OVERVIEW OF THE LOW EARTH RADIATION ENVIRONMENT VARIATIONS ON "MIR" AND INTERNATIONAL SPACE STATION OBSERVED BY LIULIN TYPE INSTRUMENTS IN 1991–2022

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Abstract: *The space weather and the connected with it ionizing radiation are among the main health concerns to the space station crews. Estimation the effects of radiation on humans on the International space station (ISS) requires at accurate knowledge of the accumulated by different radiation sources absorbed dose rates. The latter depend on the global space radiation component distribution and the local variations generated by the 3D surrounding shielding distribution.*

ОБЗОР НА ВАРИАЦИИТЕ НА РАДИАЦИОННАТА СРЕДА В НИСКА ОКОЛОЗЕМНА ОРБИТА НА СТАНЦИИТЕ „МИР" И МКС, РЕГИСТРИРАНИ С ИНСТРУМЕНТИ ОТ ТИПА „ЛЮЛИН" В ПЕРИОДА 1991–2022 Г.

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Резюме: *Космическото време и свързаното с него йонизиращо лъчение се разглеждат като един от основните рискове за здравето на екипажа на космическата станция. Оценката на въздействието на радиацията върху хората на борда на Международната космическа станция (МКС) изисква на първо място точни данни за мощностите на погълнатата доза от различни източници на лъчение. Тези стойности зависят както от глобалното разпределение на компонентите на космическата радиация, така и от локалните вариации, породени от триизмерното разпределение на заобикалящата защитна обвивка.*

Introduction

The Low Earth Orbit (LEO) radiation environment sits below roughly 2,000 km altitude and is partially shielded by Earth's magnetic field and atmosphere, though it remains a dynamic mix of trapped radiation, cosmic rays and solar events.

Galactic and extragalactic cosmic rays

The dominant radiation component in near Earth space environment are the galactic cosmic rays (GCR) modulated in anti-correlation by the solar activity. The GCR are charged particles that originate from sources beyond our solar system. They are thought to accelerate at the highly energetic sources like neutron star collisions, black holes and supernovae stars within our Galaxy and beyond. GCR are the most penetrating of the major types of ionizing radiation. The distribution of GCR 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, heavier ions (baryon component), 2% electrons, and positrons (lepton component). The baryon component is composed of 87% protons, 12% helium ions (alpha particles) and 1% heavy ions.

Trapped radiation belts

There are two distinct belts of toroidal shape surrounding Earth, where the high-energy charged particles are trapped in the Earth's magnetic field. Energetic protons and electrons within the Earth's radiation belts pose a hazard to both astronauts and spacecraft. The inner radiation belt (IRB), located between about 0.1 to 2 Earth radii, consists of both electrons with energies up to 10 MeV and protons with energies up to ~ 400 MeV. The outer radiation belt (ORB) starts from about four Earth radii and extends to about 9–10 Earth radii in the anti-sun direction. The outer belt mostly consists of relativistic electrons whose energy is between 2 and 10 MeV. The electron flux may cause problems for components located outside a spacecraft (e.g. solar cell degradation). They 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 extra vehicular activity (EVA) [1–4]. ORB was first observed By LIULIN instrument on "MIR" space station [1]. Also, with this instrument were observed the unique "New" radiation belt [5]

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. The time profile of a typical SEP starts 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 Moon, 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 hours, although some high-energy protons can arrive in as little as 20 minutes. 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.

The radiation field at a location, either outside or inside the spacecraft is affected both by the shielding and by the distribution of the masses in the surrounding materials [6, 7]. Dose characteristics in LEO depend also on many other parameters such as the solar cycle phase; spacecraft orbit parameters, geophysical parameters.

Instruments description

The data from six different Liulin type instruments were used in this study. First row of figures of Fig. 1 contains six pictures of these instruments. They are presented as six but the R3DR and R3DR2 instruments in the right side are the same because ESA colleagues decided to use again the returned back to Earth R3DR instrument flown on ESA EXPOSE-R facility in EXPOSE-R2 facility [8].

