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ADVANCES IN BULGARIAN SCIENCE '2016

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National Centre for Information and Documentation

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• Joint actions and projects with related national information and documentation centers in the EU.

NATIONAL SCIENTIFIC PROGRAMMES WITH EUROPEAN DIMENSIONS

BULGARIAN INSTRUMENTS FOR SPACE RADIATION MEASUREMENT

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Abstract. *Ionizing radiation has been recognized as one of the main health concerns for the humans in the near Earth and space radiation environment. The estimation of the radiation effect on health requires at first order accurate knowledge of the accumulated absorbed dose, which depend on the global space radiation distribution, solar cycle and local variations generated by the 3D mass distribution surrounding the space vehicle. This paper presents an overview of the Bulgarian-built spectrometer-dosimeters of Liulin-type and their main scientific results, which were obtained in space, at aircraft, balloon and rocket since 1988.*

INTRODUCTION

The radiation field in the interplanetary space and around the Earth is complex, composed of GCRs, trapped particles of the Earth's radiation belts, solar energetic particles, albedo particles from Earth's atmosphere and secondary radiation produced in the shielding materials around the biological objects [1-4]. Dose characteristics in near Earth and space radiation environment also depend on many other parameters such as the orbit parameters, solar cycle phase and current helio-and geophysical conditions.

Galactic cosmic rays

The dominant radiation component in the near Earth and free space environment are the galactic cosmic rays (GCR). The GCR are charged particles that originate from sources beyond our solar system. GCR are the most penetrating of the major types of ionizing radiation. 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 [5]. 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 [2]. HZE particles, especially iron, possess high-LET (Linear energy transfer) and are highly penetrating, giving them a large potential for radiobiological damage [6]. Up to 1 GeV energy, the flux and spectra of GCR particles show modulation that is anti-correlated with solar activity.

Trapped radiation belts

Radiation belts are the regions of high concentration of the energetic electrons and protons trapped within the Earth's magnetosphere. There are two distinct belts of toroidal shape surrounding the Earth where the high energy charged particles get trapped in the Earth's magnetic field. 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 ~700 MeV. The outer radiation belt (ORB) starts from about 4 Earth radii and extends to about 9-10 Earth radii in the anti-sun direction. The outer belt mostly consists of electrons whose energy is not larger than 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 International space station (ISS) wall, but may deliver large additional doses to astronauts during extra vehicular activity [7-9]. The ORB daily dose rate is practically 0 on magnetic quiet days and reaches maximal dose rates up to 28,840 μGy h^{-1} in the disturbed periods after magnetic storms on the EXPOSE-R2 mission.

The South-Atlantic Anomaly (SAA) is an area where the IRB comes closer to the Earth surface due to a displacement of the magnetic dipole axes from the Earth's center. The daily average SAA doses reported by Reitz et al., (2005) [10] inside of the International Space Station (ISS) vary in the range 74-215 μGy d^{-1} for the absorbed dose rates and in the range 130-258 μSv d^{-1} for the averaged equivalent daily dose rates.

During the analysis of the R3DE and R3DR data it was discovered that the US space shuttle dockings with ISS decrease the IRB dose rate [64]. The effect was described by the additional shielding, provided by the 78-tons Shuttle against the IRB 30–150 MeV proton fluxes.

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 10^4 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 hours, although some high energy protons can arrive in as early 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 [12].

We succeeded to measure the characteristics of SEPs in September-October 1989 inside the Russian space station “MIR” with the first Liulin type instrument [54, 86, 87] and with the Liulin-5 dosimetric telescope (DT) inside the ISS in March 2012 [63a, 88, 89].

With the R3DR2 instrument we performed one of the first SEP measurements outside of the ISS [90]. The highest SEP hourly dose rate measured during the EXPOSE-R2 mission was 5251 μGy h-1 on 22 June 2015.

Atmospheric Ionizing Radiation

The natural radiation level at cruising aircraft altitudes is much higher than it is at ground level. The radiation field arises as a result of the interaction of primary GCR particles with the Earth’s atmosphere. An additional flux of albedo secondary GCR is observed at altitudes below 3 km, which contributes to the forming of the flux minimum around 1.6 km altitude [13]. The intensity of the atmospheric radiations, composed of GCR primary and secondary particles and their energy distribution vary with altitude, location in the geomagnetic field, and the time in the sun’s magnetic activity (solar) cycle [11]. The atmosphere provides shielding, which depends on the overhead atmospheric depth. The geomagnetic field provides a different kind of shielding, by deflecting low-momentum charged particles back to space. Because of the orientation of the geomagnetic field, which is predominately dipolar in nature, the Polar Regions are susceptible to penetrating GCR (and SEP) particles. At each geographic location, the minimum momentum per unit charge (magnetic rigidity) a vertically incident particle can have and still reach a given 3 location above the Earth is called the geomagnetic vertical cutoff rigidity [14]. The local flux of incident GCR at a given time varies widely with geomagnetic location and the solar modulation level. When the solar activity is high, the GCR flux is low, and vice versa.

Natural radioactivity

The larger fractions of the Earth's surface where people live and work has as natural soil cover resulting from weathering processes. The lower atmospheric radiation and the associated external exposure are mainly from gamma rays emitted from the top 25 cm of the surface layer of the Earth and the construction materials of the buildings [15]. At ground level the space radiation (originating from outside the Earth's atmosphere, including solar radiation) generate about 11 % of the effective dose which the average US population, is exposed to, while the terrestrial one (radiation emitted by radionuclides in soil and rocks) is 7 %. The major amount of the effective dose is produced by inhaled Radon and ingested Potassium, Thorium and Uranium [16].

INSTRUMENTATION

All Liulin type dosimetric instruments use one or more silicon detectors and measure the deposited energy and number of particles into the detector/s when charged particles hit the detector, that allow to calculate the dose rate and particle flux.

The first used in space Bulgarian build dosimetry instrument named LIULIN (see Table 1, Part 1, Item No 1) was developed for the scientific program of the second Bulgarian astronaut [17].

The measurements in the LIULIN instrument were based on a single silicon detector followed by a charge-sensitive and shaping amplifier (CSA). The number of the pulses at the output of CSA above a given threshold was proportional to the particle flux hitting the detector; the amplitude of the pulses at the output of CSA was proportional to the particles deposited energy and further to the deposited dose. The same measurement procedure was used for the RADIUS-MD instrument (see Table 1, Part 1, Item No 2). The instrument was developed and qualified for space together with French and Russian colleagues for the unsuccessful Mars-96 mission [18]. LIULIN and RADIUS-MD instruments were designed to provide data just for the dose rate and particle flux in a single detector, but not data for the deposited energy spectrum. Later this design was no more used, that is why in this paper we will not describe comprehensively it but will summarize the major results obtained during the operation of the LIULIN instrument on MIR space station between April 1988 and September 1994.

Many other instruments was developed and used in space, on ground, aircraft and balloons since then. The paper aims to review the major milestones of their development, calibrations and scientific results.

Table 1, Part 1 and Part 2 collect information for all developed and build in Bulgaria instruments that have been used in near Earth radiation environment, around the Moon, in the interplanetary space and in Mars orbit.

Totally 17 different space instruments were developed, build and qualified for space between 1988 and 2016. 3 of them were lost because of problems with the rockets of the Mars-96, Foton-M1 and Phobos-Grunt missions. R3D-B1 instrument for Foton-M1 mission is not shown in the table because it was very similar to the R3D-B2/B3 instruments for Foton-M2/M3 missions.

The first column of the Table 1 gives information about the name of the satellite, begin and end time and number of available measurements. The second column lists the name of the experiment, Principal investigator (PI) and Co-PIs. Also major references describing the instrument and obtained data are listed. The third column gives the name of the instrument, technical specifications, location, shielding and resolution of the instrument. The last 2 columns present images of the instruments and their locations (carriers).

There are 2 major measurement systems developed by the team till this moment. The first one is based on one detector and is known as Liulin type Deposited Energy Spectrometer (DES) [19, 20], while the second one is dosimetric telescope (DT) by 2/3 detectors [21, 22]).

DES instrumentation

DES description

The main purpose of the 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 and balloons altitudes, at low earth orbits, outside of the Earth magnetosphere on the route, around and on the surface of the planets of the solar system.

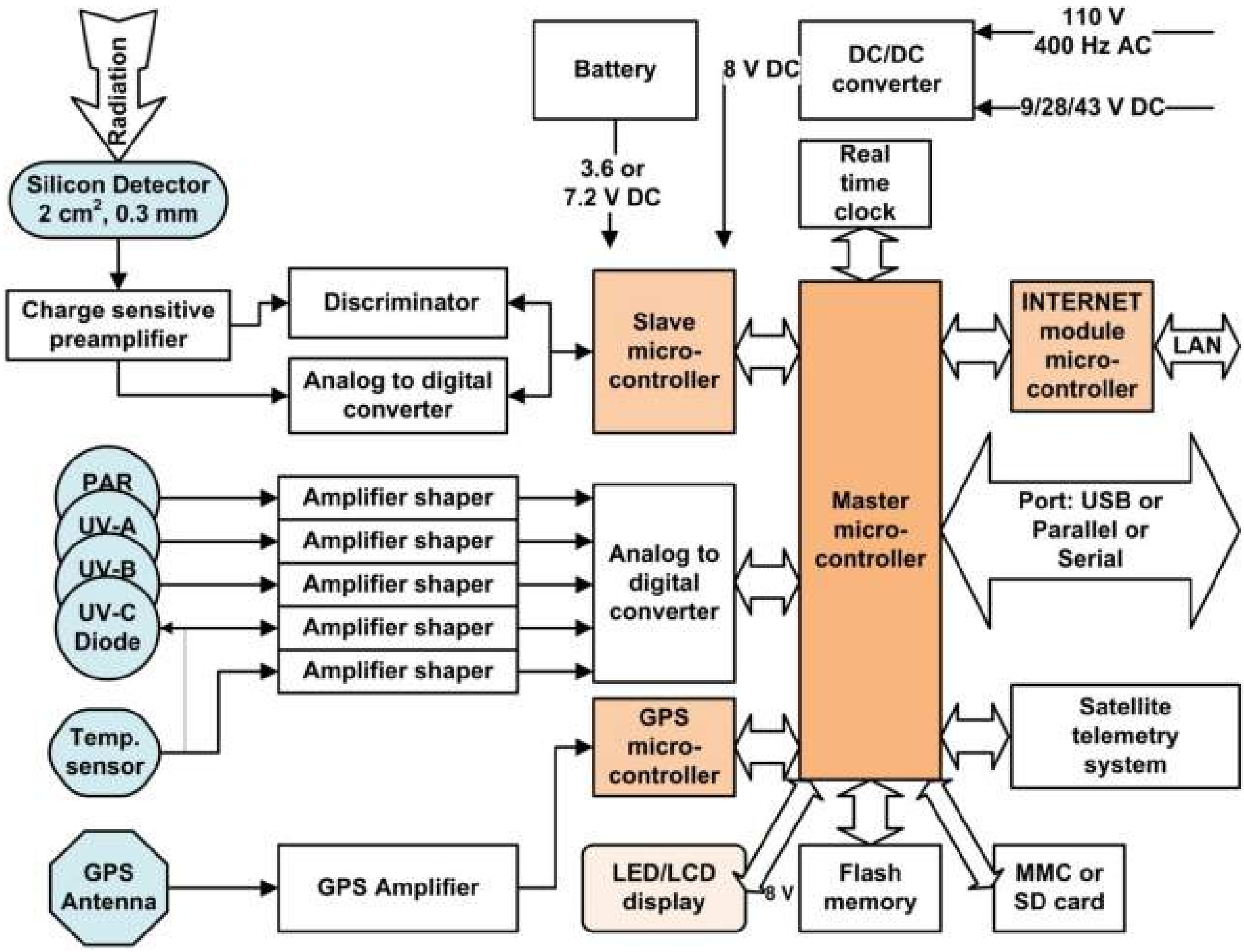

Fig. 1. Generalized block diagram of Liulin-type DES instruments.

Historically the first development of DES was for the Liulin-3M instrument [19] for use on aircraft and balloons [23] and for BION-11/12 missions. Later the redevelopment of the Liulin-3M instrument was named Liulin-4 or Liulin-6, which are synonyms of DES.

Fig. 1 presents a generalized block diagram of Liulin type DESs [24]. DES usually contains: one semiconductor detector, one charge-sensitive preamplifier, a fast 256 channel analog-to-digital converter (ADC), discriminator, real time clock, 2 or more microcontrollers and a flash memory. Different modifications of DESs use additional modules such as: UV sensitive photo diodes, temperature sensor, Global Positioning System (GPS) module with antenna and receiver, LED or LCD display, multimedia card (MMC) or SD card.

Pulse analysis technique is used to obtain the deposited energy from each photon/particle crossing partially or fully the silicon detector. The deposited energies organised in 256 channels form the deposited energy spectrum for each measurement cycle. It is further used for the calculation of the absorbed dose and flux in the silicon detector from primary and secondary particles. The analysis of the shape of the spectrum and the dose to flux ratio, known also as specific dose (SD), permits the characterization of the predominant radiation source in the DES environment [25].

The unit is managed by the microcontrollers through specially developed firmware. The ADC and the slave microcontroller measure organize and keep in RAM memory the 256 channels deposited energy spectrum. The master microcontroller (seen in the right part of Figure 1.) manages the whole work of the spectrometer and data outputs. The developed modifications permits: store of the spectrum data on flash memory or on SD/MMC card; transmission of the spectra data toward parallel, serial or USB port; transmission of spectra data toward internet module and further to LAN network; dose and flux data visualization on alpha numeric or graphic display.

For the two R3D-B2/B3 instruments on Foton satellites and for the R3DE/R instrument on ISS (see Table 1, Part 1, Item No 4/7 and Part 2 Item No 9/11), 4 photodiode with filters in different wavelengths and 1 temperature input channels were also developed and used.

Another type of input is the GPS tract, which consists of GPS antenna, receiver and microcontroller unit (MCU). This is used by aircraft instruments for positioning of the measurements versus the geographic longitude, latitude, altitude above the sea level and Universal Time (UT).

Different power supplies were used in the different instruments. They are presented on the upper part of Figure 1 and include 3.6 V or 7.2 V rechargeable or primary batteries, 28 V or 43 V DC aircraft and satellite power and 110 V, 400 Hz AC aircraft power line.

The main measured parameter in the DESs is the amplitude of the pulse after the CSA, generated by a particle or a photon crossing partially or fully the detector [20]. The amplitude of the pulse is proportional by a factor of 240 mV MeV^{-1} to the energy deposited in the detector and to the dose, respectively. By 8 bit ADC these amplitudes are digitized and organized in a 256-channel deposited energy spectrum.

By definition the dose in the silicon detector DSi [Gy] is one Joule deposited in 1 kg of matter. The DES absorbed dose is calculated by dividing the summarized energy deposition in the spectrum in Joules to the mass of the detector in kilograms:

$$D_{Si}[Gy] = K\sum_{i=1}^{255}(EL_i i)[J]/MD[kg] \qquad (1)$$

K is a coefficient. *MD* is the mass of the detector, and EL_i is the energy loss in Joules in the channel *i*. The energy in MeV is proportional to the amplitude *A* of the pulse:

ELi[MeV]=A[V]/0.24[V/MeV],

where *0.24[V/MeV]* is a coefficient dependent on the preamplifier used and its sensitivity.

All 255 deposited dose values, depending on the deposited energy for one exposure time, form the deposited energy spectrum. The energy channel number 256 accumulates all pulses with amplitudes higher than the upper energy of 20.83 MeV measured by the spectrometer. The methods for characterization of the type of incoming space radiation are described in [25, 26].

