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RADIATION ENVIRONMENT INVESTIGATION RESULTS OBTAINED WITH LIULIN-5 EXPERIMENT IN THE HUMAN PHANTOM OF MATROSHKA-R PROJECT ABOARD THE INTERNATIONAL SPACE STATION

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Key words*: space radiation dosimetry, International Space Station, tissue-equivalent phantom, charged particle telescope*

Abstract: *The Liulin-5 experiment for investigation of ionising radiation distribution in a spherical tissue-equivalent phantom has been conducted aboard the International Space Station (ISS) since June 2007. It is an adherent part of the MATROSHKA-R international project on the Russian Segment of ISS for investigating space radiation dose distribution in the human body using a human model – tissue-equivalent phantom equipped with a set of radiation detectors. The charged particle telescope Liulin-5 measures the time resolved energy deposition spectra, the linear energy transfer (LET) spectrum, flux and absorbed dose rates for electrons, protons and the biologically relevant heavy ion components of cosmic radiation simultaneously at three depths of the phantom's radial channel. In this report, we present new results for the radiation quantities obtained from different components of the complex radiation field on the ISS at the minimum of the 23-th solar activity cycle and compare them with data from other radiation detectors on the ISS.*

РЕЗУЛТАТИ ОТ ЕКСПЕРИМЕНТ ЛЮЛИН-5 ЗА ИЗСЛЕДВАНЕ НА РАДИАЦИОННАТА ОБСТАНОВКА В ЧОВЕШКИ ФАНТОМ ПО ПРОЕКТ МАТРЬОШКА –Р НА МЕЖДУНАРОДНАТА КОСМИЧЕСКА СТАНЦИЯ

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Ключови думи*: космическа радиационна дозиметрия, Международна Космическа Станция, тъканно-еквивалентен фантом, телескоп на заредени частици*

Резюме: *Експериментът Люлин-5 за изследване разпределението на йонизиращата радиация във сферичен тъканно-еквивалентен фантом се провежда на борда на Международната Космическа Станция (МКС) от месец юни 2007г. Той е съществена част от международния проект „Матрьошка-Р" на МКС за изучаване на разпределението на радиационните дози в човешкото тяло чрез използуване на модел на човека- тъканно-еквивалентен фантом, оборудван с набор от радиационни детектори. Телескопът на заредени частици Люлин-5 измерва в реално време спектрите на депозирани енергии, спектъра на линейно поглъщане на енергията, потока частици и мощността на погълнатите дози на електроните, протоните и биологически значимите тежки йони на космическата радиация едновременно в три дълбочини на радиалния канал на фантома. В работата са представени нови резултати за радиационните величини, получени от различните компоненти на комплексното радиационно поле на МКС в минимума на 23-ия цикъл на слънчевата активност, както и сравнение с данните от други радиационни детектори на станцията.*

Introduction

Space radiation is a concern for astronauts' health and safety and investigation of the radiation influence on space vehicles and their crew has been conducted since the early times of human spaceflight. Predicting the effects of radiation on humans in space flight requires accurate knowledge and modeling of the space radiation environment, calculation of primary and secondary particle transport through the shielding materials and through the human body, and assessment of the biological effect of cosmic particles. The radiation field in the ISS is complex, composed by galactic cosmic rays (GCR), trapped radiation of the Earth radiation belts, solar energetic particles, albedo particles from Earth's atmosphere and the secondary radiation produced in the shielding materials of the spacecraft and in human body.

The GCRs, consisting of 99% protons and He nuclei and 1% heavy ions with energies up to tens of GeV/nuc are permanent source of ionising radiation in the ISS. The GCR radiation in the near – Earth free space is approximately isotropic.

Another component of the incident radiation field in the ISS orbit is the trapped protons and electrons. The trapped protons of the inner radiation belt have energies up to several hundreds of MeV and contribute a large fraction of the dose rates outside and inside ISS. The trapped protons are encountered by low Earth orbit (LEO) spacecraft in the region of South Atlantic Anomaly (SAA). The trapped radiation in the inner radiation belt shows a pronounced directionality. Due to the East – West asymmetry in the SAA, at a given point the flux of protons coming from west is higher than the flux from east. The average kinetic energy of the inner zone trapped electrons is a few hundred keV. These electrons are easily removed from the spacecraft interior by the slightest amount of shielding and are mainly of concern to an astronaut in a spacesuit. At higher latitudes ISS crosses the earthward part of the outer electron radiation belt. The average energy of these electrons is also about few hundred keV.

