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SPACE RADIATION DOSE AND PARTICLE FLUX DISTRIBUTION FROM LOW EARTH TO MOON ORBITS

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Abstract: *The space radiation is a very important component of the space weather and affects both the space crew and electronic devices in space flights. The Bulgarian scientists together with number of international partners for more than 20 years conduct research of the ionizing radiation distribution from the Earth surface to the Moon orbit. In this paper we present some results for space radiation doses observed during number of experiments on the Mir manned space station, International Space Station, on unmanned satellites Foton-M2, Foton-M3 around the Earth and on Chandrayan-1 satellite around the Moon. Discussed is the contribution of the galactic cosmic rays and trapped radiation to the particle fluxes and absorbed doses.*

Key words: *Ionizing **S**pace radiation, Galactic cosmic rays, Solar cosmic rays, Earth radiation belts, Space radiation measurements, Low Earth orbit, Moon orbit*

I. INTRODUCTION

The ionizing radiation has been recognized as a main health concern to space crew and investigation of the radiation influence on space vehicles and their crew has been conducted since the early times of human space flight. Estimating 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 a spacecraft in low Earth orbit (LEO) like the manned Mir station and International Space Station (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 ionizing 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 LEO spacecraft in the region of South Atlantic Anomaly

(SAA). Although only about 5% of ISS mission time is spent in the SAA, the astronauts may collect more than 50% of their total dose during this short time period (Apathy et al., 2007) [1]. 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, but a prominent feature is the appearance under certain geomagnetic conditions of the so called 'killer electrons' – electrons with relativistic energies of the order of MeV, which could cause spacecraft charging and spacecraft anomalies [2]. Dachev et al. [3] reported measurements of the outer belt relativistic electrons on ISS and concluded, that though they produce an enhancement in the dose rate, the observed doses do not result in a dangerous increase of the radiation doses.

The radiation field at a location, either outside or inside the spacecraft is affected both by the shielding and surrounding materials [4-6]. Dose characteristics in LEO depend also on many other parameters such as the solar cycle phase, spacecraft orbit parameters, helio – and geophysical parameters.

The biological impact of space radiation to humans depends strongly on the particle's linear energy transfer (LET) 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 [7]. For radiation protection the quality factor (Q) was introduced to describe the different biological effectiveness of the different radiation types. The quality factor is defined as a function of LET [8]. The biologically significant dose equivalent is obtained as the absorbed dose is weighted by the quality factor.

The dominant radiation component at 100 km above the surface of the Moon [9] are GCR modulated by the solar activity. The Solar Particle Events (SEP-short-term high-intensity bursts of protons and ions accelerated to hundreds of MeV) and produced by solar flares, sudden sporadic eruptions of the chromosphere of the Sun also contribute transient increases to the radiation environment in LEO and around Moon. The lunar albedo radiation (principally neutrons) [9] is produced by the interactions of GCRs and SEPs in the surface. The neutron albedo can contribute as much as 20% to the effective dose when the radiation environment is dominated by GCRs, whereas when SEPs dominate, the neutrons contribute about 2% to the effective dose [10].

From 1989 to 1994 the radiation environment in Mir manned station has been observed by Liulin dosemeter-radiometer developed by Bulgarian and Russian scientists [11]. Since 2001 the radiation environment inside and outside of ISS and in a human phantom in ISS as well as on number of unmanned spacecrafts in LEO has been studied with various arrangements of radiation detectors developed by Bulgarian scientists and their international partners [12-21]. The Chandrayaan-1 Indian spacecraft was launched on 22 October 2008 [22]. RADOM instrument for radiation environment investigations onboard Chandrayaan-1 was provided by the Bulgarian Academy of Sciences [23].

In this paper we present some results for space radiation doses observed during number of experiments on the Mir space station, ISS, Foton M2 and Foton M3 satellites and on Chandrayan-1 satellite.

II. METHODS OF MEASUREMENT AND INSTRUMENTS

II.1 Dosimeter-radiometer Liulin on Mir space station

The Liulin dosimeter-radiometer was designed to measure the dose and flux of penetrating in Mir space station particles. It uses a silicon detector with a thickness of 306 microns and area of 2 cm^2 [11]. Simultaneous measurement of the energy absorbed in the detector and of the particle flux were recorded and transmitted to Earth.