DES calibrations

Fig. 2 presents deposited energy spectra from different calibrations of DES, which are compared with proton, electron and GCR spectra obtained at aircraft altitudes and on spacecraft. The individual spectra seen in the figure are obtained after averaging of various numbers of primary spectra and are plotted in coordinates Deposited energy per channel/Deposited per channel dose rate. This allows better understanding of the process of formation of the spectra in the different deposited energy ranges. According to formula (1) the absorbed dose in Si is the area between the curve of the deposited energy spectrum and the abscissa. That is why from bottom to top the spectra position against the ordinate axes depends on the value of the deposited dose rates in Si seen in the legend at the top of the figure.

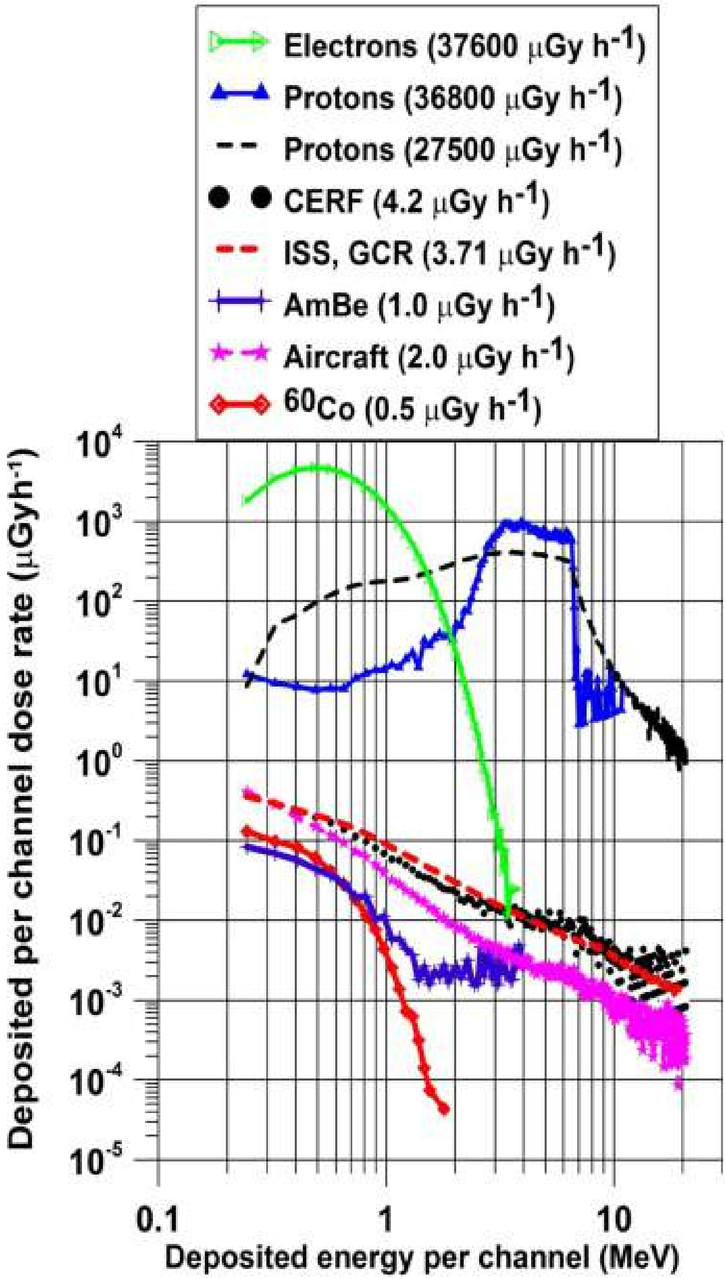

Fig. 2. Different spectrum shapes obtained by DES instruments during calibrations and on aircraft and spacecraft.

Lowest diamonds line spectrum in Fig. 2 (D=0.5 μGy h^{-1}) was obtained by Prof. Frantisek Spurny during the calibrations of the Liulin-4C MDU#2 (see Table 2, Item No 1) with ^{60}Co reference radiation source in Nuclear Physics Institute of Czech Academy of Sciences [27]. This spectrum is the shortest because ^{60}Co photons delivered relatively small energy depositions. The absolute values of the dose rates obtained from the spectra are in very good agreement with the dose rates calculated by means of EGS 4 transport code (*http://rcwww.kek.jp/research/egs/*). The values of the measured doses were found to be with 2.8% difference than the reference value for ^{137}Cs source and with 8% difference for ^{60}Co source [27]. The calibrations revealed that except for charged energetic particles, the DES has high effectivity towards gamma rays, which allowed monitoring the natural background radiation.

Next above – crosses line spectrum in Fig. 2 is again by reference radiation source of AmBe emitting neutrons with average energy of 4.4 MeV. This spectrum continues up to about 4 MeV deposited energy with very well seen change of the curve slope around 1.2 MeV deposited energy. The neutrons sensitivity of the DES was further studied in CERN-EU high-energy reference field (CERF) facility [28] on aircraft and in near Earth radiation environment. The spectrum with heavy dots in Fig. 2 is obtained in the CERF facility field, which generates a spectrum containing events in all channels of DES including the 256th channel devoted for energy depositions above the upper level of the spectrometer of 20.83 MeV. The events seen below 1 MeV in AmBe and CERF was supposed to represent the contribution of low LET radiation (electrons, muons, etc), while the events above 1 MeV that of high LET component (neutrons). This idea was further developed and allows from the deposited energy spectrum in the Silicon detector to be calculated the ambient dose equivalent *H*(10)* at aircraft altitudes [29, 30].

The CERF energy deposition spectrum is very similar to the averaged aircraft spectrum shown with asterisks line in Fig. 2. This spectrum is obtained by averaging Czech airlines aircraft data during mean solar activity at altitudes close to 10.6 km on routes between Prague and North America towns New York and Montreal [31]. The International Space Station (ISS) R3DE instrument (see Table 2, Item No 5) mean GCR deposited energy spectrum shown with heavy dashed line did have shape even closer to the CERF spectrum. The spectrum was obtained by R3DE instrument outside ISS by averaging of all measurements with 10 sec resolution for 2418 hours in the period 20 February – 31 December 2008 [32].

CERF, ISS and aircraft spectra in Fig. 2 show similar knee around 6.5-7 MeV deposited energy. To explain this knee on Fig. 2 is added the heavy triangle line spectrum (36800 μGy h^{-1}), that was obtained during calibrations of DES (non-shielded detector) with 7.8 MeV protons beam at the Cyclotron facilities of the University of Louvain, Belgium [20]. The knee seen at about 6.3 MeV corresponds to the place where the incident energy of the normally falling to the 0.3 mm thick detector protons is equal to the deposited energy. All normally falling protons, which have smaller energies than 6.3 MeV are stopped inside of the detector. The exact value of the CSDA (continuous-slowing-down approximation) range in g/cm^2 for 0.3 mm silicon is 6.04 MeV [33].

The light dashed line spectrum in Fig. 2 with 27500 μGy h^{-1} absorbed dose rate is obtained by RADOM instrument (see Table 1, Part 2, Item No 10) on Chandrayaan-1 satellite after averaging of 60 primary 10 seconds resolution spectra [34]. This spectrum shows very similar shape to the cyclotron facilities spectrum shape (see the 36800 μGy h^{-1} full triangle spectrum) and the knee is at the same position. This is so because the energy of the inner belt protons falling on the detector is calculated to be 7-8 MeV e.g. equal to the energy of the cyclotron facilities mono energetic protons falling on the non-shielded detector. Main differences of both spectra are seen in the deposited energy range 0.244 – 2.8 MeV where except protons in space is observed large amount of low LET depositing particles and electrons. Smaller slope of the space spectrum after the knee can be explained with additional amount of ions heavier than protons in space.

The open triangle spectrum is the highest one in Fig. 2. It is obtained on Chandrayaan-1 satellite at altitudes of the ORB (22000 km). This spectrum with predominant electron population is the result of averaging of 120 spectra with 10 seconds resolution. Only the part, in the deposited energies up to 4.0 MeV is shown. Further the spectrum continue with form and shape similar to the ISS GCR spectrum (shown with thick line without symbols in Fig. 2) but here because of the very high count rate of the spectrometer and respectively large dead time the incoming CGR particles are not well detected and presented.

The exact position of the knee depends from the thickness of the detector's shielding and from the exact detector thickness, which are different for the different instruments. As larger these values are as larger is the value of the knee in the spectrum. That is why on Figure 2 the knee is observed above the calculated value of 6.04 MeV in the range 6.0-7.0 MeV. The average value of 6.2 MeV deposited energy is responsible for the channel number 78, which means that all other channels up to 256 of the spectrometer are populated by long pathlength low LET particles (protons) or by neutrons and heavier ions.

More comprehensive the DES calibrations with protons in the Louvain la-Neuve cyclotron facility are presented in [20]. Uchihori et al. in 2002 [35] performed calibrations with protons and heavy ions at Heavy Ion Accelerator at the National Institute of Radiological Sciences (NIRS) in Chiba, Japan (HIMAC) facility in Japan. In both cases of proton calibrations good agreement was found between the measured and the spectra predicted by the GEANT code. Nice coincidence between the predicted and obtained by Liulin-4J (MDU-3) response function was reported by Uchihori et al. [36] (Please see Figure 2 there). The response function was accumulated by points obtained in H^+, He^+, C^+(400 MeV) and Ca+(400 MeV) beams.

The DES effectiveness for neutrons depends on their energy, being minimal for neutrons with energy 0.5 MeV and has a maximum of a few percent for neutrons with energy of 50 MeV in the CERN field [29]. According to the "neutron induced nuclear counter effect" introduced for the Hamamatsu PIN diodes of type S2744-08 (same are used in all DESs) [37] neutrons could be observed in all channels of the spectrum with a probability at least one order of magnitude higher in first 14 channels.

DES data intercomparison with other instruments data

Post-flight calibrations with Liulin-E094 MDUs (see Table 1, Part 1, Item No 3) were performed in HIMAC heavy ion accelerator during the 1st IC-CHIBAN (Inter Comparison for Cosmic-ray with Heavy Ion Beams At NIRS) Project run in Chiba Japan in February 2002 with 400 MeV/u Carbon ions. The deposited energy spectra obtained with all 4 MDUs show a sharp maximum close to 6.1 MeV, which is in good agreement with theoretical prediction and with measurements of the same source with the DOSTEL-1 instrument [38].

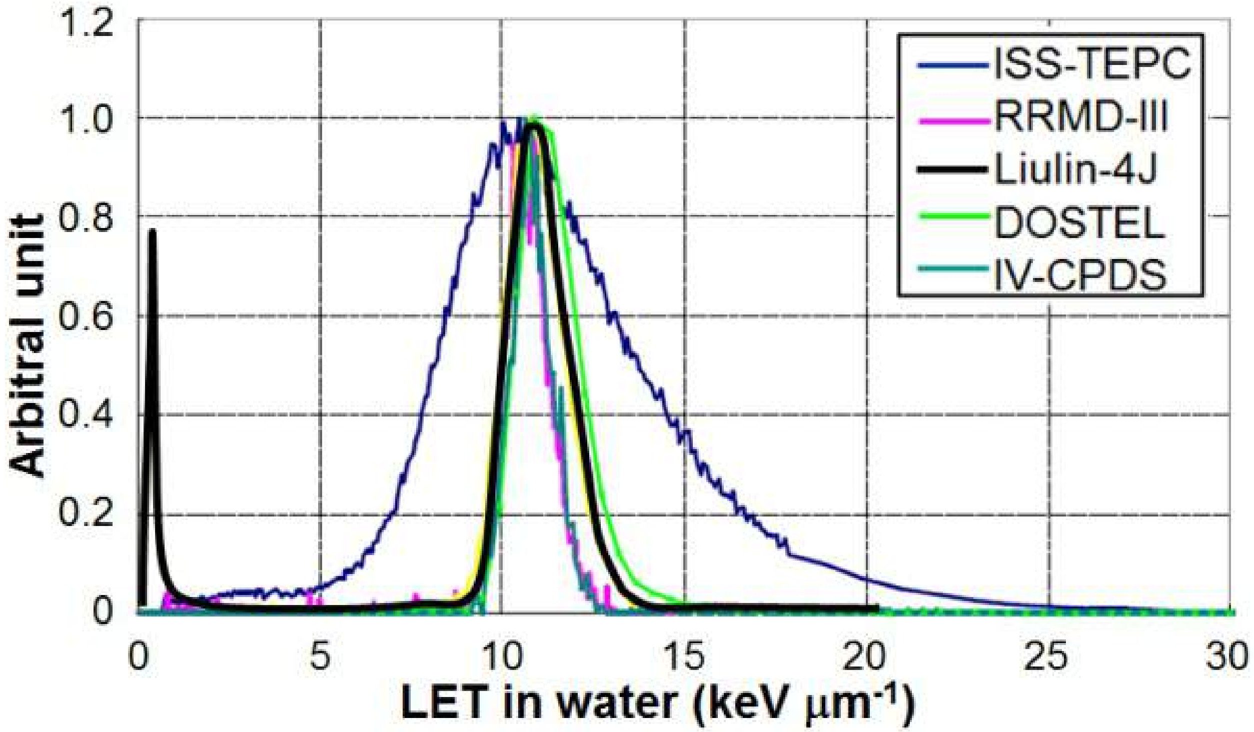

Fig. 3. Comparison of the deposited energy spectra obtained by Liulin-4J instrument with another 3 Si telescopes and ISS-TEPC obtained during the ICCHIBAN-1 test run with 400 MeV/u Carbon ions.

Fig. 3 presents comparison of the deposited energy spectra obtained by Liulin-4J instrument (see Table 2, Item No 2) with another 3 Si telescopes (RRMD-III, DOSTEL, IV-CPDOS) and ISS-TEPC obtained during the ICCHIBAN-1 run with 400 MeV/u Carbon ions [39]. It is seen that the silicon detectors show good agreement of LET spectrum. The ISS-TEPC spectrum is wider but it comes from its structure (chord length).

For the purpose of in-space intercomparison between Liulin data with data from another instrument was prepared Fig. 4, which contains data from tissue equivalent proportional counter (TEPC) and 2 Liulin DES instruments – R3DE/R (see Table 1, Part 2, Item No 9 and 11). The TEPC data are plotted in Fig. 4 using the opportunity provided by Zapp (2013) [40] and by the 'Coordinated Data Analysis Web' at the Goddard Space Flight Center (*http://cdaweb.gsfc.nasa.gov/*).