Solar Particle Events (short-term high-intensity bursts of protons and ions accelerated to hundreds of MeV) also contribute transient increases to the radiation environment.

The radiation field at a location, either outside or inside the spacecraft is affected both by the shielding and surrounding materials. Dose characteristics in LEO depend also on many other parameters such as the solar cycle phase, spacecraft orbit parameters, helio – and geophysical parameters.

Computational models indicate that about half of the ionising radiation exposure at the 51.6^0 inclination orbit near solar minimum results from GCR and the bulk of the remainder - from trapped particles [1]. Although only about 5% of the mission time of ISS is spent in the SAA, the astronauts may collect more than 50% of their total dose during this short time period [2].

The biological impact of space radiation to humans depends strongly on the particle's linear energy transfer and is dominated by high LET radiation. Especially important is the effect of the high energy heavy ion component of GCR, possessing high LET and highly penetrating in human body, which provides them with a large potential for radiobiological damage [3]. Cosmic radiation must be measured not just as absorbed dose, but also as dose equivalent, or absorbed dose weighted by biological effectiveness. Biological effectiveness or quality factor (Q) is a function of LET [4].

For the estimation of the organ doses from the complex radiation field in ISS, and thus the radiation risk, measurements in human phantoms are essential. Recently research programs have been proposed to provide the necessary depth-dose-equivalent measurements using fully instrumented phantoms on ISS. In 2004 the ESA project MATROSHKA with an anthropomorphic phantom [5,] and the MATROSHKA-R international experiment were started on the Russian segment of ISS. The experiment MATROSHKA-R includes the Russian spherical tissue–equivalent phantom [6, 7], equipped with passive and active experiment packages for studies of the depth dose distribution of the orbital radiation field at various sides of organs of a human body exposed to cosmic radiation. Liulin-5 is an active experiment in the spherical phantom [8, 9]. The aim of Liulin-5 experiment is long-term investigation of the depth-dose distribution and continuous monitoring of the particle fluxes, dose rates, energy deposition and LET spectra in a radial channel of the phantom, using a telescope of three silicon detectors. The first stage of Liulin-5 experiment on ISS took place from June 2007 to June 2010.

2. Liulin-5 method and instrument

The investigation of the radiation environment in the phantom in ISS by Liulin–5 experiment envisages: i) measurement of the depth distributions of the energy deposition spectra, flux and dose rate, and absorbed dose D; ii) measurement of the LET spectrum in silicon, and then calculation of LET spectrum in water and Q, according to the Q(L) relationship given in ICRP60 [4], where L stays for LET. Q(L) is related functionally to the unrestricted LET of a given radiation, and is multiplied by the absorbed dose to derive the dose equivalent H. H, D and Q are related by:

(1) $H = QavD$,

where D is the absorbed (integrated over all particles) dose, and Qav is the dose averaged quality factor, given by:

(2) $Qav = \int Q(L)D(L)dL/D$.

Liulin-5 instrument consists of two units: a detector module and an electronics module. The detector module is mounted in the radial channel of the phantom, while the electronics is outside the phantom (Fig.1).

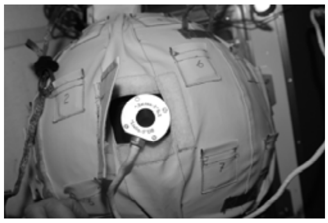

Fig.1. Liulin-5 onboard ISS. On the top-the electronic block, bottom- the detector module in the spherical phantom

More detailed description of Liulin-5 method and instrument can be found in [8]. The detector module contains three silicon detectors D1, D2 and D3 arranged as a telescope. The detectors axis is along the radial channel. The D1 detector is at 40 mm, D2 is at 60 mm and D3 is at 165 mm distance from the surface of the phantom. Data for flux, energy deposition spectra and absorbed dose rate measured in each detector is recorded. Detectors D1 and D2 operate in coincidence mode. The position of D1-D2 telescope in the phantom corresponds to the position of blood forming organs in human body, while the D3 is placed very close to the phantom's centre. This arrangement allows measuring the dose-depth distribution in the radial channel. The energy deposition spectrum measured in the D1 detector in coincidence mode with the D2 is recorded and used to obtain LET spectrum. The LET spectra in silicon obtained are used for calculation of the LET spectra in water and quality factors. Data are stored and returned to Earth on memory cards. The data format contains the time of the measurement, operational mode, and measured data. The instrument provides time resolved:

- Absorbed dose rate in each detector.
- Flux rate in the range 0 - $4x10^2/(cm^2.s)$, measured in each of the detectors.
- Energy deposition spectra in D1 detector in the range 0.45 — 63 MeV in 512 spectral channels.
- Energy deposition spectra in D2 detector in the range 0.45 — 60 MeV in 512 spectral channels.
- Energy deposition spectra in D3 detector in the range 0.2 – 10 MeV in 512 spectral channels.
- LET(H_2O) spectra in the range 0.65 – 90 keV/µm in 512 spectral channels.

The events exceeding the upper energy deposition or LET limit of each detector are recorded in the corresponding 512-th channel.

3. Results and discussions

The period July 2007 - 2009 corresponds to the minimum of solar activity cycle and quiet solar and geomagnetic conditions. The altitude of ISS was varying in the interval 317 - 380 km. The obtained results concern the dose rate and flux distributions at 3 different depths in the radial channel of the phantom, LET spectra, Qav and dose equivalent. Obtained are the dosemetric quantities from the different components of the radiation environment in ISS.

3.1. Energy deposition spectra, LET spectra, and quality factor

The differential energy deposition spectra in the detector D1 and LET spectra, obtained from GCR (left panels) and trapped protons in SAA (right panels) for the time interval 3 to 13 May 2008, are plotted in Fig. 2. The top panels represent the deposited energy spectra. Written under each of these panels are the calculated average dose rate (DRcal) and the average dose rate (DRlow), calculated in the energy deposition range 0.45-10 MeV ($0.65 \leq$ LET (H_2O) $\leq$ 14 keV/µm) for each detector. DRlow allows comparing the doses obtained in the different detectors (respectively at different depths) in one and the same energy deposition range. On the second panel the differential LET spectra are plotted, under the panels written are the calculated average dose rate DRcal in the telescope D1-D2, and the average quality factor Qav calculated according to equation (2) and using data from the LET spectrum. The values Qav are obtained when all events, exceeding the upper LET measurement limit are considered as events with LET 90 keV/µm (corresponding to almost maximum Q). In SAA a difference between the dose rates DRcal in D1, calculated from the energy deposition spectrum and from the LET spectrum is observed. This is due to West-East asymmetry of trapped protons leading to anisotropic incident particle fluxes on Liulin-5 detectors and due to sharply anisotropic shielding distributions of D1 and D2 detectors during the experiments with Liulin-5 in the phantom [10].

