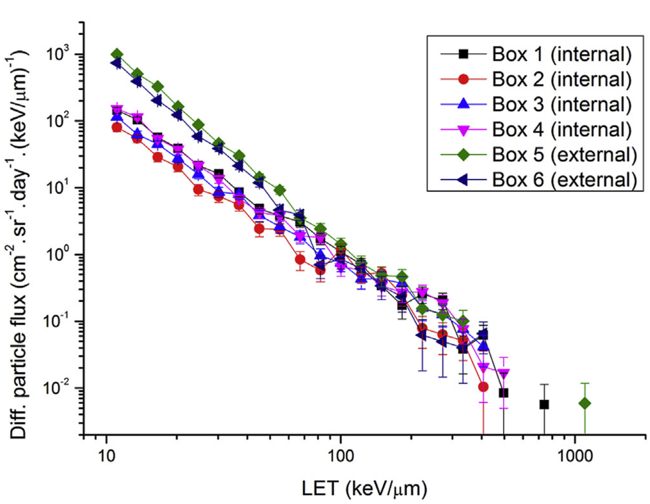

Fig. 2. Differential LET spectra for 4 internal boxes (boxes 1-4) and two external boxes (boxes 5 and 6) onboard BION-M1.

For external detectors, Fe peak was found at about 135 keV/μm (lower than expected), so the correction was needed. This was done by fixing the position of the peak to the value 147 keV/μm (LET for 1 GeV Fe ions calculated by SRIM). The position of the peak for internal detectors were around 150–160 keV/μm, which corresponds well to 1 GeV/n Fe after passing through the wall of satellite and some surrounding material.

After the sensitivity corrections, the absorbed doses and dose equivalents measured with PNTD are about 1.2 times higher than uncorrected values.

Differential spectra of particle fluxes measured with PNTD for six positions inside the ISS are shown in Fig. 3. The spectra do not differ too much for individual locations.

Absorbed doses measured with TLD, PNTD and total absorbed doses, dose equivalents, and quality factors for ISS are then summarized in Table 2.

In Piers-1 and Small Research Module 2, which are less shielded, the absorbed doses and dose equivalents are higher, by 93% for absorbed dose and by 45% for dose equivalent. The average absorbed dose rate in the Service Module is 273 μGy/day and the average dose equivalent rate is 709 μSv/day.

In Fig. 4 there are compared differential particle flux (after sensitivity correction for external detectors) for BION-M1 and ISS. For BION-M1 there are more particles detected because of higher altitude (575 versus 409 km) and lower shielding – the shielding for BION-M1 was about 5 g/cm^2, whereas the shielding of the Russian segment of the ISS is about 10 g/cm^2. The shielding of the external detectors was estimated to be about 1.5 g/cm^2 (0.3 g/cm^2 from the Aluminum box cover and about 1.2 g/cm^2 from other detectors packages in front of our detectors).

When we compare dose characteristics, the total dose equivalent rate inside ISS ranged from 666 μSv/day to 1 mSv/day, inside the BION-M1 from 1.7 to 3.2 mSv/day and outside the BION-M1 from 4.6 to 5.8 mSv/day.

5. Conclusions

Dose characteristics in two missions at LEO (onboard ISS and BION-M1 satellite) were determined using the combination of TLD and PNTD. For detectors placed outside the BION-M1 capsule, sensitivity correction (because of uncontrolled temperature and lack of oxygen) was necessary, it was done using the galactic iron ions.

Due to higher altitude and lower shielding, dose characteristics were higher for BION-M1 than onboard ISS; average absorbed dose rate and dose equivalent rate were almost 4 times higher inside BION-M1 than in the ISS Service Module. Average measured total absorbed dose inside BION-M1 (1 mGy/day) is in a good agreement with the dose determined using active instrument RD3-B3 (985 μG/day) (Dachev et al., 2015). Absorbed doses and dose equivalents outside BION-M1 were at least two times higher than inside the capsule. The absorbed dose measured with TLD outside BION-M1 was about 2.2 mGy/d; similar absorbed doses were measured also with OSL and RPLD in cylindrical holders installed on the outside of the recovery capsule (Sihver et al., 2016).

In the past many experiments with passive detectors onboard ISS were performed, also at the same locations within the Russian part of ISS (Ambrozova et al., 2011; Jadrnickova et al., 2009; Inozemtsev et al., 2015a). However, it is difficult to directly compare our results with the results measured during previous missions because of different ISS altitude and solar activity. Higher doses and dose equivalents were in all cases measured in Piers-1 module compared to Service Module.

Table 1
Dose characteristics for BION-M1. Low-LET D is absorbed dose measured with TLD after subtraction of high-LET fraction; high-LET D and H are absorbed dose and dose equivalent measured with PNTD.