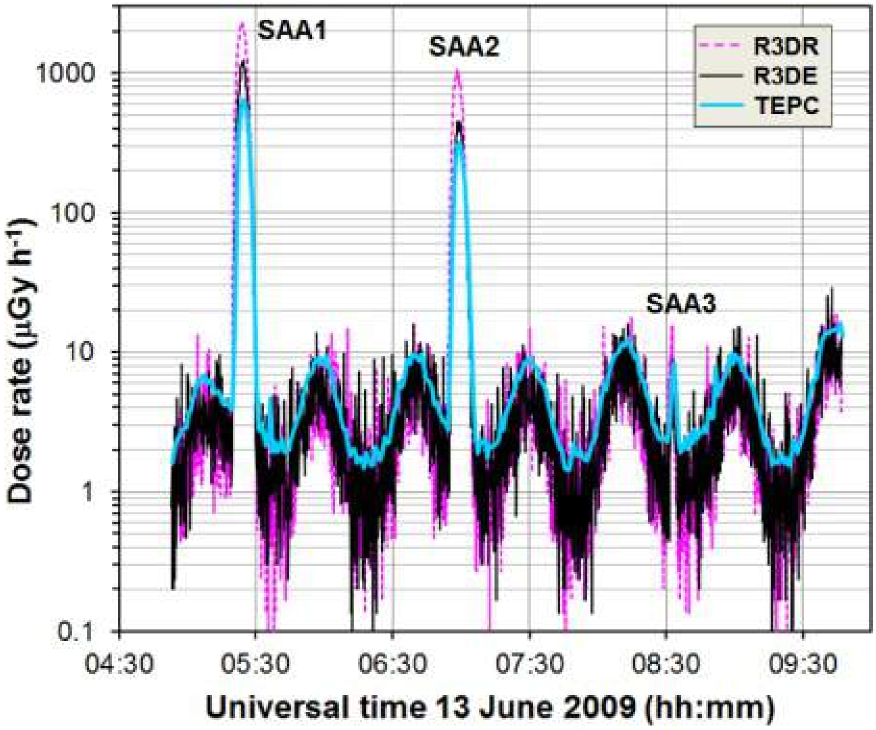

Fig. 4. Comparison of the dose rates measured simultaneously by the R3DE/R instruments and NASA TEPC for a period on 13 June 2009 between 4:53 and 9:46 UT.

The dose rate data presented in Fig. 4 is plotted versus the UT and show three passes across the SAA region, which is denoted with labels SAA1-SAA3, seven passes across the high latitude GCR regions in both hemispheres and six passes across the magnetic equator. The analysis of the dose rate dynamics in Fig. 4 shows the following: 1) The R3DR SAA dose rates are the largest and reach 2304 µGy h^{-1} during the SAA1 maximum because R3DR is the lightest shielded instrument [41]. The more shielded by surrounding masses R3DE dose rates are about half that (1222 µGy h^{-1}), whereas the TEPC dose rates (heaviest shielded inside ISS) are the smallest (645 µGy h^{-1}). 2) The TEPC GCR dose rates are higher than the most of the dose rates measured with the R3DE/R instruments. This is because secondary particles build up additional doses in it. In the regions of the magnetic equator the smallest dose rate values are obtained by the R3DR instrument. The R3DE dose rates are in the middle, whereas the TEPC dose rates are the highest. The doses accumulated by the three instruments for 4 h and 56 m are 261 µGy (R3DR), 132 µGy (R3DE) and 100 µGy (TEPC).

DES intercomparison of dose rate measurements on aircraft was performed in a lot of cases. Below in the text we will report some of the more significant.

The exposure of aircraft crew to cosmic radiation has received a great deal of attention after the recommendation by the International Commission on Radiological Protection (ICRP) in 1990, that exposure to cosmic radiation in the operation of jet aircraft should be recognized as occupational exposure, initiated a number of new dose measurements onboard aircraft [42]. In the cited above report there is a large amount of DES dose rate measurements performed by Prof. Frantisek Spurny and compared with other instruments and computer codes, which confirm the ability of DES to characterize the radiation field at aircraft altitudes.

The response of a LIULIN-4 spectrometer was compared by Green et al. [43] to that of the HAWK TEPC *http://www.npl.co.uk/science-+-technology/ionising-radiation/neutron-metrology/hawk-tepc* on 42 aircraft flights in 2003–2004 covering the full range of cutoff rigidity values. On all flights, the absorbed dose measured by both instruments agreed to within 5%. These data provide an in-flight validation of the calibration factor determined by us in ground-based studies.

Getley et al. [44, 44a] performed intercomparison measurements by different detectors including TEPC and Liulin-4SA (see Table 3, Item No 5) on board Boeing 747-400 Qantas Airways flights from August 2008 to March 2009. The flight routes involved cross-equatorial flights between Sydney, Melbourne, and Los Angeles. A northern latitude flight traveled between Sydney, Hong Kong, London, and Singapore, and numerous high southern latitude flights were flown between Sydney and Johannesburg and Sydney and Buenos Aires. In the summary of the paper they wrote: “Comprehensive testing of both the Liulin and QinetiQ QDOS/Rayhound over a 6 month period, at both high northern and southern latitudes as well as in crossequatorial flights, suggests that both of these spectrometers have the ability to provide reliable dose assessments for aircrew monitoring.”

Meier et al., 2016, [93] wrote: “The assessment of the corresponding radiation exposure of aircrew and passengers has been a challenging task as well as a legal obligation in the European Union for many years. The response of several radiation measuring instruments operated by different European research groups during joint measuring flights was investigated in the framework of the CONCORD (COmparisoN of COsmic Radiation Detectors) campaign in the radiation field at aviation altitudes… Each co-operation partner (DLR, Institute of Aerospace Medicine, Germany; Institut de Radioprotection et de Sûreté Nucléaire, France and Nuclear Physics Institute, Czech Republic) operated several Liulin semiconductor devices during the CONCORD campaign. The comparison of the results is based on the averaged values of all devices of the respective institution… The measured absorbed dose rates in silicon show a deviation from the mean value Liulin of less than 10% on average.”

The boxes and additional constructive materials of the most of the DES instruments described in this paper provide between 0.41 and 0.6 g cm^{-2} shielding. For the lover boundary of 0.41 g cm^{-2} shielding the calculated stopping energy of normally incident particles to the detector is 0.78 MeV for electrons and 15.8 MeV for protons [33]. For 0.6 g cm^{-2} shielding these values are 1.18 MeV for electrons and 27.5 MeV for protons. This means that only protons and electrons with energies higher than the above mentioned values can reach the detector of the instrument.

Dosimetric telescope (DT) instrumentation

DT description

First application of the Liulin DT method was for the Liulin-5 instrument on ISS. Liulin-5 (see Table 1, Part1, Item No 6) is an active experiment in the spherical phantom [45]. 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 Russian spherical tissue– equivalent phantom MATROSHKA-R [46, 47], using a telescope of three silicon detectors. Liulin-5 is sensitive to photons, electrons, protons and heavy ions. Liulin-5 charged particle telescope was launched to ISS by Progress-60 cargo craft in May 2007.

The investigation of the radiation environment in the phantom on 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 ICRP – 60, 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:

$$H = Q_{av}D \qquad (2),$$

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

$$Q_{av} = \int Q(L)D(L)dL\ /D \qquad (3)$$

Liulin-5 consists of two units: a detector module and an electronics module (see Table 1, Part1, Item No 6). The detector module is mounted in the radial channel of the phantom, while the electronics is outside the phantom. More detailed description of Liulin-5 method and instrument can be found in [45, 48]. The detector module contains 3 silicon detectors (D1-D3) arranged as a particle telescope.

Fig. 5 is a schematic diagram of Liulin-5 and the spherical phantom. The sensitive thickness of the detectors D1 and D3 is 370 μm, of D2 it is 360 μm and the detectors' diameter is 17.2 mm. The D1 detector is placed at 40 mm depth in the phantom, D2 is at 60 mm and D3 is at 165 mm distance from its surface.

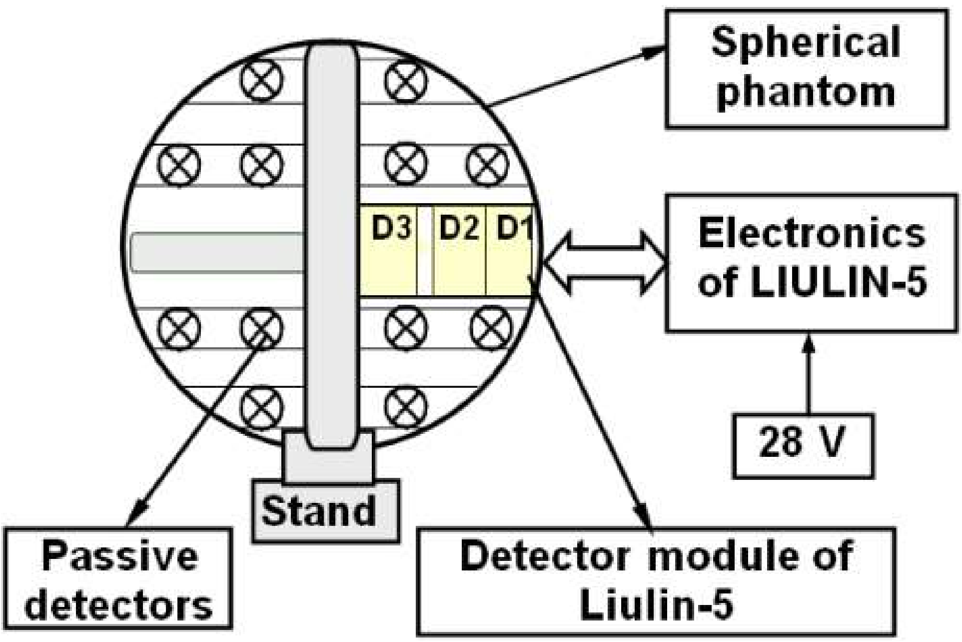

Fig. 5. Schematic diagram of Liulin-5 experiment in the spherical phantom.

From each detector the energy deposition spectrum for a cycle of measurement is recorded in two 256 channels' sub-ranges. Then the overall energy deposition spectrum is constructed in 512 channels. The amount of energy ΔE deposited in the detector is proportional to the value $k1\Sigma(iN_i)+k2\Sigma(jN_j)$, and the incident particle flux is proportional to $\Sigma N_i + \Sigma N_j$. Here i and j are the spectral channel numbers in the two sub-ranges (LLET and HLET), N_i and N_j are the amount of particles registered in channels i and j of the corresponding sub-ranges, k1 and k2 are coefficients. The values $\Sigma(iN_i)$, $\Sigma(jN_j)$, ΣN_i, ΣN_j are recorded for given time intervals and are used for calculation of the doses and particle fluxes rates.

The absorbed dose in the detector is calculated as

$$D = \Delta E/m, \quad (4),$$

where m is the detector's mass.

The geometry factor for converting the measured in a single detector amount of particles into differential flux is 14.6 cm^2 sr, assuming the incident flux is isotropic.

Detectors D1 and D2 operate in coincidence mode. The distance between D1 and D2 is 20 mm. The viewing angle of D1-D2 assembly is 81.4^0. When a particle enters the telescope within the 81.4-degree sensitivity cone, with energy enough to make it through both the D1 and D2 detectors, it is considered a coincident event. The energy deposition spectrum measured in the D1 detector in coincidence mode with the D2 is recorded and used to obtain LET spectrum. Since the incidence angle of the particles is not measured, the energy deposition is converted into mean LET in silicon as:

$$LET(Si_i) = \Delta E_i/h_{D1} \quad (5),$$

where ΔE_i is the deposited energy in channel i, LET (Si_i) is the LET in silicon in channel i (here i =1-512), and h_{D1} is the D1 thickness. Calculations show that the dependence of the telescope's effective area on particle incident angle is practically linear and decreases from 2.324 см^2 at 0^o between the telescope axis and flux to 0 см^2 at 40.7^o. The average increasing of particle range in the detector in case of non-parallel to the axis incidence is 7%.

The LET spectra in silicon obtained are used for calculation of the differential and integral LET spectra in water, the absorbed dose rates and the quality factors. The geometry factor for converting the measured by the D1-D2 telescope amount of particles into differential isotropically incident flux is 2.01 cm^2.sr. The energy deposition in water (tissue) relative to that in silicon is taken to be 1.24, independent of particle energy. LET for water LET (H_2O) is then found by the following relation:

$$LET(H_2O) = 1.24xLET(Si)/2.34 \quad (6),$$

Taking into account that the relation between LET (H_2O) and LET (Si) changes with proton energy Ep from 1.27 for Ep =30 MeV to 1.21 for Ep = 1000 MeV, and that for a typical energy Ep = 100 MeV the conversion coefficient is 1.24, the maximum difference of LET (H_2O) obtained by using real conversion function and the simple conversion factor is less than 3%.

To obtain the LET spectrum dose of isotropically incident particles, the dose calculated from the D1-D2 coincidences spectrum is multiplied by 13.5.

The instrument provides time resolved: Absorbed dose rate in each detector; Flux rate in the range 0 -

4x102 (cm^2 s^{-1}), 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^{-1} 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.

Second application of the DT method was for the Liulin-Phobos instrument (see Table 1, Part2, Item No 12) developed for the Phobos-Grunt mission [22]. The main goal of the Liulin-Phobos experiment was the investigation of the radiation environment and doses in the heliosphere at distances of 1 to 1.5 AU from the Sun and in the near-Mars space.

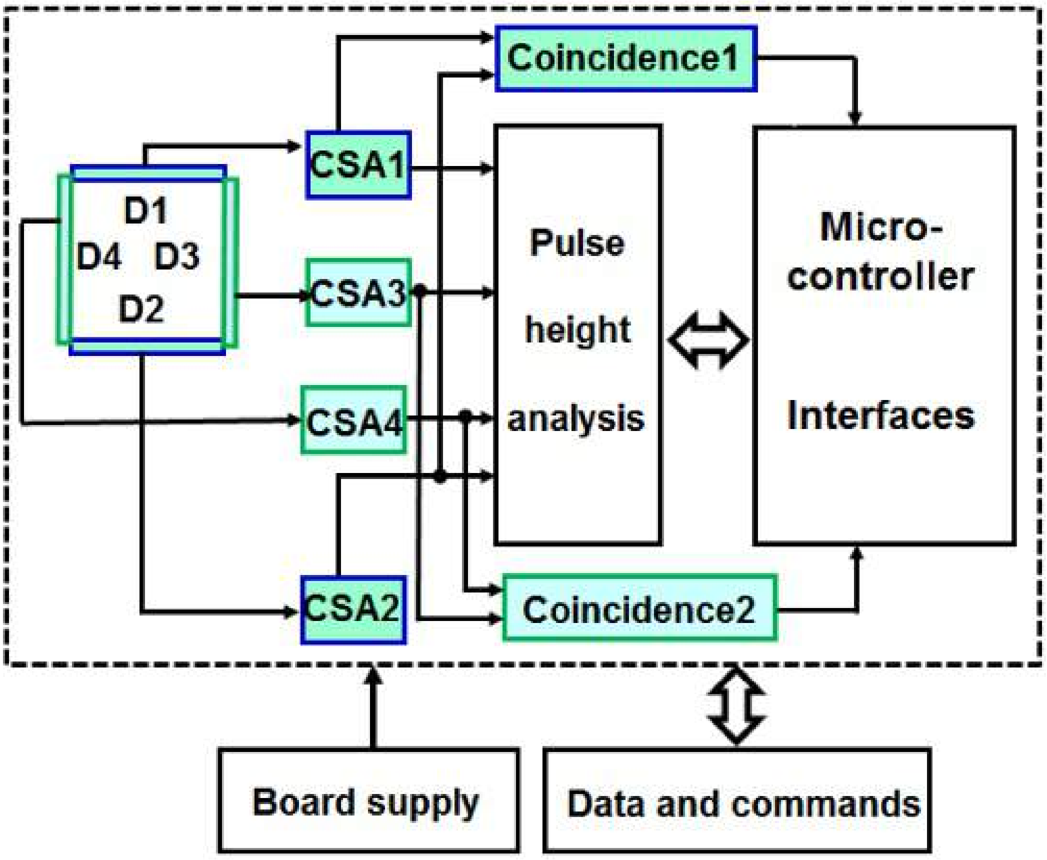

Fig. 6. Block-schema of Liulin-Phobos charged particle telescope.