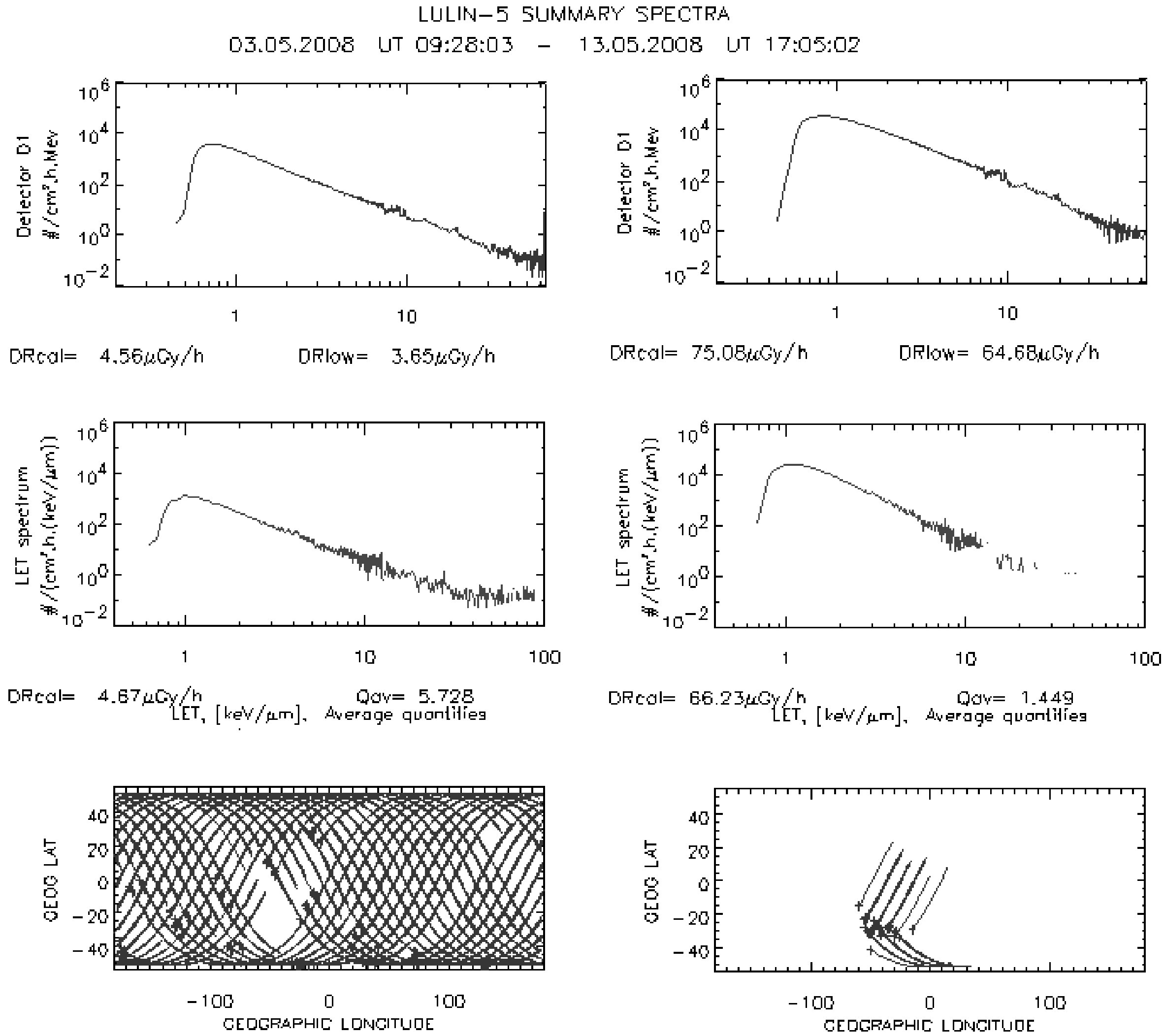

Fig. 2. Differential energy deposition spectra in the detector D1 and LET spectra, obtained from GCR (left panels) and trapped protons in SAA (right panels) for the time interval 3 to 13 May 2008. On the top -the deposited energy spectra, middle- the differential LET spectra and bottom - the parts of ISS trajectories at which the corresponding data are obtained.

On the bottom panels are presented the parts of ISS trajectories at which the corresponding data for GCR and trapped radiation are obtained.

Well seen are the differences in the spectra from GCR and trapped protons, their dose rates and quality factors. The dose rate measured in SAA is much higher (75 µGy/h) than outside it (4.6 µGy/h). But the percentage of high LET heavy ions (LET ≥ 10 keV/µm) in LET spectrum from GCR is higher than it is in SAA spectrum. This is the reason for higher Qav (about 5.7) of GCR compared to Qav of trapped protons (about 1.4). The calculations are based on 15 minutes cycle of measurement of spectra in SAA region and on 85 minutes cycle outside it.

3.2. Distribution of flux and dose rates along the ISS trajectories

A typical distribution of dose rates in geographic and geomagnetic coordinates along the ISS trajectories is presented in Fig. 3. The data represent the measurements in the detector D2 (placed at 60 mm from the phantom's surface - the depth of blood forming organs in the phantom) of Liulin-5 particle telescope recorded in the period 10.01 - 27.05.2009. Maximum dose rate are registered from the trapped protons of the inner radiation belt in the region of SAA. The dose rate reaches maximum 812 µGy/h at the centre of SAA (L ~1.35, B~0.2). Minima values of about 0.6 µGy/h dose rates from GCR were recorded at equatorial and low-latitude regions. At high geographical latitudes the dose rate