LIULIN instruments [4] was designed in 1986–1988. It was used in the Russian "MIR" space station from April 1988 to August 1994 (pl. look Fig. 1.1). The measurements in the LIULIN instrument were based on a single silicon detector followed by a charge-sensitive shaping amplifier (CSA) Armtek A225 type (https://www.amptek.com/internal-products/a225-charge-sensitive-preamplifier-shaping-amplifier). The number of the pulses at the output of the CSA, above a given threshold, is proportional to the particle flux hitting the detector. The integral amplitude of the pulses in one exposition period at the output of the CSA is proportional to the particles' deposited energy. Thus, the integral of the energy depositions of the particles accumulated in the detector during the measurement interval allowed calculation of the dose rate.

LIULIN device (Fig. 1.1) was located in the workstation section of the "MIR" space station where the effective thickness of shielding was about 5 g cm^{-2} of matter. Therefore the contribution to the device readings could be supplied by electrons, protons and a-particles with an energy outside the space station equal to ***Ee >*** 10 MeV, ***Ep >*** 70 MeV and ***Ea >*** 200 MeV respectively [9].

The Mobile Radiation Exposure Control System Liulin-E094 (pl. look Fig. 1.3) was part of the experiment “Dosimetric Mapping” E094. It was placed in the US Laboratory module as a part of the Human Research Facility of ISS Expedition Two, Mission 5A.1 [10]. The system consists of four Mobile Dosimetry Units (MDU) and one Control and Interface Unit (CIU). The four MDUs were moved to different spots by the American astronauts to study the radiation distribution in the American Laboratory Module and NODE-1 of the American segment of the ISS [11, 12]. MDU number 2 (MDU-2) data are used in this study.

The MDU contains: one semiconductor detector with 0.3 mm thickness and 2.0 cm^2 area Canberra RF-14*14- 300-EB type; one low noise, hybrid, charge-sensitive preamplifier A225 type of AMPTEK Inc.; a fast 12 channel ADC; 2 microcontrollers and an 0.5 MB flash memory. A specially developed software manages the unit. The pulse amplitudes are proportional by a factor of 240 mV/MeV according to the AMPTEK A225F preamplifier specifications (https://www.amptek.com/internal-products/a225-charge-sensitive-preamplifier-shaping-amplifier). The amplitudes are digitized and organized in a 256-channel spectrum. Using the System International (SI) definition, the dose D (in Grey) is calculated from the sum of 256 channels amplitudes in MeV divided by the mass of the detector in kilograms. The described above schematics were multiplied in all further Liulin type instruments.