Liulin-Phobos instrument consisted of two dosimetric telescopes - D1&D2, and D3&D4 arranged at two perpendicular directions. The block-schema of the instrument is shown in Fig. 6. Every pair of telescopes consists of two 0.3 mm thick Si PIN photodiodes, operating in coincidence mode to obtain LET. One of the detectors in every telescope measures the energy deposition spectrum in the range 0.1-10 MeV, and the other in the range 0.45-90 MeV. In that way every dosimetric telescope provides data in the energy deposition range 0.1 - 90 MeV. The instrument was designed to measure absorbed dose rate and particle flux every 60s, energy deposition spectra and LET spectrum every 60 min.

The parameters featured by Liulin-Phobos DT were: Absorbed dose rate in the range $4x10^{-8}$-0.1 Gy h^{-1}, and absorbed dose D, measured by every single detector; Particle flux in the range 0-10^4 cm^{-2} s^{-1}, measured by every single detector; Energy deposition spectra in the range 0.1-90 MeV, measured by every dosimetric telescope; LET spectrum (in H_2O) in range 0.75–155 keV/μm, measured by every DT; Quality factor Q = f(LET) and average quality Qav; Dose equivalents H = Qav D, measured by two DT.

A similar to the Liulin-Phobos DT instrument, called Liulin-MO has been developed for the first mission of the joint ESA-Roscosmos ExoMars program, which was launched to Mars in March 2016 [49]. Liulin-MO is a part of the Russian Fine Resolution Epithermal Neutron Detector (FREND) onboard the Trace Gas Orbiter (TGO) satellite of ExoMars 2016 mission.

The primary science objectives of the Liulin-MO investigation are:

- To measure dose and determine dose equivalent rates for human explorers during the interplanetary cruise and in Mars orbit.

- Measurement of the fluxes of GCRs, SEPs, secondary charged particles and gamma rays during the cruise and in Mars orbit.

- Together with other detectors of FREND instrument to provide data for verification and benchmarking of the radiation environment models and assessment of the radiation risk to the crewmembers of future exploratory flights. The parameters, provided by Liulin-MO simultaneously for two perpendicular directions have the following ranges: absorbed dose rate in the range 10^{-7} Gy h^{-1} ÷ 0.1 Gy h^{-1}; particle flux in the range 0 ÷ 10^4 cm^{-2} s^{-1}; energy deposition spectrum and coincidence energy deposition spectrum in the range 0.08 ÷ 190 MeV. The dose rates and the fluxes are resolved every minute, while the energy deposition spectra and the LET spectra are resolved every hour.

Liulin-ML dosimeter is a part of the Russian active detector of neutrons and gamma rays ADRON-EM.*DT calibrations*

Liulin-5 was exposed to 400 MeV/n ^{16}O and 300 MeV/n ^{56}Fe beams during the ICCHIBAN-7 experiments [50] at the HIMAC in September 2005.

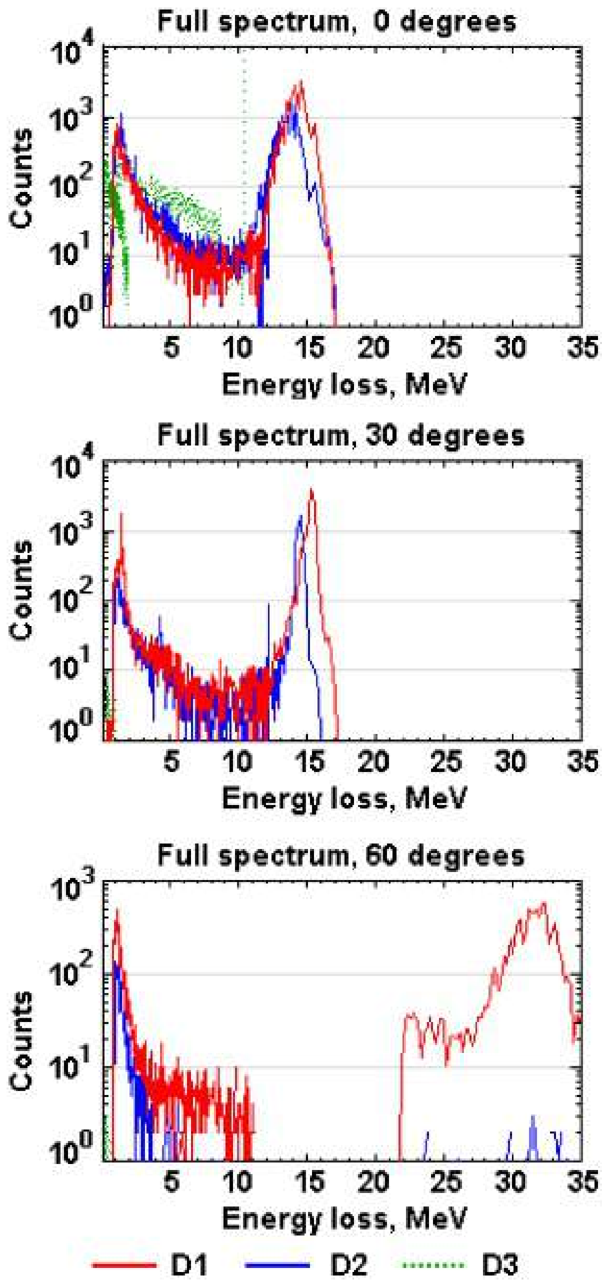

Fig. 7. Deposition energy distributions of ^{16}O beam in the silicon detectors D1–D3 of Liulin-5.

Fig. 7 shows the deposited energy distribution in the silicon detectors of Liulin-5 obtained during the exposures to 400 MeV/n ^{16}O [45]. At first the detector module of Liulin-5 was exposed perpendicular to the beam with beam center at the center of the detectors (0^0 inclinations). After that detector module of Liulin-5 was inclined at angles of 30^0 and 60^0 relative to the beam line and rotation was made around the center of D1 detector. On each plot two distributions are seen – the left represents measured spectra in LLET range and the right represents measured spectra in HLET range of the detectors. We assume that HLET peaks correspond to the distribution of the main ^{16}O beam, and the LLET peaks correspond to scattered background beams. Most of HLET events registered in D3 detector exceed the upper energy loss range limit of that detector and were registered in the highest spectral channel as events of 10 MeV.

For the 30^0 exposure D3 detector was outside the main beam, and for the 60^0 exposure both D2 and D3 detectors were outside the main beam. That is why only scattered background beams in LLET ranges were registered in them.

As a result of the calibrations the Liulin-5 measurement range of LET(H2O) was estimated to be 0.65 –90 keVμm^{-1}. This makes it possible for Liulin-5 to measure the low-LET components of cosmic radiation, as well as a significant part of biologically relevant high-LET heavy ion component of GCR that contribute to the radiation doses on ISS.

The Liulin-Phobos flight unit was calibrated with proton and heavy ion beams at the cyclotron and at the HIMAC accelerator at the NIRS, Japan in January-February 2009. The calibrations were performed in agreement with the Memorandum of Understanding on collaboration concerning development, calibration, space flight measurements and data analysis of the Liulin-F instrument onboard the Phobos-Soil mission, which was signed between STII-BAS, IBMP-RAS NIRS, Chiba, Japan.

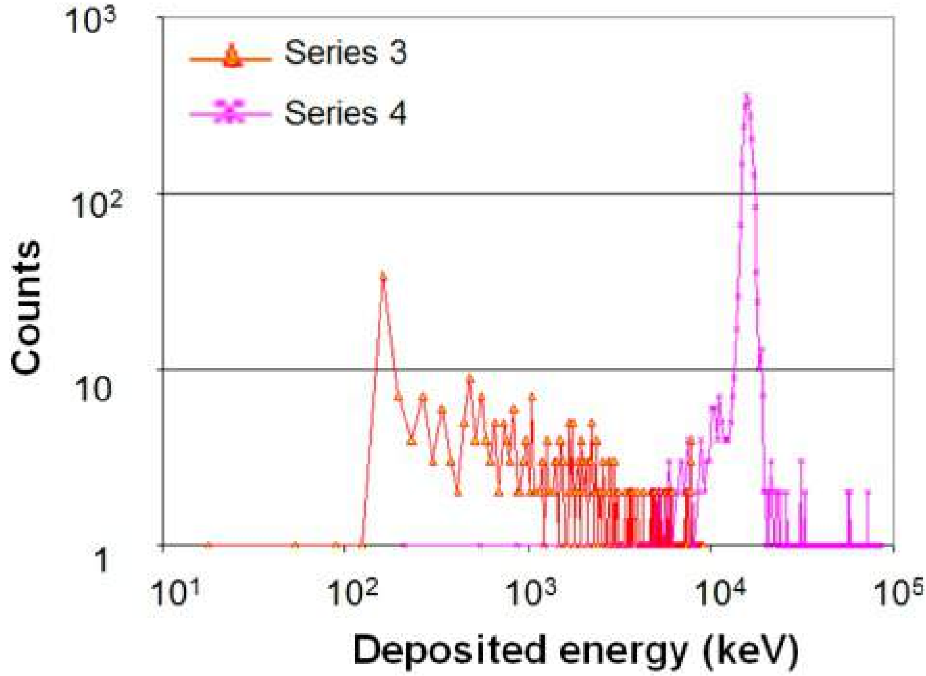

Fig. 8. LET spectrum of 20Ne 600 MeV/u, obtained in D1&D2 telescope at 00 inclination of the telescope axis to the incident beam.

As an example of the obtained results Fig. 8 shows the energy deposition spectrum in the D2 detector in a coincidence mode with D1 (LET spectrum) of ^{20}Ne ions with energy 600 MeV/n [51]. The distribution was obtained at 0° inclination of the telescope's D1-D2 axis to the ion beam. The left part of the LET distribution was measured in low LET range of the detector and is mainly due to secondary radiation, resulting from interactions of primary neon beam with surrounding materials. The main peak represents the LET distribution of the neon ions and was measured in high LET range of this detector. The obtained LET(H2O) of ^{20}Ne 600 MeV/n is 26.7 keV/μm –it is in good agreement with the theoretically calculated value of 25.5 keV/μm, having in mind the shielding of the detectors. The results of the Liulin-Phobos calibrations at NIRS confirm the correctness of the electronic calibrations made preliminary.

Liulin-MO has been physically calibrated at the Research Department of Ionizing Radiation Metrology of the Scientific Research Institute of Physical, Technical and Radio Measurements - Russia. Calibrations were conducted by means of the ^{60}Co source of the State Primary Standard unit of absorbed dose of photon and electron radiation with a dose rate more than 5 mGy h^{-1} and a set of work standard ^{137}Cs sources (with dose rates up to 5 mGy h^{-1}). These calibrations confirm the large dynamic ranges of the flux (up to 10^4 particle cm^{-2} s^{-1}) and the dose rate (10^{-7} Gy h^{-1} ÷ 0.1 Gy h^{-1}) measurements that allow Liulin-MO to measure the fluxes and dose rates both of the relatively low–intensity GCR and the occasional high–intensity powerful SEP events. The instrument has also enough sensitivity to measure the natural radiation background on the Earth surface that was used to control the proper operation of its detectors during the pre-flight tests.

MAIN EXPERIMENTS AND RESULTS IN SPACE

LIULIN experiment on MIR space station

The Bulgarian-Russian dosimeter-radiometer LIULIN (see Table 1, Item No 1) was installed in the working compartment of the MIR space station [17]. The effective mass thickness of screening matter inside the working compartment of MIR is evaluated to be 6-15g cm^{-2}. Thus the main contribution to the count rate is given by protons and electrons that, outside MIR space station, have energy large than 100 MeV and 10 MeV respectively. It uses a silicon detector with a thickness of 306 microns and area of 1.8 cm^2. Simultaneous measurement of the energy absorbed in the detector and of the flux of particles are recorded and transmitted to Earth. The noise level of the detector and electronics was 83 keV. The dose sensitivity is 1 nGy/pulse. The detector unit (see Table 1, Item No 1) is a miniature, portable, self-indicating devise. LIULIN-Microcomputer unit (MCU) is an eight-bit microprocessor unit.

Main results obtained by the LIULIN device can be listed as follows:

- During the declining phase of 22^{nd} solar cycle the GCR fluxes observed at L > 4 have been enhanced from 50-70 μGy day^{-1} in 1989-1990 up to 130-140 μGy day^{-1} in 1993-1994. In same time the GCR flux increased from an average value of 0.58 cm^{-2} s^{-1} in 1991 up to 1.53 cm^{-2} s^{-1} in 1991 [52];

- The peak value of the dose rate

and flux of particles measured by LIULIN in the SAA increase gradually by a factor of 2 between 1991 and 1994 at the altitude of 410 km. The increase is attributed to the decrease of the atmospheric density during the declining phase of solar activity, which is due to the lower rate of heating of the upper atmosphere when the solar UV and EUV radiation diminishes during the minimum of solar cycle A power law relationship has been deduced between local atmospheric density at the altitude of MIR station and the maximum dose rate in the center of the SAA when the neutral density decreased from $8x10^{-15}$ g cm^{-3} to $6x10^{-16}$ g cm^{-3} the maximum dose increases from 200 to 1200 mGy h^{-1}, while the flux of particles increased from 30 to 120 cm^{-2} s^{-1} [52];

- LIULIN measurements represent the low altitude manifestation of radiation belts dynamics. Before the 23-26 March1991 solar-geomagnetic events LIULIN dose and flux data exhibited one maximum located at L ~1.4 the region of the SAA. It is due to the particles from the inner radiation belt. After the March 23 1991 geomagnetic storm a “new” maximum in LIULIN flux data was created at 1.8<L<2.2. This was an unique phenomenon, not reported previously and after *http://www.stp.isas.jaxa.jp/akebono/RDM/rdm/rdmflux_1989_2010.gif*. It was a relatively stable configuration observed during the whole of 1991 independently of the geomagnetic conditions. It was identified in LIULIN data till the middle of 1993. The outer radiation belt maximum was frequently observed after geomagnetic disturbances as a dynamic structure for 1-3 months. ORB in MIR data was usually located at 2.5<L<3.2. After long quiet conditions it disappeared [53];

- Several outstanding SEP took place during the LIULIN observations. SEP data are available for September 29, 1989, October 18, 1989, March 23, 1991, June 8 and 15, 1991, and June 26, 1992. Data analysis of them is presented in the paper by Shurshakov et al. [54].

Experiments and results on ISS

The largest amount of Liulin experiments in space since 2001 was performed on ISS. Listing them we have to mention: Liulin-E094 (April-August 2001), Liulin-ISS (September 2005-till now), Liulin-5 (May 2007-September 2015), R3DE (February 2008-September 2009), R3DR (March 2009-August 2010) and R3DR2 (October 2014-January 2016) (see Table 1, Part 1 Items No 3, 5, 6 and Part 2 Items 9, 11 and 15).

DES data selection procedure

The data selection procedure was established for DES instruments to distinguish between the three expected radiation sources: (i) GCR particles, (ii) protons with more than 15.8 MeV energy in the SAA region of the IRB and (iii) relativistic electrons with energies above 0.78 MeV in the ORB [25].

Fig. 9 is prepared to confirm these features with the R3DR data. The abscissa plots the measured flux in cm^{-2} s^{-1}, while the ordinate shows the dose rate in μGy h^{-1} and dose rate to flux ratio (D/F) (or specific dose SD) in nGy cm^{-2} $particle^{-1}$ [25, 55] for the period 1 April–7 May 2010, which is remarkable with very high ORB fluxes and respectively dose rates [8]. The large amount of experimental points (295374 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 points present the D/F ratio.