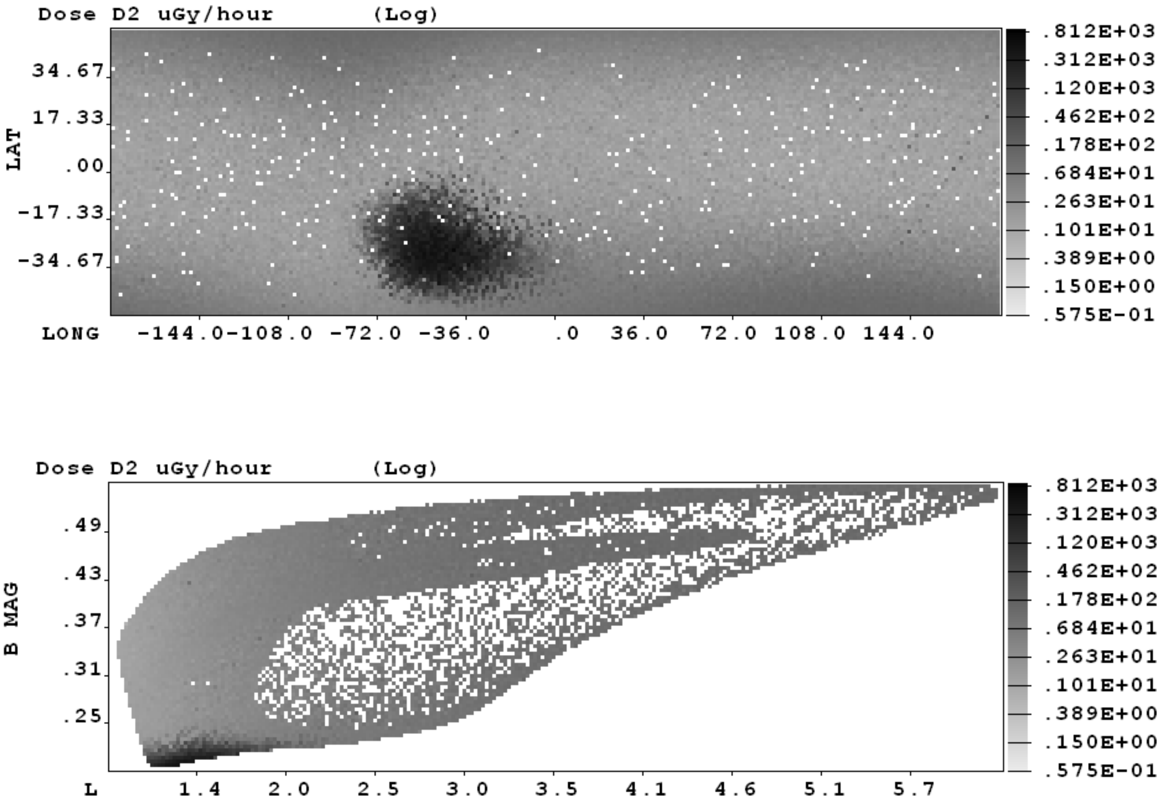

Fig. 3. Dose rates distribution in the period 10.01 - 27.05.2009 at the depth of blood forming organs in the phantom. Data are plotted in geographic (top panel) and geomagnetic coordinates (bottom panel) along the ISS trajectories.

from GCR was up to 20 µGy/h. The calculations are based upon 90 s cycles of measurements of the dose rate and particle flux for GCR and 20 s cycles for trapped protons.

Fig. 4 shows a good agreement of dose rate measurements by D1 detector of Liulin-5 and the DB-8 active dosemeter [11] in the Russian segment of ISS. The peaks of dose rate distributions of both instruments correspond to SAA crossings. The maxima of the quasi-sinusoidal distribution represent the GCR dose rates at high latitudes and minima –the near equator GCR dose rates. Data were taken on 7 February 2008 from 12:00 to 16:48 UT.