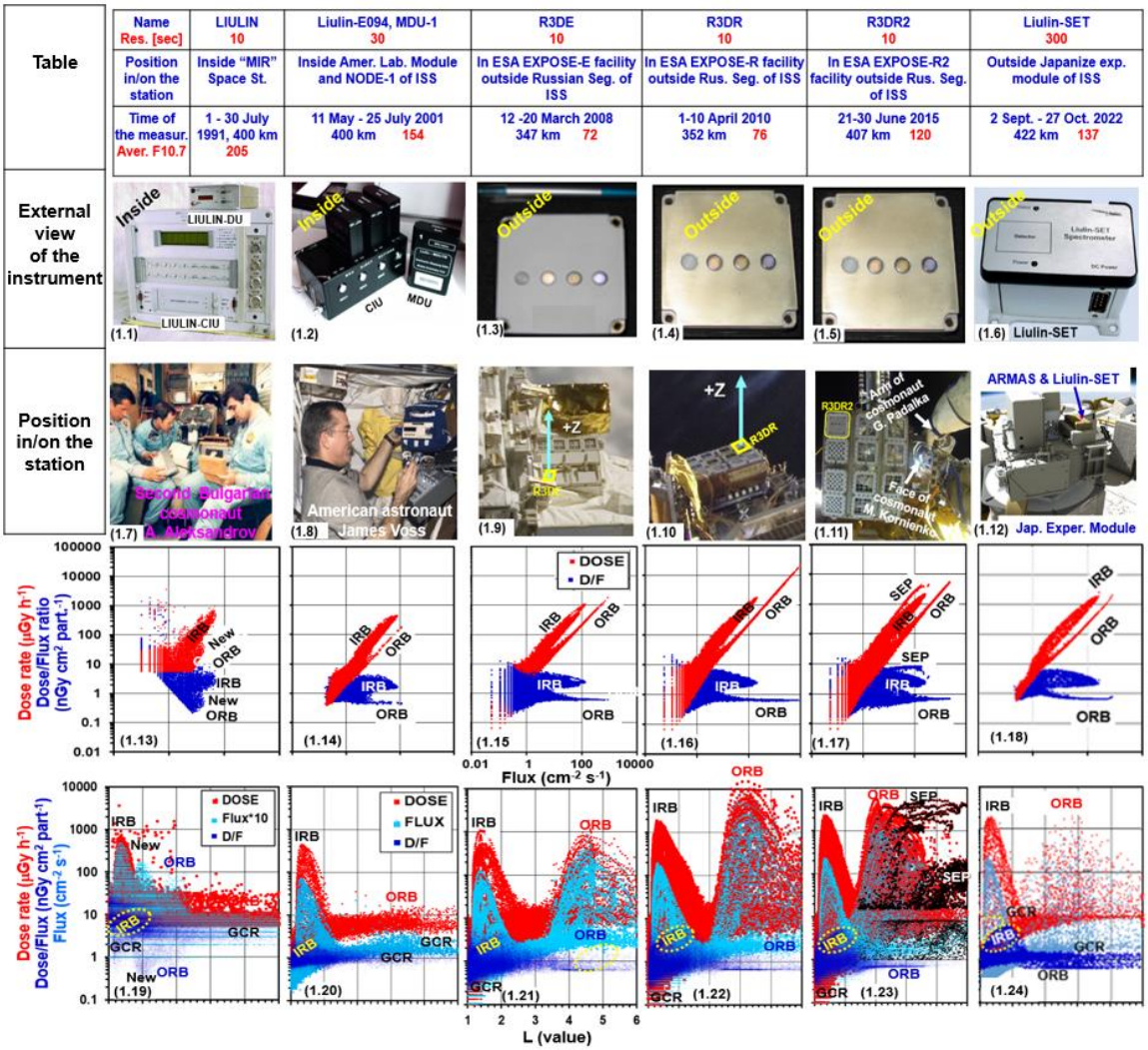


Fig. 1. Comparison of analogical graphics and data for six Liulin type experiments on “MIR” and ISS in the time July 1991-September 2022.

The European Space Agency (ESA) EXPOSE-E, EXPOSE-R and EXPOSE-R2 facilities [8] accommodated three Bulgarian-German Radiation Risk Radiometer-Dosimeters (R3D). R3DE instrument (pl. look Fig. 1.3) [2] was used at the EXPOSE-E facility on the Columbus module of ISS in 2008–2009. R3DR spectrometer (pl. look Fig. 1.4) [2] worked at the EXPOSE-R facility outside the Russian segment of ISS from 2009 to 2010. R3DR2 (pl. look Fig. 1.5) is the same R3DR instrument. It was part of EXPOSE-R2 facility outside the Russian segment of ISS from 2014 until 2016 [3]. The extension “R2”, same as for the EXPOSE-R2 facility, is used to distinguish its data from the data of the previous mission. The two R3D spectrometers were built on the same schematics as the described in the previous paragraph Liulin-E094,

MDU-2 unit. The detectors in R3D spectrometers are Hamamatsu S2744-08 silicon PIN photodiodes (Si PIN photodiode S2744-08 | Hamamatsu Photonics).

The Liulin-SET spectrometer (seen in Subfigure 1.6 of Fig. 1), was developed at the Space Research and Technology Institute of the Bulgarian Academy of Sciences and integrated within the Automated Radiation Measurements for Aerospace Safety (ARMAS) Flight Module Number 9 (FM9). Space Environment Technologies in Los Angeles, California, USA developed the ARMAS FM9 [13]. It was launched on February 19, 2022 with the Northrop Grumman-Antares rocket from NASA's East Coast Virginia space site and operated externally on the Japanese Experimental Module of the ISS for 216 days, from March to December 2022.

During the calibrations of Liulin-type instruments, it was found that the absolute values of the measured doses were within 2.8% and 8% of the reference value for the ^{137}Cs and ^{60}Co sources, respectively. The response of a LIULIN-4 spectrometer (identical in construction to R3D instruments was compared in [14] to that of the HAWK TEPC (http://www.fwt.com/detector/fw-ad1ds.htm) on 42 aircraft flights in 2003–2004. On all flights, the absorbed dose measured by both instruments agreed to within 5%. We consider that the flux and dose rate errors of the R3DR type measurements on ISS are within 10%.

The calibration procedures, performed with analogical to Liulin-E094 and R3D/E/R/R2 instruments, are described in [15, 16]. The response curve of these instruments is expected to be very similar to that published in [16] because since 2002 all Liulin instruments were manufactured using identical electronic parts and schematic.