Liulin instrument consists of detector and microcomputer units (Fig.1). The detector unit is a miniature, portable, self-indicating devise with a semiconductor detector. The fixed locations of the instrument in the MIR manned compartment behind effective shielding of 6-15 g/cm^2 gave homogeneous series of particle fluxes and doses measurements collected during the flight of the second Bulgarian cosmonaut (June 1988) and between September, 1989 -April, 1994.

The main contribution to the count rate measured by Liulin is due to protons and electrons that have energy respectively higher than 100 MeV and 10 MeV outside Mir space station.

II.2. Liulin -4 type deposited energy spectrometers

The main purpose of Liulin type Deposited Energy Spectrometer (DES) is to measure the spectrum (in 256 channels) of the deposited energy in a silicon detector from primary and secondary particles at the aircraft altitudes, at LEO, outside of the Earth magnetosphere on the route and on the surface of the planets of Solar system. The DES is a miniature spectrometer–dosimeter containing: one semiconductor detector, one charge-sensitive preamplifier, two or more microcontrollers and a flash memory. Pulse analysis technique is used for the obtaining of the deposited energy spectrum, which further is used for the calculation of the absorbed dose and flux in the silicon detector. The unit is managed by the microcontrollers through specially developed firmware. Plug-in links provide the transmission of the stored

Fig.2 RADOM instrument.

in the flash memory data toward the standard Personal Computer (PC) or toward the telemetry system of the carrier. The following instruments of Liulin-4 type were flown on different space missions: (1) The Liulin-E094 4 Mobile dosimetry units flown in

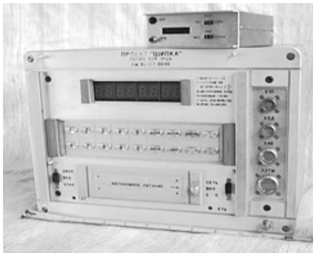

Fig. 1. External view of Liulin instrument on Mir space station

2001 on American Destiny module of International Space Station (ISS) [12] in the frame of the European DosMap Project [17]; (2) R3D-B2/B3 instruments flown on the FotonM2/M3 spacecrafts in 2005/2007 [16, 24]; (3) R3DE instrument which worked between February 2008 and September 2009 on the EuTEF platform of European Columbus module of ISS as part of the EXPOSE-E Facility [14]; (4) R3DR instrument, which operate outside the Russian Zvezda module of ISS till January 2011, (5) RADOM instrument (Fig.2.) launched on Chandrayaan-1 mission [23].

II.3. Liulin-5 dosimetric telescope [18-20]

Liulin-5 (Fig.3.) is an active instrument within the Russian spherical tissue–equivalent phantom [25, 26] on the ISS. The spherical phantom consists of 13 tissue–equivalent slices. The phantom has a diameter of 35 cm and 10 cm central spherical hole. There are 4 perpendicular radial channels and additional holes inside the phantom body for detectors placement. The weight is 32 kg. The phantom is stuffed with passive detectors that measure an integral absorbed dose, Linear Energy Transfer (LET) spectrum, or its mean value. Passive dosimeters are also placed in pockets of the phantom's case. The Liulin-5 particle telescope was mounted inside the largest diameter channel.

The detector module of Liulin-5 contains three silicon detectors D1, D2 and D3 arranged as a telescope. The detectors axis is along the phantom's radius.

The D1 detector is at 40 mm, D2 is at 60 mm and D3 is at 165 mm distance from the phantom's surface. The position of D1 and D2 in the phantom corresponds approximately to the depth of blood forming organs in human body, while D3 is placed very close to the phantom's centre. This arrangement allows measuring the dose-depth distribution along the sphere's radius.