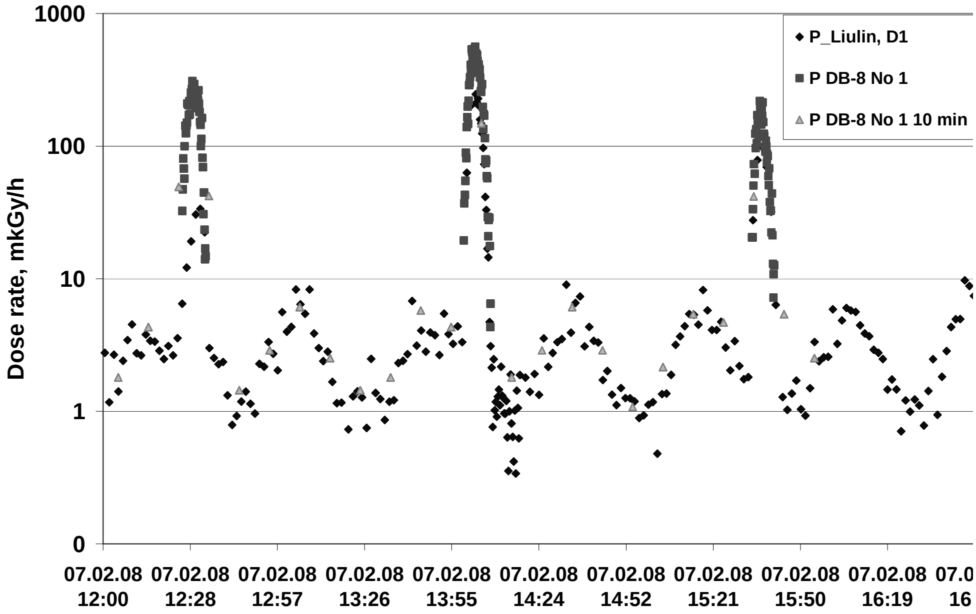

Fig. 4. Comparison of dose rate measurements by D1 detector of Liulin-5 (rhombi) and the DB-8 dosemeter (triangles and quadrates) in the Russian segment of ISS.

3.3. Dosimetric quantities from GCR and trapped radiation

The results of the averaged daily absorbed doses, average quality factors and dose equivalents in D1 from GCR and trapped protons obtained from particles of 0.65 ≤ LET (H_2O) ≤ 88.1 keV/µm in different periods from July 2007 to February 2009 are shown in Table 1. It is seen that the averaged daily absorbed doses at the depths of blood forming organs in the phantom are between 180 µGy/day and 220 µGy/day. At those depths the contribution of the trapped protons is about 50-60% of the total absorbed doses and the rest of the dose is from the GCR. A slight increase of daily doses from GCR is observed. The results obtained agree well with the data from thermo-luminescent detectors (TLD) measurements in the spherical phantom conducted from May 2007 to December 2008. TLD data show that at 40-60 mm distances from the phantom surface the averaged daily absorbed doses in containers near Liulin-5 are 170-180 µGy/day [12].

The total averaged quality factors without taking into account the counts in the last 512 channel of LET spectra are between 1.7 and 2.6. Under these circumstances the averaged dose equivalents in D1 detector are between 370 and 480 µSv/day. When all counts in the last 512 channel of LET spectra are considered as events of 90 keV/µm the averaged total quality factors and dose equivalents increase by a factor of 1.4-1.6. Due to the bigger quality factor of GCR their contribution to biologically significant dose equivalents is much higher than those of the trapped protons. The obtained results are indicative of the GCR high LET heavy ions (LET ≥ 10 keV/µm) contribution to the average quality factor and dose equivalent in the human body. About 70% of dose equivalent at the depth of blood forming organs in the phantom is from GCR and their secondary particles and the other part is from trapped protons of the inner radiation belt and their secondaries. Similar results are obtained with the NASA tissue-equivalent proportional counter (TEPC) for the period June 2007 - September 2008 in the US and ESA modules of ISS [13] showing that about 70% of dose equivalent in ISS is from GCR.

Table1. Absorbed average daily dose at the depth of blood forming organs, Qav and averaged daily dose equivalents obtained in different periods in 2007-2009

Date	Dose [µGy/day]			Qave			Dose equivalent [µSv/day]		
	GCR	SAA	Total	GCR	SAA	Total	GCR	SAA	Total
3-10.07. 07	79.8	117.2	197	3.3	1.22	2.03	261.1	143.3	400.4
5-10.09. 07	82.7	134	216.7	2.7	1.15	1.7	224.8	153.9	378.7
3-13.05.08	83.8	97.7	181.5	3.9	1.35	2.6	330.6	132.2	462.8
24.10-01.11.08	86.8	111.9	198.7	2.8	1.18	1.9	238.8	132.6	371.4
23.02-28.02.09	88	95.7	183.7	4	1.31	2.6	356.3	125.4	481.7