The semiconductor detector of the R3D instruments was mounted approximately 7 mm below the 0.8 mm thick aluminium cover plate. Furthermore, there was shielding from 0.07 mm copper and 0.2 mm plastic, which provided 0.3 g cm^{-2} of total shielding from the front side. The calculated required kinetic energy of particles arriving perpendicular to the detector was 0.835 MeV for electrons and 19.5 MeV for protons. This means that only electrons and protons with energies exceeding the values listed above can cross the R3D shielding materials and reach the detector surface.

Data analysis

Radiation source selection procedure

The following four primary radiation sources were expected and recognized in the data obtained with the R3DR2 instrument: (i) globally distributed primary GCR particles and their secondary products; (ii) protons in the South Atlantic Anomaly (SAA) region of the IRB; (iii) relativistic electrons and/or bremsstrahlung in the high latitudes of the ISS orbit where the ORB is situated; and (iv) solar energetic particles (SEP) in the high latitudes of the ISS orbit. Together with the real SEP particles, a low flux of what were likely to be mostly secondary particles (SP) (protons, neutrons and heavier than protons ions) some of them associated with detector interactions were observed in the data.

The procedure is based on the experimental formulas for the dose to flux ratio for protons in the range 1–1000 MeV and for electrons in the range 1–10 MeV as published in the book of Haffner [17]. In [3] was demonstrated that according to Haffner's formulas [17] the data could be simply split into two parts by using the dose to flux ratio (D/F). When the measured by the R3DR2 instrument D/F is less than 1.12 nGy cm^2 particle^{-1}, the expected predominant type of radiation in a 10 s interval is ORB electrons. When the D/F is bigger than 1.12 nGy cm2 particle^{-1}, the expected type of radiation is IRB or SEP protons. The GCR source is divided between the two ranges. The new procedure allows the separation of electrons and protons into the internal radiation belt and the electrons and the SEP protons in the outer radiation belt.

Comparison of data from "MIR" and ISS stations in 1991–2022

The aim of Fig. 1 is to compare analogically data obtained at "MIR" and ISS by Liulin type instruments in the period 1991–2022. The main idea is to find the four-radiation sources and analyzed the dose rate dynamic in L-value distributions. Special attention is payed to the ORB relativistic electron source, observed at all studied missions as we are the first measuring the flux and dose rate from ORB relativistic electrons on "MIR" [5] and on the ISS [3].

There are four rows of figures and one row of table in the Fig. 1. In the first row is situated a table, which contains information for the name and position of the instruments, its measurement resolution in seconds (in red), the time interval of the measurements, the average altitude of the vehicle in km and the average for this time interval F10.7 cm Radio Flux (in red color) in solar flux units (Solar Cycle Progression | NOAA / NWS Space Weather Prediction Center).

The first row of figures (Fig. 1.1 – Fig. 1.6) visualize the external views of the instruments: First is the picture of LIULIN, next is Liulin-E094, further are the R3DE, R3DR and R3DR2 instruments. The last is the Liulin-SET instrument (Fig. 1.6). As already, mentioned R3DR2 instrument is R3DR but with different name to distinguish from R3DR.

The second row of figures contains pictures showing the position of the instruments “inside” or “outside” of the stations. In Fig. 1.7, the Second Bulgarian cosmonaut Aleksandr Panayotov Aleksandrov inside the “MIR” space station is seen. The American astronaut James S. Voss, who preferably worked with the “Dosimetric mapping” devices, including Liulin-E094 [10], is seen in Fig. (1, 8).

The third row of figures in Fig. 1 presents six graphics of the dose rate from flux and dose to flux (D/F) from flux dependencies. On the horizontal axis is the flux in cm^{-2} s^{-1}, while on the vertical axes are two parameters: the dose rate in μGy h^{-1} (red points) and the dose to flux ratio in nGy cm^2 $particle^{-1}$ (blue points). These graphics are a fast and easy way of visualizing the four different radiation sources components registered at the stations altitudes.

Following common features can be mentioned, analyzing Fig.1:

a) SEP particles are observed only in figures Fig. 1.17 and Fig. 1.23.

b) The dose rates in the IRB and ORB sources in figures Fig. 1.13, Fig.1.14, Fig. 1.19 and Fig 1.20 are the smallest because both data sets are obtained inside the “MIR” and the ISS space stations. The walls of the stations reduce the amount of energetic electrons and protons from other and inner belts respectively.