The investigation of the radiation environment in the phantom in ISS by Liulin–5 experiment envisages: i) measurement of the depth dis-

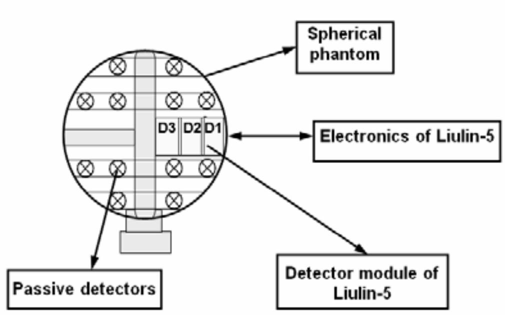

Fig. 3. The spherical phantom with Liulin-5 onboard ISS. Sketch of the detectors arrangement in the phantom.

tributions 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 [8], where L stands 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.

The first stage of Liulin-5 experiment on ISS took place from June 2007 to March 2010. In that period

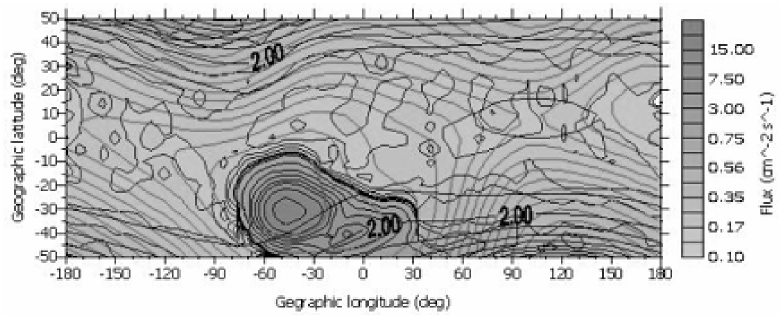

Fig.4. Global distribution of Liulin flux for July 1991

the spherical phantom was located inside the docking module PIERS-1 of the Russian Segment (RS) of ISS.

III. RESULTS AND DISCUSSION

III.I. Results obtained by Liulin instrument onboard Mir space station

Measurements by Bulgarian-Russian dosimeter-radiometer Liulin were used to study the time and spatial variations of the MIR radiation environment. Liulin measurements were carried out under a wide variety of solar and geomagnetic activity conditions. They provide an excellent opportunity to study effects on the dose-rates and fluxes in the near Earth radiation environment over long time periods, as well as rapid changes, induced by solar proton events and geomagnetic disturbances.

Global distribution of Mir radiation environment

In Fig. 4. the geographic distribution of the observed in July 1991 Liulin flux data by a color scale coding is presented. The main maximum is connected with the position of the South Atlantic Anomaly (SAA). The flux in it reaches a value of 37 $cm^{-2}\ s^{-1}$ for the case of July 1991. Generally it varies in the interval of 30-120 $cm^{-2}\ s^{-1}$ depending on the altitude, solar activity and local time. The equal flux lines out of the region of the SAA maximum follow relatively close the shape of the L values, forming in the polar regions of both hemispheres additional maxima, which are connected with the outer radiation belt. The observed southeast from SAA maximum is the result of the formation of the "new" radiation belt at the slot region after the Solar Proton Event (SPE) and the geomagnetic storm on March 23, 1991. During quiet solar conditions and quiet geomagnetic conditions out of the mentioned up maxima Liulin measures mainly GCR. The existence of solar protons at the station vicinity during solar proton events (SPE) is manifested with wide maxima in both dose rate and flux channels in the regions equator ward from north and south magnetic poles. The observed by

Liulin absolute maximum flux reached 179 cm^{-2} s^{-1} during the SPE of September 29, 1989.

Galactic cosmic rays (GCR)

GCR flux distribution during quiet solar conditions and quiet geomagnetic conditions is determined by the Earth magnetic field cut-off, which is energy dependent. The usual distribution measured by Liulin shows a minimum of 0.1-0.2 cm^{-2} s^{-1} close to the magnetic equator and a relative maximum reaching 1-2 cm^{-2} s^{-1} at high L (L>4) values [27].

Solar cosmic rays

Liulin solar energetic particles (SEP) data are available for September 29, 1989, October 18, 1989, March 23, 1991, June 8, 1991 and June 15, 1991 and June 26, 1992 [27-30].

As Mir space station was on a relative low inclination orbit (51.65°) only the orbits, which crosses the geographic equator in the region of 40°W-90°E longitude are exposed at high geomagnetic latitudes on the solar protons.