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 0.03–30 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 (0.03–0.4 30 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.

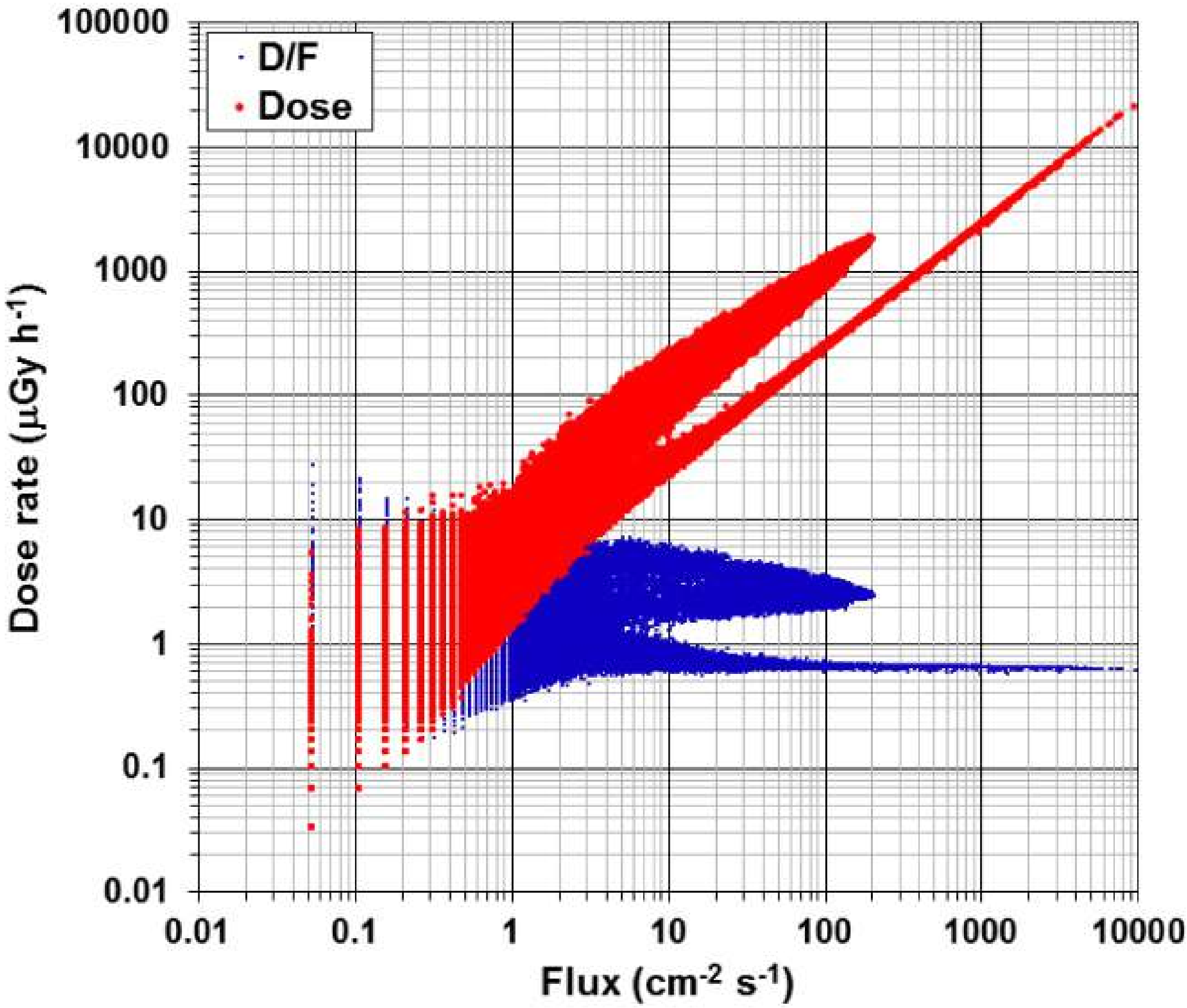

Fig. 9. Characterization of the R3DR predominant radiation sources by the dose rate from flux and dose to flux (D/F) dependencies.

The "index" finger is in the dose rate range 9–22000 μGy h^{-1} and looks as a straight line. Its representation in the horizontal graphic is a finger extending up to10000 in cm^{-2} s^{-1}, with dose to flux values below 1 nGy cm^{-2} $particle^{-1}$. This finger is based on low LET particles and could be formed only by the relativistic electrons [7] in the outer radiation belt.

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 30–1900 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 1.2–8.0 nGy cm^{-2} $particle^{-1}$. 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 formulae [55].

The conclusion which can be drawn from Fig. 9 is that the data can be simply split in two parts by the requirements for the ratio D/F < 1 and D/F > nGy cm^{-2} $particle^{-1}$. This will generate graphics, which will divide the IRB and ORB sources. GCR protons in equatorial and low latitude regions have very small fluxes of less than 1 particle cm^{-2} s^{-1} that is why the D/F ratio is not stable and varies in the range from 0.03 to 30 nGy cm^2 $particle^{-1}$ [8]. This variation makes the D/F ratio inapplicable for the characterization of the GCR radiation source.

The presence of SEP particles generate additional dose rate branches (“fingers”). This was observed during the analysis of the R3DR2 data and published by Dachev at al., 2016 (see Fig.3). [90].

Liulin-E094 results

The first use of DES in space was in the Liulin-E094 instrument (see Table 1, Part 1, Item No 3), that was developed, qualified for space and used in the ESA Dosimetric Mapping-E094 experiment [10] on the US Laboratory module of the ISS as a part of the Human Research Facility in May-August, 2001 [18]. The main purpose of this experiment was to investigate the dose rate distribution inside the US Laboratory module and Node-1 of ISS.

In the paper by Dachev et al., 2006 [56] was developed a 3-D shielding model of the MDU unit and located it at the four locations in the ISS shielding model. Using the trapped proton differential spectra generated from the SPENVIS online capability for calculation of AP8 trapped proton spectra and the high-energy proton transport code PDOSE we was able to calculate the doses at each locations of MDUs. The differences between the observed Liulin-E094 MDUs doses and calculated do not exceed 15%. The obtained data were also used for statistical validation of the high-charge and energy (HZE) transport computer (HZETRN) code [57-59].

The Liulin-E094 data were widely used by Dr Francis Badavi, Old Dominion University, Norfolk, USA for validation of the NASA AE8/AP8 and AE9/AP9/SPM trapped models [102, 103].

Liulin-ISS results

Liulin-ISS instrument (see Table 1, Part 1, Item No 3) was launched to the Russian segment (RS) of ISS in September 2005. It contains four Mobile Dosimetry Units (MDU) with displays and Control and interface unit and was used in the Service Radiation Monitoring System of the RS of ISS [60]. Following information may be displayed: Current dose in μGy h^{-1}, Current event rate (Flux) cm^{-2} s^{-1}, Accumulated from the "Switch ON" dose mGy. The battery operation time of the MDU is about 7 days. The 4 MDU can be used as personal dosimeters in case of dangerous SEP. Because some problems with the telemetry system connections the instrument was not used as planned and now under development is a new instrument named Liulin-ISS-2 [105] with similar functions, which is expected to be in space in the next 2-3 years.

Liulin-5 results

Liulin-5 DT instrument (see Table 1, Part 1, Item No 5) [21] was launched to the RS of ISS in May 2007. Measurements with Liulin-5 were conducted in the spherical tissue equivalent phantom of Matroshka- R experiment located in the PIRS-1 module of ISS in the period July 2007 – March 2010, corresponding to the minimum of solar activity in 23rd solar cycle (I-st stage of the experiment). Also measurements slose to the maximum of 24th solar cycle were conducted from December 2011 till September 2015 both inside and outside the phantom located in the MIM1 module of ISS (II-nd stage of the experiment).

The main results obtained during the minimum of 23rd solar cycle were published in [61-63]. (Semkova et al., 2012, 2013a, 2013b). From July 2007 to 2009 the dose rates in the phantom at 40 mm depth (corresponding to the shielding of blood forming organs in the human body) are 180-230 μGyd^{-1}, the dose equivalent rates are 590-880 μSv d^{-1}.

From December 2011 to September 2015 in MRM1 module of the ISS the doses outside the phantom are 150-280 μGyd^{-1}, in the phantom at 40 mm depth are 130-220 μGyd^{-1}. Dose equivalent rates are 300-700 μSv d^{-1} outside the phantom and 220-600 μSvd^{-1} at 40 mm depth in the phantom.

The comparison between Liulin-5 data during both stages of the experiment – solar minimum and solar maximum shows that during the Ist stage, when the ISS is at lower altitudes, the dose rates at 40 mm depth in the phantom are comparable with the dose rates outside the phantom during the IInd stage. The dose equivalent rates during the Ist stage are much higher. This is due to the much higher intensity of the GCR during the minimum of the 23th solar cycle and the small number of SPE with increased flux of >100 MeV protons close to maximum of the 24th solar cycle. During the SEP events of 7-12 March 2012 (see Fig. 10) at L>3 the particle flux and dose rates increased in all three detectors of Liulin-5 charged particle telescope located at 40, 60 and 165 mm depths along the radius of the tissue-equivalent spherical phantom in MIM1 module of ISS [63a].

The additional absorbed dose at 40 mm depth in the phantom received from SEP event on 7-9 March 2012 was approximately 180 μGy. The additional dose equivalent at 40 mm depth in the phantom received from that event was about 448 μSv. The additional exposures received from SEP event are comparable to the average daily absorbed dose and dose equivalent measured in the spherical phantom in ISS during quite periods.

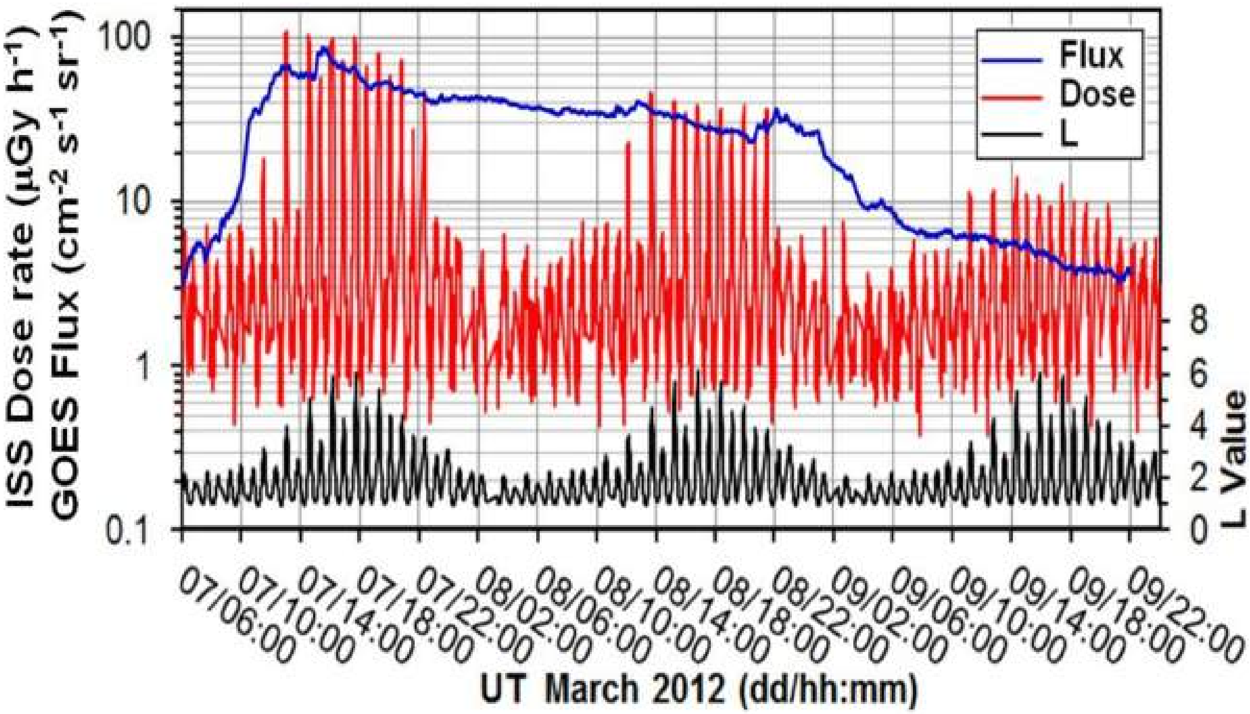

Fig. 10. Proton flux with energies ≥ 100 MeV measured by GOES-13 (blue curve), the dose rate in D1 detector of Liulin-5 measured outside the SAA (red curve), and the corresponding L-values (black curve) versus time during the March 2012 SEP event.

In Figure 10 it is seen that there is a good agreement of Liulin-5 dose rates trend during the SEP event with the proton flux of energies ≥ 100 MeV (able to penetrate inside ISS) measured by GOES – 13 satellite (blue line).

3.2.5. R3DE instrument results

R3DE instrument (see Table 1, Part 2, Item No 9) with 256 channels ionizing radiation monitoring spectrometer and 4 channels UV spectrometer worked on the ESA European Technology Exposure Facility (EuTEF) platform inside of ESA EXPOSE-E facility outside of the European Columbus module of the ISS between 20 February 2008 and 1 September 2009 with 10-s resolution behind 0.45 g cm^2 of shielding [25, 32].

There are 2 major discoveries connected with the R3DE instrument. The first one is the already mentioned large relativistic electrons doses [32, 41], while the second one is the decrease of the SAA dose rate during the dockings of the USA space shuttle with ISS [64].

Figure 11 shows the result of measurements of the SAA doses for the time span between 22/03/2008 and 01/09/ 2009. SAA proton energies in MeV, maximal dose rates in µGy h^{-1}, and daily dose rates in µGy d^{-1} are presented in the two panels. The maximal dose rates are the value in the interval from 00:00 to 24:00 h, which is larger than any other SAA 10 s measurement. The largest value here was 1708 µGy h^{-1}, and the average was 1218 µGy h^{-1}.

The relatively low dose rates at the left side of Fig. 11 have to do with the ISS altitudes in the range of 350—365 km. The increase of the station altitude up to 365—375 km after 21 June 2008 led to an increase of the maximal SAA dose rate above 1200 µGy h^{-1}.

The main feature seen in Fig. 11 is that during the five space shuttle docking times the SAA maximal doses fall by 600 µGy h^{-1} and reach an average level of 400—500 μGy h^{-1} for the STS-123 and STS-124 missions. For STS-126, STS-119, and STS-127, the drop was also 600 μGy h^{-1} from an average level of 1400 μGy h^{-1}.

The analysis of the daily average SAA dose rate for the studied period shows that before 21 June 2008 it was around 300 μGy d^{-1}, after 21 June 2008 it started to increase, and on 31 July it reached a value of 500 μGy d^{-1}, the level at which the daily average SAA dose rate stayed until the end of the observations in September 2009. The dockings of the space shuttles decreased the daily average SAA dose rate by about 200 μGy d^{-1}. Similar reductions of the SAA dose rates were observed by Semones (2008) [65] with the TEPC in the Columbus module for the period 4—24 March 2008. Because of the larger shielding inside the Columbus module, the reduction reported in [65] was from 120 to 97 μGy d^{-1} during the STS-123 docking time. Benghin et al. (2008) [66] also reported changes in the ratio of daily dose rates of the unshielded detectors numbers 2 and 3 of the DB-8 system during the shuttle dockings.