In the figures (1, 13) to (1, 18), the following radiation sources are observed: (1) GCR particles, (2) protons with more than 15.8 MeV energy in the SAA region of the IRB and (3) relativistic electrons with energies above 0.78 MeV. The dose rates (red points) from IRB and the IRB sources are seen as two maxima in the diagonal of each of the first four pictures. An additional maximum from SEP particles is seen in the Fig. (1, 17) above the usual IRB maximum. SEP measurements based on data from the R3DR2 instrument were already published [3].

The dose to flux ORB maxima (blue points) are situated horizontally in the bottom of figures from (1, 13) to (1, 18). The amount of points is narrower and below the thicker ones IRB D/F maxima. The ORB D/F maxima lies almost in all flux values below 1.12 nGy cm^2 $particle^{-1}$, which according to [3, 17], shows that the predominant amount of particles there are energetic electrons. On the opposite, the IRB D/F maxima lies in all flux values in the range 1.12–9.0 nGy cm^2 $particle^{-1}$, which according to Haffner’s formulas shows that the predominant amount of particles there are energetic protons. The SEP D/F maximum in Fig. (1. 17) shows D/F values larger than IRB maximum values and reveal that the protons there are with smaller energies than in the protons in the IRB maxima.

The bottom row of Fig. 1 contains six graphics with L-value in the horizontal axes and dose rate, flux and dose to flux ratio values in the vertical axes. These are types of magnetic latitudinal profiles from the equatorial latitudes (L = 1) up to high magnetic latitudes (L = 6).

The IRB dose rate maxima are situated in the left side of the figures at L = 1.4, while the flux maxima are at a-bit lower L-values. This L-value position reflect the position of the SAA in the inner belt. The flux and dose rate IRB maxima values in Fig. (1, 19) and (1, 20) are the smallest because LIULIN and Liulin-E094 devices were inside the “MIR and ISS space stations. The larger shielding by the stations walls attenuate the IRB proton flux and lower the dose rates.

The IRB dose to flux ratio in all (1, 19) to (1, 24) figures is with small values above 1.12 nGy cm^2 $particle^{-1}$ at small L-values. At L-values between 1.4 and 2.2, a rising strait line structure is observed. It is explanted with the decreasing energy of the protons away from the SAA center.

The ORB dose rate and flux maxima are well seen in figures 1.21 to 1.24, presenting ORB data from outside the ISS. In figure (1, 20) the ORB dose rate maximum is relatively small because the position of Luulin-E094 instrument inside the ISS. Larger shielding prevent the penetration of energetic protons in ORB inside the station.

Numerical results from the observation in 1991–2022

During the experiments with the R3D/E/R/R2 instruments on EXPOSE-E/R/R2 platforms [8] in 2008–2009, 2009–2010 and 2014–2016 outside the ISS [3, 15] behind 0.25–0.5 g cm^2 shielding, the following averaged GCR daily absorbed dose rate was measured - 91.1/81.4/71.6 μGy day^{-1}. The falling trend in the averaged GCR daily doses is explained with the higher solar-activity during the EXPOSE-R2 mission in 2014–2016 in comparison with EXPOSE-E/R missions in 2008–2010.

The largest absorbed dose delivery inside the ISS is due protons and electrons of the IRB in the area of the South-Atlantic Anomaly (SAA) where the energetic particles come closer to the Earth surface owing to a displacement of the magnetic dipole axes from the Earth’s center. The daily average SAA doses reported by [10] inside of the ISS vary in the range 74-215 μGy d^{-1} for the absorbed dose rates. The IRB R3D/E/R/R2 daily average absorbed dose rates outside the ISS are 426/506/567 μGy d^{-1}, while the ORB daily average doses are 8.64/89/278 μGy d^{-1}.

Only R3D/R2 instrument observed SEP event in June 2015 [3]. The daily SEP absorbed dose rate reached 2846 μGy d^{-1}on 22 June 2015.

Conclusions

The main conclusion of the presented data is that the ORB enhancements, the PBs events and the penetrations of relativistic electrons at low L-values and in the IRB are common on the manned “MIR” and ISS space stations. Although the obtained doses do not pose extreme risks for the astronauts, being on extra vehicular activity, they have to be considered as a permanently detected radiation source, which requires additional comprehensive investigations.

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