Fig. 5 gives the global distribution of Liulin flux data for quiet (lower panel) and SEP (upper panel) solar conditions. Liulin flux data was binned and averaged for two periods in 1989 and 1991. The bin size is 5 degree by latitude and 10 degree by longitude. Two maxima are seen at each of the panels: in the region of the SAA and in the high geographic latitude regions in the both hemispheres.

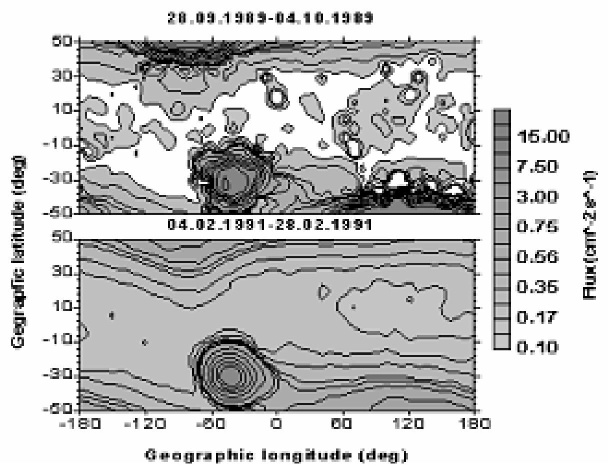

Fig.5. Global distribution of the Liulin flux for quiet (lower panel) and disturbed solar conditions (upper panel).

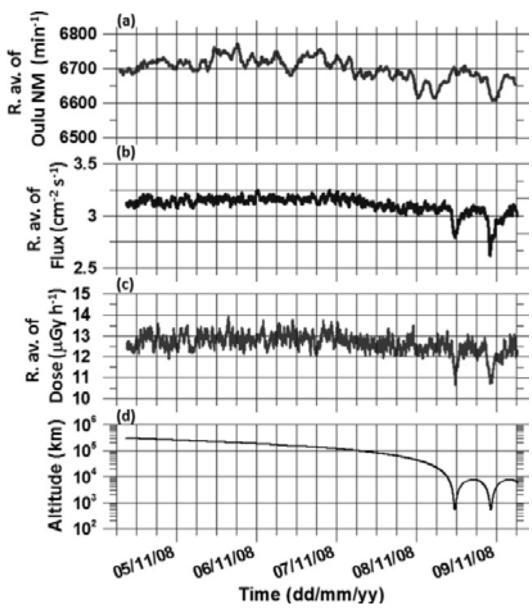

Fig.7. RADOM observations during lunar transfer trajectory and lunar orbit capture. The distance is from the Moon. The trends in particle flux coincide with the Oulu neutron monitor data trends.

The averaged for quiet conditions bin SAA maximum is about 15 cm^{-2} s^{-1}, while the SEP condition maximum is about 30 cm^{-2} s^{-1}. The difference is attributed to the difference of the mean altitude of the station in the region of the SAA, which for the lover panel is about 375 km and about 400 km for the upper panel. The average per bin flux maximum in the high latitude regions is about 0.7 for quiet conditions and 70 cm^{-2} s^{-1} for SPE conditions.

III.2. RESULTS OBTAINED BY LIULIN-4 TYPE INSTRUMENTS ON DIFFERENT SPACE MISSIONS

Dose rate distribution in LEO

The three sources of space radiation in LEO are seen in the dose rate distribution as a function of L-shells value shown in Fig. 6. Data are taken between 2001 and 2009 from measurements on ISS and on two unmanned satellites –Foton M2 and Foton –M3. The GCR are observed at all L-values, the trapped protons of the inner radiation belt in SAA are seen at L ~ 1.8 - 2.5, the trapped electrons of the outer radiation belt are at L > 3. The GCR dose rates show increase from 6.1 µGy/h in 2001 to 12.2 µGy/h in 2009 (from the maximum to the minimum of the solar activity). The doses from trapped radiation depend on the detector's shielding, solar activity, on the altitude and inclination of the spacecraft.