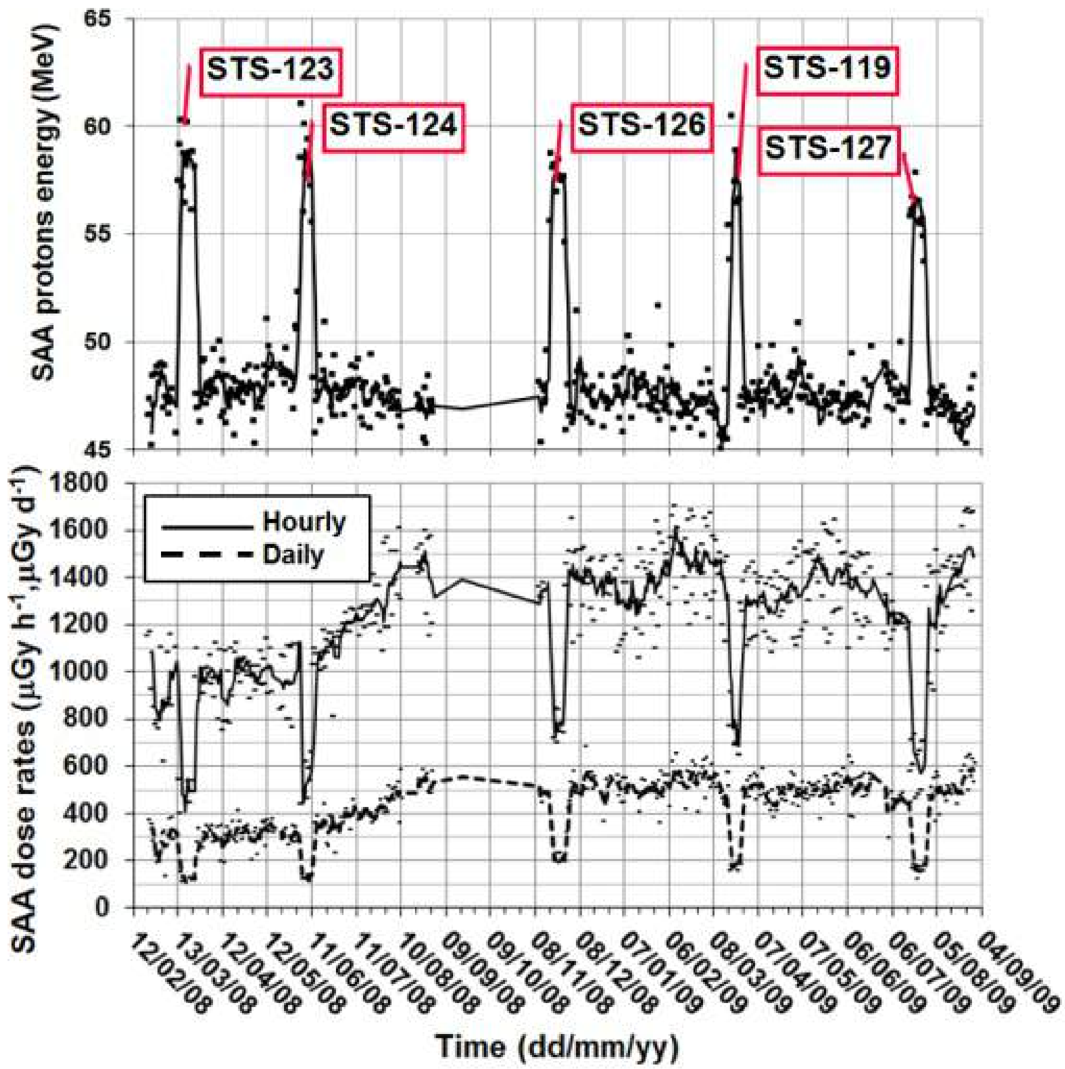

Fig. 11. Daily and hourly SAA dose rates and SAA proton energies measured with the R3DE instrument during the EXPOSE-E mission. The space shuttle dockings at the ISS create strong decreases in the hourly and daily dose rates due to the additional shielding effect of the space shuttle body on the R3DE detector. At the same time the energy of the protons in the SAA increases. The space shuttle visits are marked with the STS number of flight.

The investigation of the averaged energy of the protons in the SAA region is shown in the upper panel of Fig. 12, which reveals that the shuttle dockings increased this energy from about 48 MeV to 58 MeV. The energy of the protons incident normally to the detector is calculated by using the experimental formula described by Heffner (1971) [55]. The increase of the averaged proton energy in the SAA region during the shuttle dockings can be explained with the increase of the values in the entire energy range caused by the stopping of the lowest-energy protons in the mass of the space shuttle.

Figure 12 shows the dose rate dynamics observed by 3 different instruments around the time of Space Shuttle (STS-123) docking and undocking in the time frame 5-31 March 2008. The measured absorbed doses in each exposure interval are presented by black diamonds, while the obtained statistically moving average doses are shown with heavy (red) lines. The numbers there correspond to the number of single measurements used in the moving average calculation.

The 3 panels contain data as follows: In Figure 12a there are the NASA TEPC absorbed dose rate data, which by the selection to be higher than 100 μGy h^{-1} present only the SAA maxima. First part of the data between 5 March and 14:03:37 at 10 March are from position SM-410, while second part till 31 March is from position COL1A3. Data are obtained from *http://cdaweb.gsfc.nasa.gov/* server and prepared by N. Zapp [40]; Figure 12b contains Liulin-5 [45] dose rate data from the first detector selected in same way as the TEPC data; Figure 12c contains R3DE dose rate data selected as the other 2 data sets. Only here the lowest dose rates are 200 μGy h^{-1}.

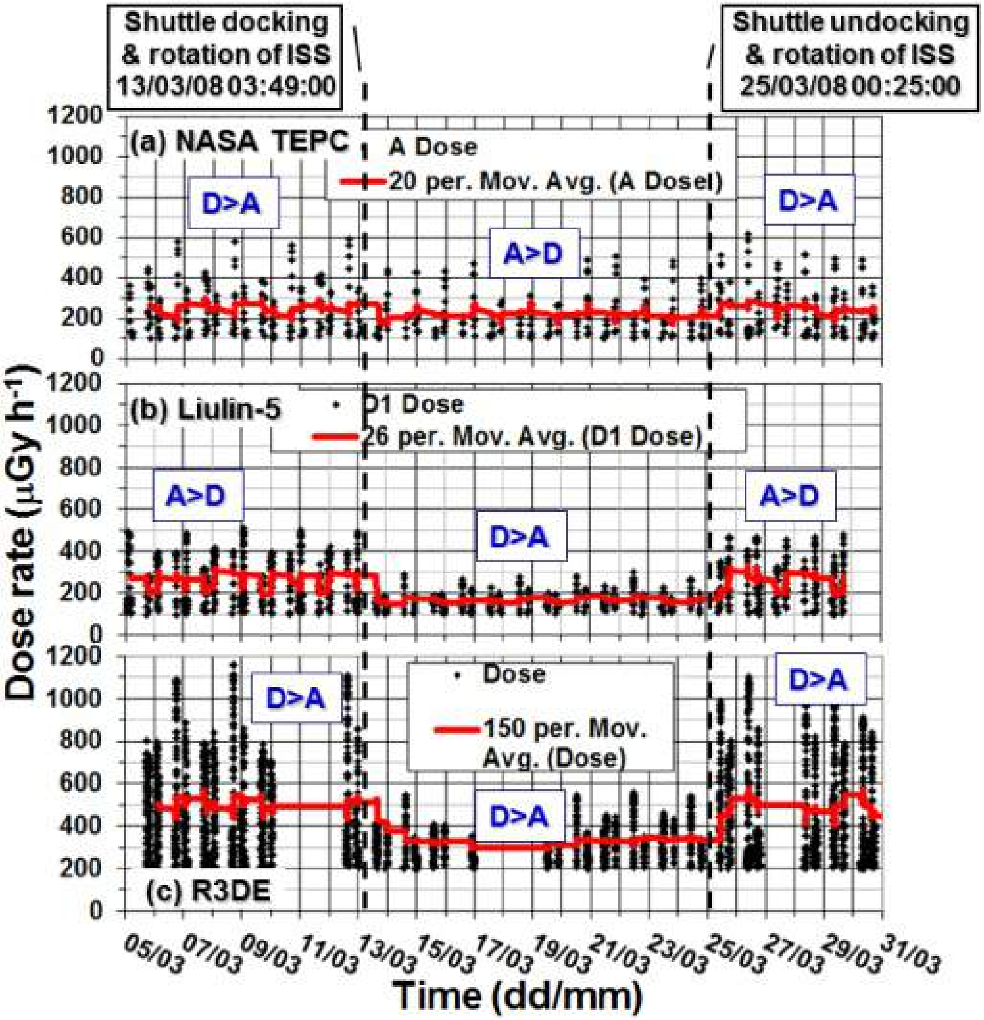

Fig. 12. Variations of the dose rates by NASA TEPC, R3DE and Liulin-5 instruments close to STS-123 docking in the time frame 5-31 March 2008.

Because of the large time interval on the X axis in Figure 6 the 6-8 ascending and descending crossings of the SAA anomaly per day are presented by a pair of 2 bars. The first one corresponds to the descending orbits, while the second one to the ascending orbits during one series of 6-8 crossings. The differences in the dose rate amplitudes are produced by the east-west asymmetries of the proton fluxes in the region of the SAA [57]. These amplitudes are additionally stimulated to changes by the attitude of the ISS, which changes by 180° during the Shuttle docking period and reversed after it [67].

The relations between ascending and descending amplitudes of the dose rates for each instruments before, during and after the Shuttle docking are underlined by text boxes, which contain inequalities labelled by D>A when the descending dose rates were greater than ascending ones and in reverse with A>D when the other relation was fulfilled. For the R3DE instrument there were no changes of the amplitudes relations. At any time the descending dose rate value was greater than the ascending one. This behaviour can be explained by the position of the R3DE instrument on the top of EuTEF where it is not shadowed by the Columbus body from SAA protons drifting to the west. The other 2 instruments showed rotation of the ascending descending inequalities connected with the Shuttle docking. These relations are explained more precisely in the next paragraph.

It is well seen that all 3 data sets recorded a decrease in the dose rates after the docking of Space Shuttle at 03:49 on 13th of March 2008. To emphasize the decreases moving averages lines are calculated and presented by heavy lines in each panel of figure 6. For R3DE the decrease in moving averages was from 500 to 300 μGy h^{-1} or about 40% from the value before the docking. The Liulin-5 data decreased from 300 to 180 μGy h^{-1} or again about 40% from the value before the docking. TEPC dose rates obtain the smallest decrease from 280 to about 200 μGy h^{-1}, which is about 30% decrease. Dose rates measured by all 3 instruments returned to the values before the docking of STS-123 after 00:25 on 25th of March, when the undocking of Space Shuttle occurred.

R3DR instrument results

The R3DR spectrometer (see Table 1, Part 2, Item No 11) was launched inside of the ESA EXPOSE-R facility to the ISS in December 2008 and was mounted at the outside platform of the Russian Zvezda module of the ISS. The first data were received on March 11, 2009. Until the end of August 2010 the instrument worked almost continuously with 10 seconds resolution. The data were recorded on the ISS and transmitted later to the ground. Comprehensive presentation of the R3DR results inside of the EXPOSE-R facility can be found in [68].

In Figure 4 there was already presented a comparison of data obtained simultaneously by R3DE/R instruments and NASA TEPC. The main conclusion from the comparisons of data between R3DE and R3DR instruments [41] is that the values of the dose rates produced by different radiation sources around the ISS did have large and rapid variations in space and time. All obtained data can be interpreted as possible doses obtained by cosmonauts and astronauts during Extra Vehicular Activities (EVA) because the R3DE/R instrument shielding is very similar to the Russian and American space suits' average shielding [3]. Fast, active measurements at the body of each astronaut to obtain the exact dynamics of the dose accumulation during EVA are required.

An instrumental solution was proposed in [69], where the possible hardware and software improvements for a new Liulin type dosimeter were proposed. New instruments will be able, on the basis of the analysis of the shape of the deposited energy spectrum and the value of the dose to flux ratio, to distinguish the different types of radiation sources in the ISS radiation environment as GCR, IRB protons and outer radiation belt electrons. They will measure, calculate, store and present on display the fast variations of the absorbed and ambient dose equivalent doses in any of the possible surrounding mass distributions. The realization of this new instrument is already started [105] and it is expected that the Liulin-ISS-2 instrument will be placed in the Russian segment of ISS before 2020.

R3DR2 instrument results

The R3DR2 spectrometer (see Table 1, Part 2, Item No 12) was switched ON inside of the ESA EXPOSE-R2 facility, mounted at the outside platform of the Russian Zvezda module of the ISS, on 23 October 2014. The instrument worked almost continuously with 10 seconds resolution until 11 January 2016. The presentation of the preliminary R3DR2 results inside of the EXPOSE-R2 facility can be found in [89, 92], while the results from the SEP event on 22 June 2015 in [90].

The following four radiation sources were recognized in the R3DR2 data: (i) globally distributed GCR particles and those derived from them; (ii) protons in the SAA region of the IRB; (iii) relativistic electrons and/or bremsstrahlung in the high latitudes of the ISS orbit where the ORB is situated; (iv) solar energetic particles (SEP) in the high latitudes of the ISS orbit. Together with the real SEP particles a low flux of most probably secondary protons (SP) were observed in the data. The radiation sources were selected by the new radiation source selection procedure, which is based on the specially developed new software and experimentally obtained formulas for the relations between the dose to flux ratio [55] and the type of the predominant radiation.

The separation statistics of the R3DR2 data shows the following results: 441 days were really covered; 3,810,240 points were under separation; 2398 were lost (0.062%) or in average less than 6 points per day; 313 points were counted twice. The average source counts per day were: GCR 7636 points, IRB 573 points, ORB 383 points, SEP counts per 27 days were 148 points; average SP counts per 414 days (days without real SEP) were 34 points. Totally the number of the daily averaged measurements for the “stable” presented sources is: 7636+573+383+34 or 8626 measurements, which were selected from a total of 8640 possible.

In Fig. 13 in 4 panels represented the end result of the separation of 4 radiation sources and their variations for the period October 24, 2014 - January 11, 2016.