For estimation the depth dose distribution, the doses in the equal for three detectors of Liulin - 5 energy deposition range 0.45-10 MeV (0.65≤ LET (H_2O) ≤ 14 keV/µm) are calculated. The results for the total doses at 3 different depths in the radial channel of the phantom as well as the contribution of GCR and trapped protons to them for the time interval 5-10.09.2007 are presented in Table2. As expected, the largest dose rates are observed in the outer-most detector, while the minimal dose rates are in the innermost detector. The total dose at the centre of the phantom is about 1.6 times less than at the depth of blood forming organs. The decreasing of the doses in depth of the radial channel is due to decreasing of doses from trapped protons in SAA, effectively shielded by the phantom itself. At the centre of the phantom the GCR contribute about 60% of the total dose. GCR doses at different depths in the phantom are practically the same. Similar data are obtained for the other periods of measurement. The typical depth-dose curve from LiF TLD detectors in the spherical phantom along the diameter perpendicular to the space station wall shows decreasing of 5-10% between the values obtained at 40 and 60 mm and decreasing by a factor 1.5-1.6 between the doses measured at 40 mm and 165 mm from the phantom's surface. The typical LiF TLD dose distribution in the phantom body versus radial depth indicates the same differences between the data for 40 and 60 mm, independently of the radial attitude [14]. This is in good agreement with the data presented in Table 2, having in mind the differences in measurement ranges of Liulin-5 and TLDs and shielding distributions.

Table 2. Absorbed averaged daily doses in the period 5-10.09.2007г, calculated in the equal for three detectors of Liulin -5 energy deposition range 0.45-10 MeV (0.65≤ LET (H_2O) ≤ 14 keV/µm) and contribution of GCR and trapped protons to the total doses.

Detector	D1 [µGy/day]	D2 [µGy/day]	D3 [µGy/day]
Total dose	191	169	110
SAA dose	126	101	44
GCR dose	65	68	66

3.4. Effect of SAA trapped protons asymmetry on Liulin5 dose rates

ISS passes the SAA region from two directions (ascending and descending nodes) as occurs during orbit precession. The east-west asymmetries of the proton fluxes in the region of the SAA lead to differences in the amplitudes in the dose rate obtained during ascending and descending nodes. It was evaluated that the shielding of the first two detectors D1 and D2 in the radial channel of the

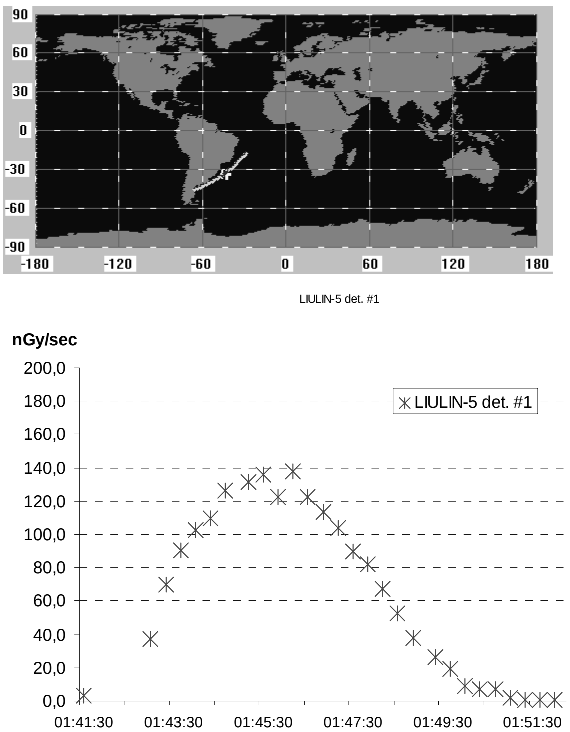

Fig.5a. Top panel -passing the SAA, March 6, 2008 from 01:42 to 01:50 UT on ascending orbit. The Liulin-5 detector axis is directed to west. Bottom panel-dose rate in D1.