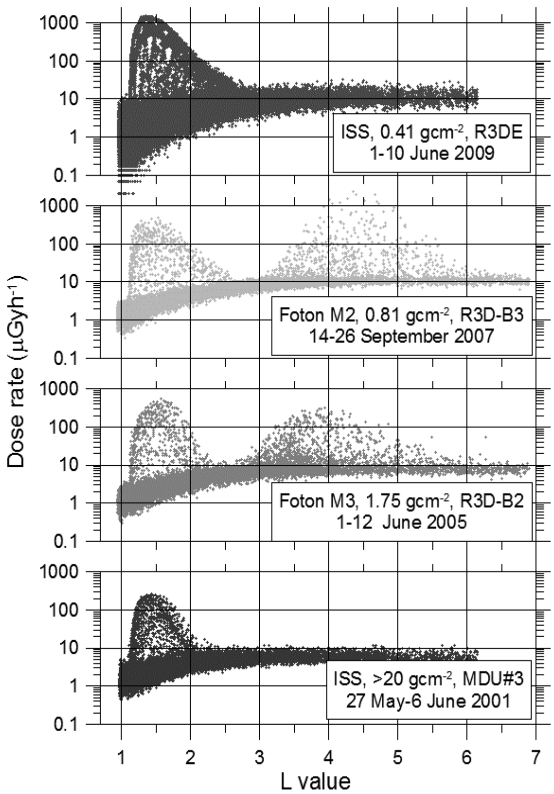

Fig. 6. Dose rate distribution measured from 2001 to 2009 on ISS, Foton M2 and Foton M3 satellites in LEO.

Altitudinal variations of the flux in Lunar orbit

When the Chandrayaan-1 satellite was away from both Earth and Moon during the lunar transfer orbits the averaged GCR dose was 12.76 µGy/h. When on 13th November 2008 the satellite entered a 100 km circular orbit around the Moon the GCR doses fall down to about 8.8 µGy/h and stayed stable around this value because of the Moon shielding. The average flux is 2.29/cm^{-2} s^{-1}. Fig. 7 show a look on the 30 s resolution moving average flux data in lunar orbit. It is seen that the flux vary in the range between 1.8 and 3 cm^{-2} s^{-1} when the altitude (dashed line) of the satellite vary between 92 and 118 km above the Moon. The moving average line shows clear tendency for maximums when the satellite is close to the aposelene points (118 km) and respectively minimums when the satellite is close to periselene points of 92 km.

III.3. LONG TERM OBSERVATIONS OF THE RADIATION ENVIRONMENT IN THE SPHERICAL TISSUE-EQUIVALENT PHANTOM ON ISS BY LIULIN-5 EXPERIMENT

Depth-dose distribution

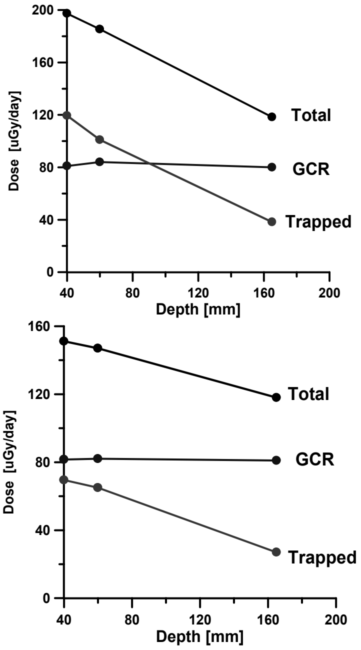

Fig.8. Comparison between two types of depth dose distributions: Upper- the typical one and bottom- Shuttle docking and ISS attitude change effect. With marks are shown the total, GCR and SAA trapped protons doses along the radius at 40, 60 and 165 mm distance from the phantom surface.

The results for the total doses at 3 depths in the radial channel of the phantom as well as the contribution of GCR and trapped protons to them are shown in Fig.8. Two types of depth dose distributions-the typical one (Fig.8-upper panel) and Shuttle docking effect (Fig. 4 –bottom panel) are presented. In both cases, the largest dose rates are observed in the outermost detector (40 mm distance from the phantom's surface), while the minimal dose rates are in the innermost detector (165 mm distance from the phantom's surface). The decreasing of the doses in depth along the phantom's radius is due to decreasing of doses from trapped protons in SAA, effectively shielded by the phantom itself. GCR doses at different depths in the phantom are practically the same.