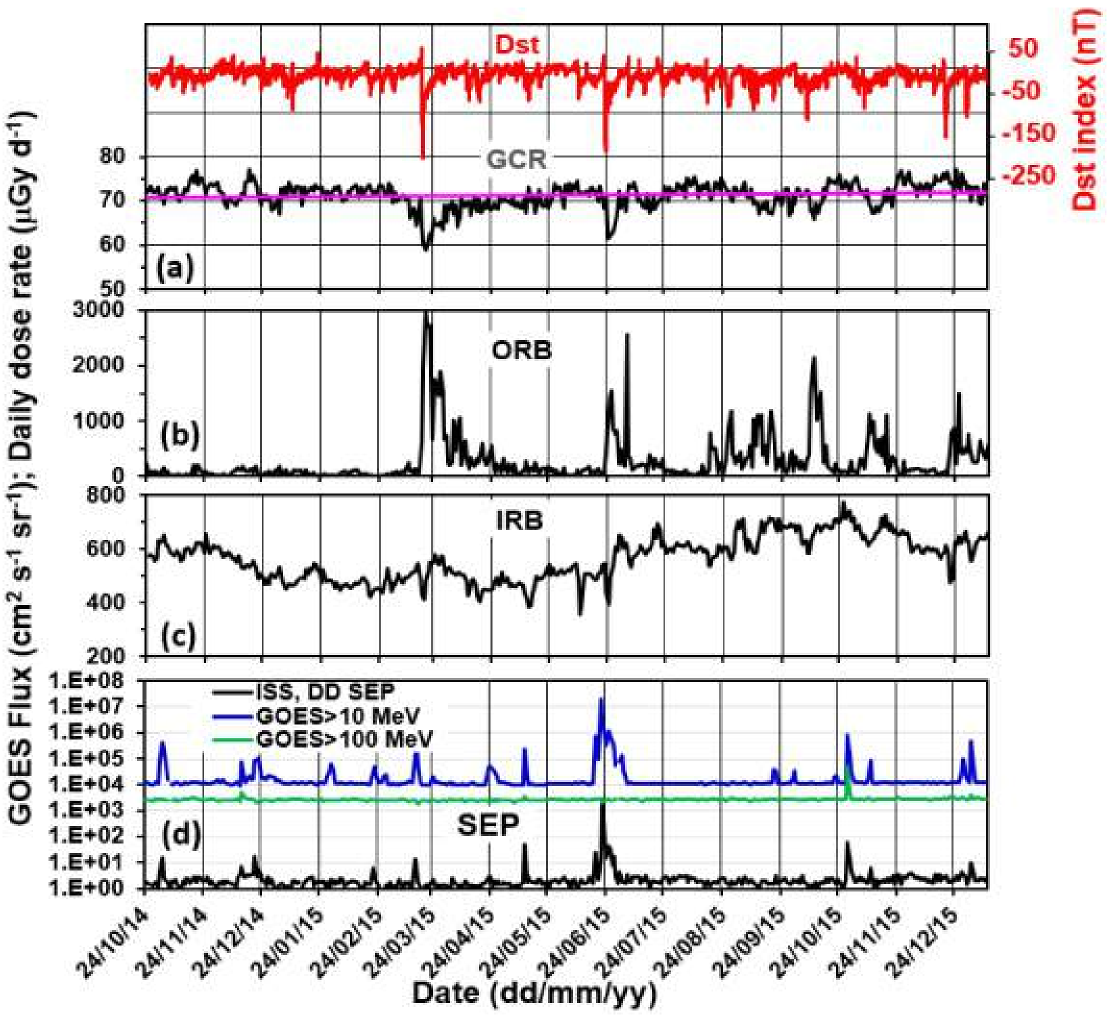

Fig. 13 Result of the separation of the R3DR2 instrument data for the period 24 October 2014–11 January 2016 in four radiation sources.

The daily average dose rate variations of GCR are presented with a thick black line in Fig. 13a. The red line at the top of the panel (a) presents the variation of Dst (Disturbance Storm Time) index (*http://wdc.kugi.kyoto-u.ac.jp/index.html*), which for the days after the beginning of the magnetic storms have negative values, reaching -223 nanoteslas on March 17 and -204 nanoteslas June 23rd. Well defined correlation between daily average dose rate and Dst index confirms a well-known phenomenon of the reduction of the GCR particles flux during the main phase of the magnetic storm, known by the term "Forbush decrease" [97].

The GCR daily average dose rate data trend is with a minimal value of 72 μGy d^{-1} in the beginning of the measurements in October 2014 and maximum of 73 μGy d^{-1} at the end of observations in January 2016. We attribute the positive trend in the GCR dose rate and flux data to the falling solar activity in the period, which by the effect of solar modulation leaded to increase of the GCR flux.

We compare the averaged R3DR2 GCR daily dose rate data of about 71 μGy d^{-1} with those measured inside of the ISS by the DOSTEL 1 and DOSTEL 2 instruments [98] in the period 24 October 2014 – 29 July 2015: Both DOSTEL instruments showed averaged daily values in the range 140-

150 μGy d^{-1} that were larger than those ascertained by R3DR2. We accept this result as confirmation of the theoretical calculations performed by Mrigakshi et al., (2013) [99] (see Fig. 4b) showing that the absorbed dose rates in a water sphere with smaller Aluminum shield thicknesses are smaller than the doses obtained behind larger shield thickness. The R3DR2 data were obtained outside of the ISS behind 0.5-1 g cm^{-2} shielding, while the DOSTEL 1 and DOSTEL 2 instruments data were measured behind larger shielding inside of the ISS.

Fig. 13b aims to present the ORB radiation source variations in the period 24 October 2014-11 January 2016. The black heavy line there is the daily average relativistic electron dose rate as measured in ORB with the R3DR2 instrument on ISS. Clearly are seen 2 periods in the data. In the relatively "quiet" period between 24 October 2014 and middle of March 2015 the ORB daily dose rate are relatively small and vary in the interval 2-200 μGy h^{-1}. In the second period, between middle of March 2015 and the end of the observations, strong variations in the ORB daily dose rate was observed. The largest maxima (up to 3000 μGy h^{-1}) in the ORB source anti-correlate well with the Dst index variations in the Fig. 13a (red line).

The IRB source is the second source, except GCR, which was observed every day in the R3DR2 data. The time profile of the IRB source is presented in Fig. 13c. It is seen that the daily average dose rate was large in the interval October-December 2014, then fell down till the end of June 2015 and rose up again till the end of measurements. These long-term variations correlate well with the variations of the average altitude of the station. The altitudinal dependence in the bottom part of the IRB was investigated by the R3DR1 data [68]. It is a well-known phenomenon, which has been competently described elsewhere [100, 101]. Therefore, it will not be discussed further here.

Higher IRB dose rates at the end of the mission are connected with the lower solar activity and lower sink of the IRB protons, respectively, in the decreased neutral atmosphere density.

Fig. 13d presents with heavy black line the SEP daily dose rate variations, measured with R3DR2 on the ISS in the period 24 October 2014-11 January 2016. They are plotted together with the solar proton fluxes measured at geosynchronous orbit with the GOES 15 "Space Environment Monitor (SEM)" instrument (*http://goes.gsfc.nasa.gov/text/databook/section05.pdf*) with energies more than 10 MeV (blue curve) and more than 100 MeV (green curve). The low dose rates of few μGy d^{-1} seen in the bottom of the figure are the named by us secondary proton (SP) source.

Nine maxima are seen in the R3DR2 SEP daily average dose rate variations. All of them coincide well with the >10 MeV GOES SEM maxima. The >100 MeV proton flux channel on GOES did have only one well seen maximum on 29 October 2015, which is measured with the R3DR2 instrument also. The largest maximum up to almost 3000 μGy d^{-1} on 22 June 2015 was not observed in the GOES >100 MeV channel; however, if a virtual extravehicular activity (EVA) was performed in the period of this SEP maximum, the obtained doses at the skin of cosmonauts/astronauts could reach 2.84 mGy during six and a half hours, which is identical to the average absorbed dose obtained inside of the ISS during 15 days [10, 90].

Experiments and results on satellites

Results obtained at Foton M2/M3 satellites

Radiation Risks Radiometer-Dosimeter (R3D) for Biopan (R3D-B) with 256 channels ionizing radiation monitoring spectrometer and four channels UV spectrometer known as R3D-B2 (see Table 1, Part 1, Item No 3) was successfully flown 31 May–16 June 2005 inside of the ESA Biopan 5 facilities on Foton M2 satellite. The operation time of the instrument was about 20 days for fulfilling of the total 1.0 MB flash memory with 30 s resolution [70]. R3D-B3 spectrometer (see Table 1, Part 1, Item No 7) was with almost same mechanical characteristics as R3D-B2. Larger 2.0 MB flash memory was used for about 30 days measurements. It was successfully flown 14–29 September 2007 inside of the ESA Biopan 6 facilities on Foton M3 satellite. Together with R3D-B3, the Liulin-Photo instrument (see Table 1, Part 2, Item No 8) was flown but inside of the capsule of the Foton M3 satellite [70a]. Most important findings in the R3D-B2/B3 data were the measurements of high doses delivered by relativistic electrons at altitudes below 300 km and latitudes above 50° geographic latitude in both hemispheres [7].

Results obtained at Chandrayaan satellite

RADOM spectrometer-dosimeter (see Table 1, Part 2, Item No 10) was successfully used on the Indian Chandrayaan-1 Moon satellite from 22 October 2008-30 August 2009. It started working 2 h after the launch with 10 seconds resolution behind about 0.45 g cm^{-2} shielding. The instrument sent data for a number of crossings of the Earth radiation belts and continued to work on 100 and 200 km circular lunar orbits measuring mainly the GCR environment [34].

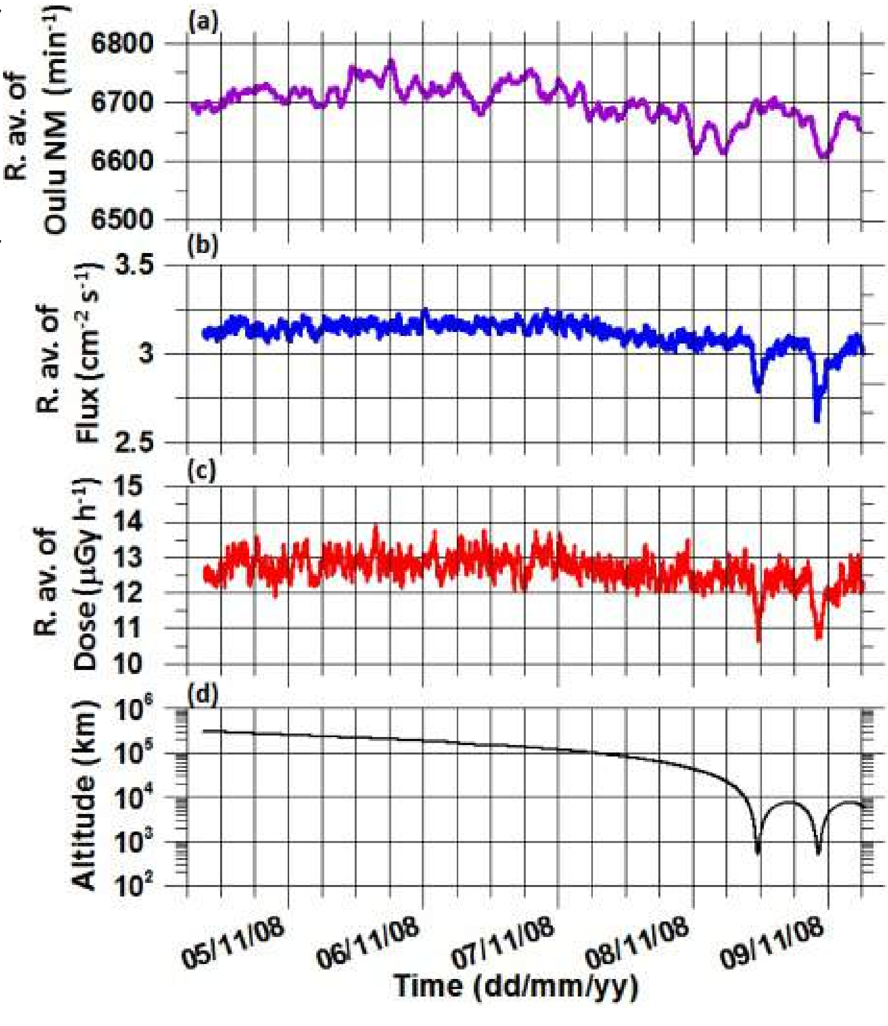

Fig. 14. RADOM observations during lunar transfer trajectory and lunar orbit capture. The distance is from the Moon. The trends in particle flux coincide with the Oulu neutron monitor data trends.

Chandrayaan-1 was placed into the lunar transfer trajectory on 3rd November 2008 (13th day after launch) and a lunar orbit capture manoeuvre was carried out on 8th November (18th day after the launch). Fig. 14 shows RADOM observations for about 3 days before the lunar orbit capture and about one day after it. More than 40000 measurements with 10 s resolution are used for the figure. Figures 14b and 14c show the moving average over 200 points of measured particle flux and the absorbed dose rate respectively. Figure 14d shows the distance from the Moon (in km), while the Figure 9a shows the Oulu Neutron Monitor running average of measured count rate per minute averaged over 10 minutes. The average dose rate from more than 33000 measurements in the altitudinal range between 308000-20000 km from the Moon is ~12.76 μGy h^{-1}. The range of the real measured dose rates is between 3.34 and 41.34 μGy h^{-1} with a standard deviation of 4.25 μGy h^{-1}. The average flux is 3.14 particles cm^{-2} s^{-1}, while the real flux range is between 1.71 and 4.82 particles cm^{-2} s^{-1} with a standard deviation of 0.41 cm^{-2} s^{-1}. Figures 14b and 14c don't show this real dynamics of the values because the moving averages are plotted there. These values of the dose rate and flux may be used as referee values for the "deep space" radiation conditions at this very low level of solar activity.

For the above mentioned altitudinal range the flux correlates with the Oulu NM count rate and respectively with the solar activity. Later on during the two closer approaches to the Moon at an altitude about 508 km the flux and the dose rate decrease because the enhanced shielding of the cosmic rays by the Moon body itself. A closer look at the Figure 14a reveals that the second periselene crossing is deeper than the first one. This is mostly related with a local increase of the solar activity as evident from the simultaneous decrease of the Oulu NM count rate.

RADOM observations which began within two hours after launch of the Chandrayaan-1 and continued until the end of the mission demonstrated that it could successfully characterize different radiation fields in the Earth and Moon environments. Signature and intensity of proton and electron radiation belts, relativistic electrons in the Earth magnetosphere as well as galactic cosmic rays were well recognized and measured. Effect of solar modulation of galactic cosmic rays could also be discerned in the data. The electron radiation belt doses reached ~40000 μGy h^{-1}, while the maximum flux recorded was ~15000 cm^{-2} s^{-1}. The proton radiation belt doses reached the highest values of ~130000 μGy h^{-1}, while the maximum flux was ~9600 particle cm^{-2} s^{-1}. Comparison of these results with other similar instruments on board ISS shows good consistency, indicating nominal performance RADOM. Outside the radiation belts, en-route to the Moon, the particle flux (~3 particle cm^{-2} s^{-1}) and corresponding dose were very small (~12 μGy h^{-1}) which further decreased slightly in the lunar orbit because of the shielding effect of the Moon. Average flux and dose in lunar orbit were ~2.45 cm^{-2} s^{-1}, and the corresponding absorbed dose rate was 9.46 cm^{-2} s^{-1} respectively at 100 km orbit. These increased to 2.73 particles cm^{-2} s^{-1} and 10.7 μGy h^{-1} respectively, at 200 km orbit. The total accumulated dose during the transfer from Earth to Moon was found to ~1.3 Gy.

Results obtained at "BION-M" №1 spacecraft

"BION-M" №1 was a low Earth orbit satellite that orbited the Earth with a period of 89.9 min, an inclination of 65°

with respect to the Earth's equator, and with an altitude above the Earth surface in the range 253–585 km. The final orbit of the satellite was almost circular with an apogee of 585 km and a perigee of 555 km altitude. The final orbital parameters were reached after 21 April 2013 [71]. Space radiation has been monitored using the RD3-B3 spectrometer-dosimeter (see Table 1, Part 2, Item No 13), which was mounted inside of the satellite in a pressurized volume together with biological objects and samples. The 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 in September 2007 [70].

The observed hourly and daily IRB dose rates at the "BION-M" №1 satellite are the highest seen by us during our measurements on "Mir" and the ISS space station and on Foton-M2/M3 satellites because the altitude of the "BION-M" №1 obit was the highest in comparison with all missions mentioned above. The same is valid for the GCR doses. The observed ORB doses are smaller than the ones measured outside the ISS because of the higher shielding on the "BION-M" №1 satellite.