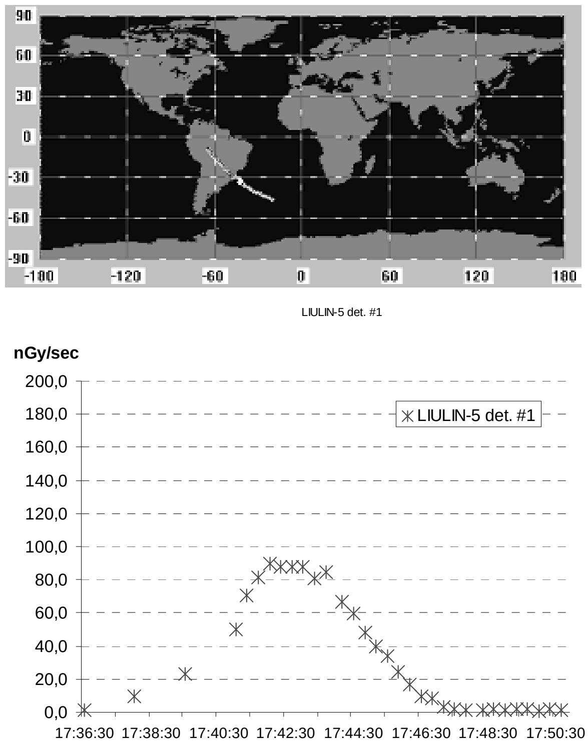

Fig.5b. Top panel -passing the SAA, March 5, 2008 from 17:38 to 17:46 UT on descending orbit. The Liulin-5 detector axis is directed to north. Bottom panel-dose rate in D1.

phantom is much lower close to the detector block axis than in other directions [10]. The usual attitude of ISS is with the US laboratory module forward the station velocity vector. Shown is that on ascending orbits at this ISS usual attitude the detector block axis, as well as the low-shielded zone of D1 and D2 is turned to west (the direction of the maximum high-energy proton flux in SAA), while on descending orbits the detector block axis and the low-shielded zone of D1 and D2 is directed to north [10]. Because of that the dose rates measured on ascending are higher than the dose rates on descending orbits at the same areas in SAA. This is illustrated in Fig. 5a and Fig. 5b showing the part of orbits of in SAA respectively on ascending and descending orbits together with the position of ISS at the moments of maximum dose rates, as well as the corresponding dose rates in D1 detector. The ratio of the maximum dose rates at ascending and descending orbits in SAA is about 1.5.

4. Conclusion

Obtained are new results from Liulin-5 experiment for radiation quantities in a human phantom on ISS at the minimum of 23-rd solar cycle.

Shown is that the dose rates at the depth of blood forming organs in the phantom reach more than 800 µGy/h at the centre of SAA, at high geographic latitudes the dose rate from GCR is up to 20 µGy/h and lowest dose rates of about 0.6 µGy/h are recorded at equatorial and low-latitude regions.

The averaged absorbed daily doses obtained from July 2007 to 2099 at the depths of blood forming organs in the phantom are between 180 µGy/day and 230 µGy/day. At those depths the contribution of the trapped protons is about 50-60% of the total absorbed doses and the rest of the dose is from the GCR.

A slight increase of daily doses from GCR is observed since July 2007 to the end of 2009.

The absorbed doses close to the centre of the phantom decrease by a factor of 1.6-1.8 compared to the doses at blood forming organs depth in the phantom. At the centre of the phantom the GCR contribute about 60% of the total dose.

The total average quality factors Qav for $0.65 \leq$ LET (H_2O) ≤ 88.1 keV/µm are between 1.7 and 2.6, the Qave of GCR is between 2.7 and 4, Qav of the trapped protons of inner radiation belt is between 1.1 and 1.35. Considering all events in the last channel of LET spectrum as events of 90 keV/µm, the Qav and dose equivalent increase by factor about of 1.4 due to increasing the GCR Qav. The dose equivalent of GCR and their secondary particles represents about 70% of total dose equivalent in blood forming organs of human body and the rest is from trapped protons. These results indicate the importance of measurement of LET spectrum (and particularly those of high LET heavy ions) onboard of the upcoming missions to Mars and Moon to obtain more precise data for the radiation exposures of a future interplanetary mission crew.

Investigated is the effect of the trapped protons east-west asymmetry on Liulin5 dose rates in the anisotropic radiation field in SAA area.

The data obtained with Liulin –5 during 2007-2009 agree enough well with the data from passive radiation detectors in the spherical tissue-equivalent phantom of Matroshka-R project and with the data from other active dosemeters on ISS and can be used for verification of radiation environment on ISS.

Further analysis of obtained data is foreseen, including comparisons with models of the radiation environment for the minimum of solar activity cycle, shielding conditions for Liulin-5 detectors, orbital parameters, and with data from other dosemeters aboard ISS.

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