Box	TLD	Low-LET	High-LET	High-LET	Total	Total	Total
	D [μGy/d]	D [μGy/d]	D [μGy/d]	H [μSv/d]	D [μGy/d]	H [μSv/d]	Q
1 (internal)	1370 ± 86	1267 ± 87	151 ± 23	1940 ± 291	1418 ± 90	3207 ± 304	2.3
2 (internal)	603 ± 8	546 ± 10	84 ± 13	1202 ± 180	630 ± 16	1748 ± 181	2.8
3 (internal)	789 ± 8	713 ± 11	112 ± 17	1494 ± 224	825 ± 20	2207 ± 224	2.7
4 (internal)	1105 ± 50	1008 ± 51	141 ± 21	1760 ± 264	1149 ± 55	2768 ± 269	2.4
5 (external)[a]	2272 ± 162	1859 ± 167	434 ± 65	3356 ± 503	2293 ± 179	5215 ± 530	2.3
6 (external)[a]	2207 ± 330	1964 ± 331	307 ± 46	2264 ± 340	2271 ± 334	4227 ± 474	1.9

[a] No correction to environmental conditions (temperature, lack of oxygen).

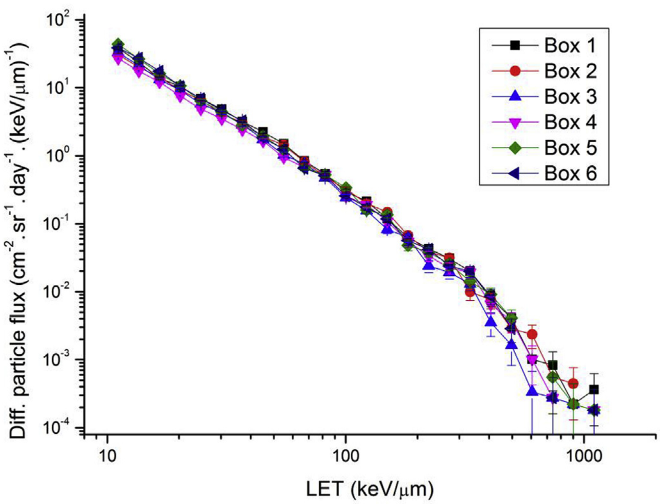

Fig. 3. Differential LET spectra for 6 positions inside the ISS.

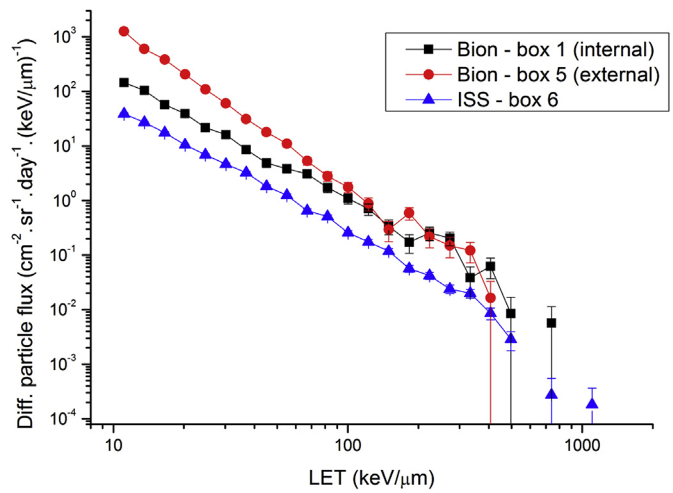

Fig. 4. Differential LET spectra for BION-M1 (both inside and outside) and ISS.

Table 2
Dose characteristics for ISS.

Box	TLD	Low-LET	High-LET	High-LET	Total	Total	Total
	D [μGy/d]	D [μGy/d]	D [μGy/d]	H [μSv/d]	D [μGy/d]	H [μSv/d]	Q
1	506 ± 9	476 ± 9	44 ± 7	564 ± 85	520 ± 11	1040 ± 85	2.0
2	503 ± 11	476 ± 11	41 ± 6	544 ± 82	517 ± 13	1020 ± 82	2.0
3	259 ± 4	235 ± 5	34 ± 5	431 ± 65	270 ± 7	666 ± 65	2.5
4	266 ± 5	243 ± 5	34 ± 5	458 ± 69	277 ± 7	701 ± 69	2.5
5	290 ± 2	262 ± 3	41 ± 6	507 ± 76	303 ± 7	769 ± 76	2.5
6	231 ± 4	203 ± 5	40 ± 6	498 ± 75	243 ± 8	701 ± 75	2.9

During the same period, averaged absorbed dose measured with the same type of TLD in the Columbus Module was about 275 μGy/d (Berger et al., 2016) very similar to the averaged TLD absorbed dose in the Service Module (262 μGy/d).

The dose characteristics both inside ISS and BION-M1 can vary by factor of about 2. As expected, the highest values were obtained for less shielded locations (boxes 1 and 2 for ISS and box 1 for BION-M1), lower values were measured in more shielded locations. Similar results were obtained also by (Inozemtsev et al. (2015b).

The total absorbed dose is mainly due to low-LET radiation – particles with LET <10 keV/μm represent 81–92% of the total absorbed dose (higher contribution is for less shielded detectors). Particles with LET >100 keV/μm contribute only about 2.5–5.1% to the total absorbed dose, however their contribution to the total dose equivalent is significant, 26–42% (higher contribution is for more shielded detectors).

Data obtained in these studies could bring additional information about the radiation situation in space and help to estimate the radiation risk of crewmembers. They can be also used for benchmarking of various codes and models.

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