The typical depth dose distribution presents measurements for the time interval 18 -23.11.2007. The average altitude of ISS during that period was 349.16 km. The daily-absorbed dose at 40 mm depth is about 200 μGy. The total dose at 165 mm depth (close to the centre of the phantom) is about 1.7 times less than at depths corresponding to the depth of blood forming organs. At 40 mm depth the SAA protons dose is about 60% of the total dose, while near the centre of the phantom the GCR contribute about 60% of the total dose.

Similar data are obtained for other periods of measurement- the averaged daily absorbed doses at 40 mm distance from the phantom's surface are between 180 μGy/day and 220 μGy/day and about 60% of them are due to SAA protons contribution. At 165 mm depth in the phantom the doses decrease by a factor of 1.6-1.8 compared to 40 mm depth [20]. The docking of the Shuttle to ISS causes significant changes in Liulin-5 dose rates measured in SAA because of changes in the detectors' shielding. It is demonstrated in lower panel of Fig.8 – the dose rates for the period 29.10 –02.11.2007 in SAA are significantly lower in comparison to the values in the upper panel of Fig.8. From 23.10 to 07.11.2007 the Shuttle (STS-120 mission) was docked to ISS. The daily-absorbed dose at 40 mm depth is about 150 μGy and the SAA protons dose is about 70 μGy/day –only about 46% of the total absorbed dose. At 165 mm depth the

Time	F3max [part/cm^2.s]	L [R_E]	B [Gs]	Longitude [degree]	Latitude [degree]	Altitude [km]
03.07-30.11.07	39.31	1.28	0.203	-44.88	-25.95	339.56
04.01-08.04.08	37.83	1.39	0.207	-51.71	-35.23	346.8
09.04-10.05.08	37.83	1.31	0.202	-46.77	-28.64	347.07
24.10.08-28.02.09	54.43	1.26	0.198	-54.61	-28.2	362.33
16.03.09-16.06.09	51.04	1.27	0.198	-53.84	-28.57	362.64
17.06-04.09.09	52.9	1.26	0.198	-51.8	-28.85	361.24
23.11.09-12.03.10	48.86	1.25	0.198	-55.31	-27.76	354.07

Table 1. Maximal particle fluxes measured at 165 mm depth in the phantom from July 2007 to March 2010 as a function of ISS orbit parameters.

total absorbed dose is about 1.3 times less than at 40 mm. The main part of the total absorbed doses in different depths during that time is from GCR that stay unchanged. The average ISS altitude during the period was 350.55 km. The Shuttle provides additional shielding from trapped radiation leading to a decrease of dose rates in SAA. Similar decrease of dose rate in SAA and of total dose rate is observed every time when the Shuttle arrives to ISS [31, 32].

For the purpose of Shuttle docking ISS attitude is changed by 180 degrees. That is an additional factor for Liulin-5 doses decreasing in SAA. The case is discussed in details in [31, 32].

Distribution of flux and dose rates along the ISS trajectories

The high time resolution of particle flux and dose rate (20 s in SAA and 90 s outside it) allows for detailed mapping of the radiation environment in the phantom with time and the ISS orbit parameters.

Table 1 shows the data for the maximum particle fluxes registered at 165 mm depth in the phantom for periods of 3-5 months from July 2007 to March 2010. The biggest fluxes are observed in SAA at L ~ 1.26-1.27, B ~ 0.198 Gs, at following geographical coordinates: longitude ~ -51 to -54 degree, latitude ~ -28 degree and altitude about 362 km. Increasing of maximal SAA fluxes is observed with increasing the ISS altitude.

CONCLUSIONS

Since 1988 the Bulgarian scientists together with their international partners conduct research of the ionizing space radiation distribution from low Earth to the Moon orbit. Investigations are made both on manned space stations and on unmanned spacecrafts. Obtained are many new results for the space radiation quantities and characteristics during 22 and 23 solar cycles. The investigations will be continued on the International Space Station and other spacecrafts in LEO, as well as on new space missions to Moon and Mars in order to obtain data for the space radiation doses expected to the crew and technological systems of future interplanetary flights.

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