Results obtained at ExoMars, TGO spacecraft

ExoMars is a joint investigation of Mars carried out by ESA and Roscosmos that has two launches - in 2016 and 2020. Trace Gas Orbiter, a satellite part of the 2016 launch carries the Fine Resolution Neutron Detector instrument as part of its payload. The instrument aims at mapping hydrogen content in the upper meter of Martian soil with spatial resolution of up to 40 km [104]. The FREND's dosimeter module Liulin-MO particle telescope provides information for the radiation environment in the interplanetary space and in Mars orbit [49].

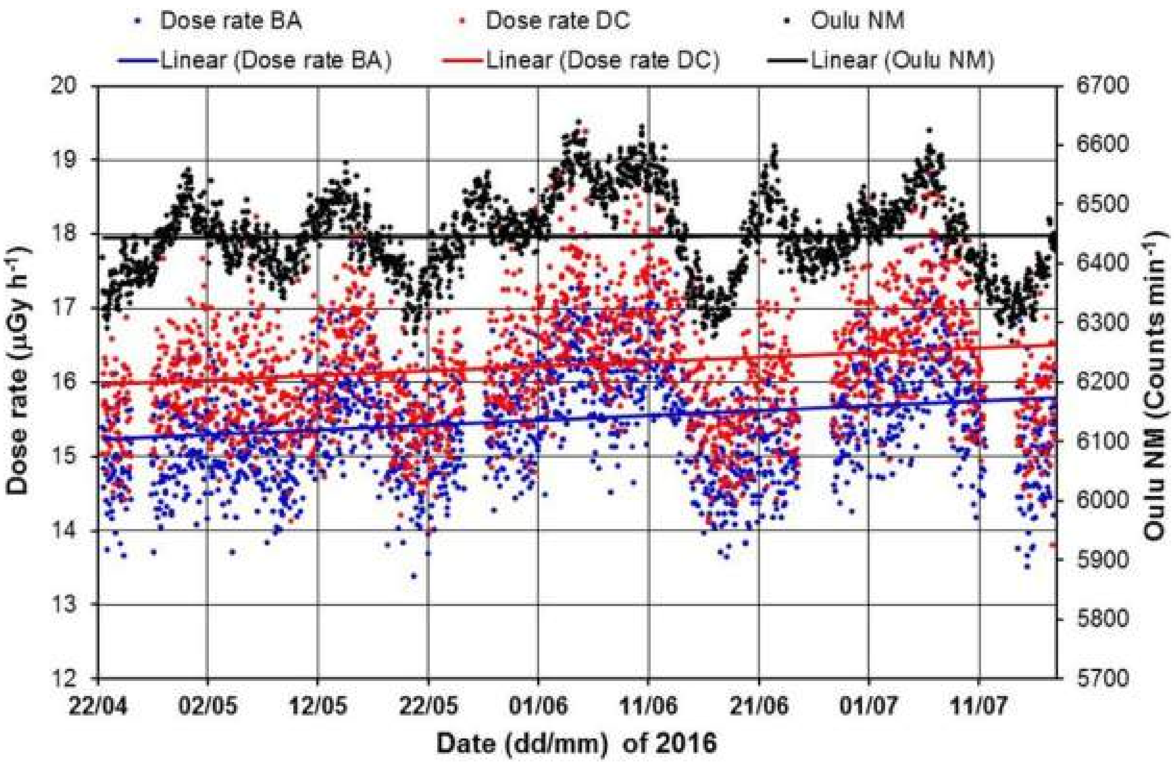

Fig. 15. Liulin-MO observations during the cruse of ExoMars-TGO satellite toward Mars. The variations and the linear trends in the dose rate coincide with the Oulu neutron monitor data variation and trends.

FREND was operating almost continuously during TGO cruise between Earth and Mars. An example of first science results obtained by Liulin-MO during the interplanetary cruise is shown in Fig 15. Presented are preliminary results from measurements of dose rates of GCR in single detectors B(A) and D(C) of DM, located in perpendicular directions. The average daily dose rate between 22.04.2016 and 18.07.2016 are 372 ± 37 µGy d^{-1} in B(A) and 390 ± 39 µGy d^{-1} in D(C). Figure 15 also shows Oulu Neutron Monitor cosmic ray count rate (*https://cosmicrays.oulu.fi/*) for the same time interval. A good agreement of the variations in Liulin-MO dose rates with the Neutron Monitor count rate over the time is observed.

Presently (November - December 2016) Liulin-MO provides data for the radiation environment in high elliptic orbit around Mars.

Main experiments and results at aircraft balloon and rocket

Table 2 lists DES Liulin type experiments on aircraft, balloon, rocket and mountains peaks. The pictures shown for items 2 and 8 are the latest versions of the instruments used in this category. For some of the mentioned in these rows references the instruments was housed in different that the shown in the pictures.

The Liulin-4C, MDU#2 instrument (see Table 2, Item No 1) worked successfully during the flight of French balloon up to 32 km altitude in the region of the Gap town in Southern France on 14th of June 2000. This experiment was performed by the Nuclear Physics Institute, Czech Academy of Sciences [72].

One battery-powered DES of Liulin-4J (see Table 2, Item No 1) type performed dosimetric measurements of the ionizing radiation environment at ~20 km altitude aboard NASA's Lockheed ER-2 high altitude research aircraft in October-November 2000 from Edwards Air Force Base (AFB) in Southern California and flew over the border region dividing Central California from Central Nevada [73].

Mobile Dosimetry Units MDU-5 and 6 (see Table 2, Item No 2) was used for long-term measurements between 2001 and 2014 on Czech Airlines (CSA) aircraft at different routes. Data obtained were used for comparison with model calculated doses for the purposes of individual monitoring of aircrew [30, 31]. Fig. 16 presents almost one solar cycle data from these flights, which are publicly available in database of measurements. (*http://hroch.ujf.cas.cz/~aircraft/*) [74].

Please see Fig. 16 captions for more details.

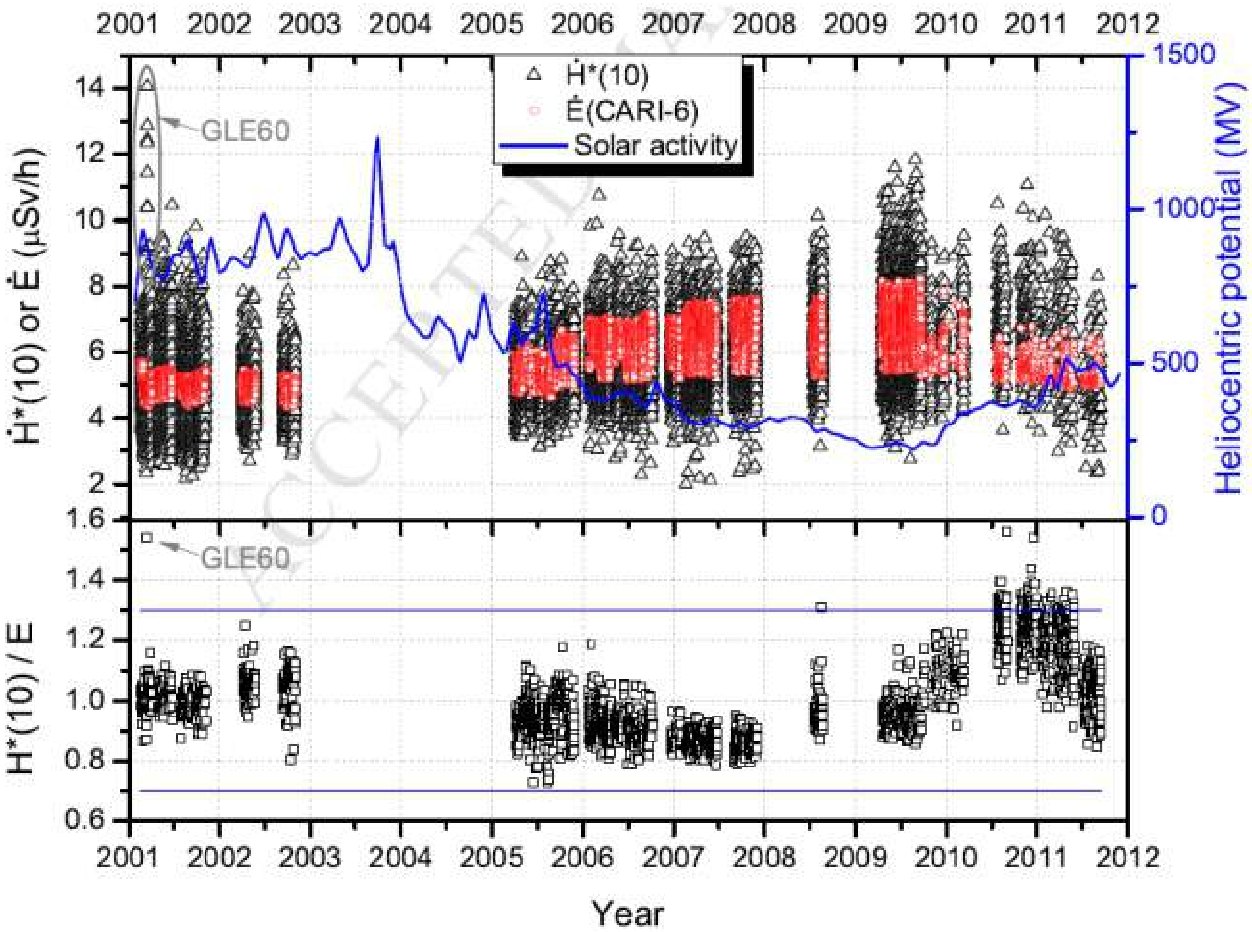

Fig. 16. Top panel: Ambient dose equivalent (H*(10) - black triangle) dose rates determined by Liulin and effective dose rates (E(Cari-6) – red circles) calculated with CARI-6 code[75] plotted as a function of time (only data at 35000 (10.67 lm) and effective vertical cut-off rigidity [14] (VCR) VCR≤3.5 GV are shown). Solar activity is expressed via the heliocentric potential). Bottom panel: Ratios of integral values per whole flight between ambient dose equivalents, H*(10), estimated with Liulin, and effective doses, E, calculated with CARI-6 plotted as a function of time. ±30 % confidence band is plotted with 2 horizontal blue lines.

Very similar instruments to the Mobile Dosimetry Units MDU-5 and 6 was used by scientific groups in Spain [76] and Korea [77] for radiation measurements at aircrafts.

Three battery-powered DES (see Table 2, Item No 3) were operated during the 8 June 2005 certification flight of the NASA Deep Space Test Bed (DSTB) balloon at Ft. Sumner, New Mexico, USA. The duration of the flight was about 10 hours (*http://wrmiss.org/workshops/tenth/pdf/08_benton.pdf*).

Liulin-6S, Lilun-M, Liulin-6MB and Liulin-6R (see Table 2, Item No 4) were internet based instruments [78]. They use internet module to generate web page. The obtained deposited energy spectra data were transmitted via LAN interface by HTTP and FTP protocols. They worked for different periods since 2005 at Jungfrau (Switzerland) 3453 meters Above Mean Sea Level (AMSL) *http://130.92.231.184/*), Moussala (Bulgaria) 2925 meters AMSL *http://beo-db.inrne.bas.bg/moussala/* and Lomnicky Stit (Slovakia) 2633 meters AMSL *http://147.213.218.13/* peaks and at ALOMAR observatory in Norway (*http://128.39.135.6/*) [78].

Liulin-4SA (see Table 2, Item No 5) spectrometer was designed in 2005 under the request of Capitan Ian Getley pilot of Boeing 747-400, Qantas Airways aircraft [44]. Liulin-4SA was used inside of the cockpit of Boeing 747-400 aircraft and provided on LCD display data for the local dose rate and flux simultaneously with the flight altitude, longitude and latitude, obtained from build-in GPS receiver for each measurements interval (usually 60 sec). Pre-programed alert signals was able to be initiated when the measured dose rate exceed preliminary set levels for 3 subsequent measurement intervals.

The presented in Table 2, Item No 6 two Liulin DES systems consists of 4 dosimetry units (DU) and 1 control and interface unit (CIU). The Liulin-6U instrument was delivered to NASA, Marshall Space Flight Center, USA in 2005. It was planned to be used in a balloon experiment [79]. The second one was delivered to the Skobeltsyn Institute of Nuclear Physics at Lomonosov Moscow State University in 2010. It was planned to be used in the RAZREZ system for RADIOSCAF experiment on ISS [80, 81].

Liulin-R instrument (see Table 2, Item No 7) was successfully launched on HotPay2 rocket from Andoya Rocket Range (ARR), Norway, on 31st of January, 2008 at 19:14:00 and rising up to 380 km altitude, as a part of an EU financed scientific program called eARI (ALOMAR eARI project) [82].

Wissmann et al. [83] performed 5 balloon experiments up to 30 km altitude using Liulin-6RG spectrometers (see Table 2, Item No 8) between July 2011 and August 2012. The Liulin instruments were powered and transmitted the obtained in 30 sec deposited energy spectrum to data logger, developed in Physikalisch-Technische Bundesanstalt (PTB), Germany.

The presented in Table 2, Item No 9 Liulin spectrometer is the last generation of series of instruments with build-in GPS receiver and 1 or 2 MB SD card. First this type of instruments (LIULIN-4N) was used by colleagues from Department of Chemistry and Chemical Engineering, Royal Military College of Canada in 2003-2005 [43, 84]. Two different methods of determining the route H*(10) value from the LIULIN data were examined, which agree very well the H*(10) values measured by the TEPC (within the 20% error inherent within both instruments).

The presented in Table 2, Item No 10 Liulin-6SA1 spectrometer [94] was operated during the NASA RaD-X stratospheric balloon flight mission on 25 September 2015 from Fort Sumner, New Mexico (34.5° N, 104.2° 12 W). The RaD-X balloon flight was supplemented by contemporaneous aircraft measurements, which included Liulin instruments also [95, 96]. The German Aerospace Center (DLR) conducted a flight campaign in support of the RaD-X mission which consisted of dosimetric measurements from a TEPC and a Liulin on two Lufthansa German Airlines commercial flights [95]. The Columbia Scientific Balloon Facility (CSBF) - NASA aircraft was equipped with a Liulin and two TEPCs [96].

Profile of the ionizing radiation exposure between the Earth surface and free space

Fig. 16 presents the synthesized altitudinal profiles of the moving averages (over 4 points) of 3 parameters: absorbed dose rate in μGy h^{-1} (heavy line), flux in cm^{-2} s^{-1} (long (red) dashed line) and specific dose (SD) in nGy cm^2 particle-1 (short (blue) dashed line). On the left side of the figure are listed the carriers, instruments, time, averaged geographic coordinates of the measured values and their altitudinal range in km. On the right side are listed the conditions and predominant radiation sources for the places pointed with the arrows. The figure is similar to the published in [86] Fig.2 but improved with the new data obtained with RD3-R3 instrument on "BION-M" No1 satellite and Liulin-5 data on ISS for the period of flight of "BION-M" No1 satellite - 21/04/-13/05/2013.

Fig. 17 contains original experimental data, which are compared and plotted to reveal a unified picture how the different ionizing radiation sources contribute and build the space radiation exposure altitudinal profile from the Earth surface up to the free space. The dose rate and flux data cover 7 orders of magnitude and can be used for educational purposes and also as reference values for new models. The presentation of data in kilometers above the Earth surface instead in L values allows space agencies medical staff and that not specialized in the geophysics support to use them for a first approach for the expected human exposure at different altitudes and also the general public and students to have a simple knowledge about the position of the most common maxima of exposure around the Earth and up to free space.

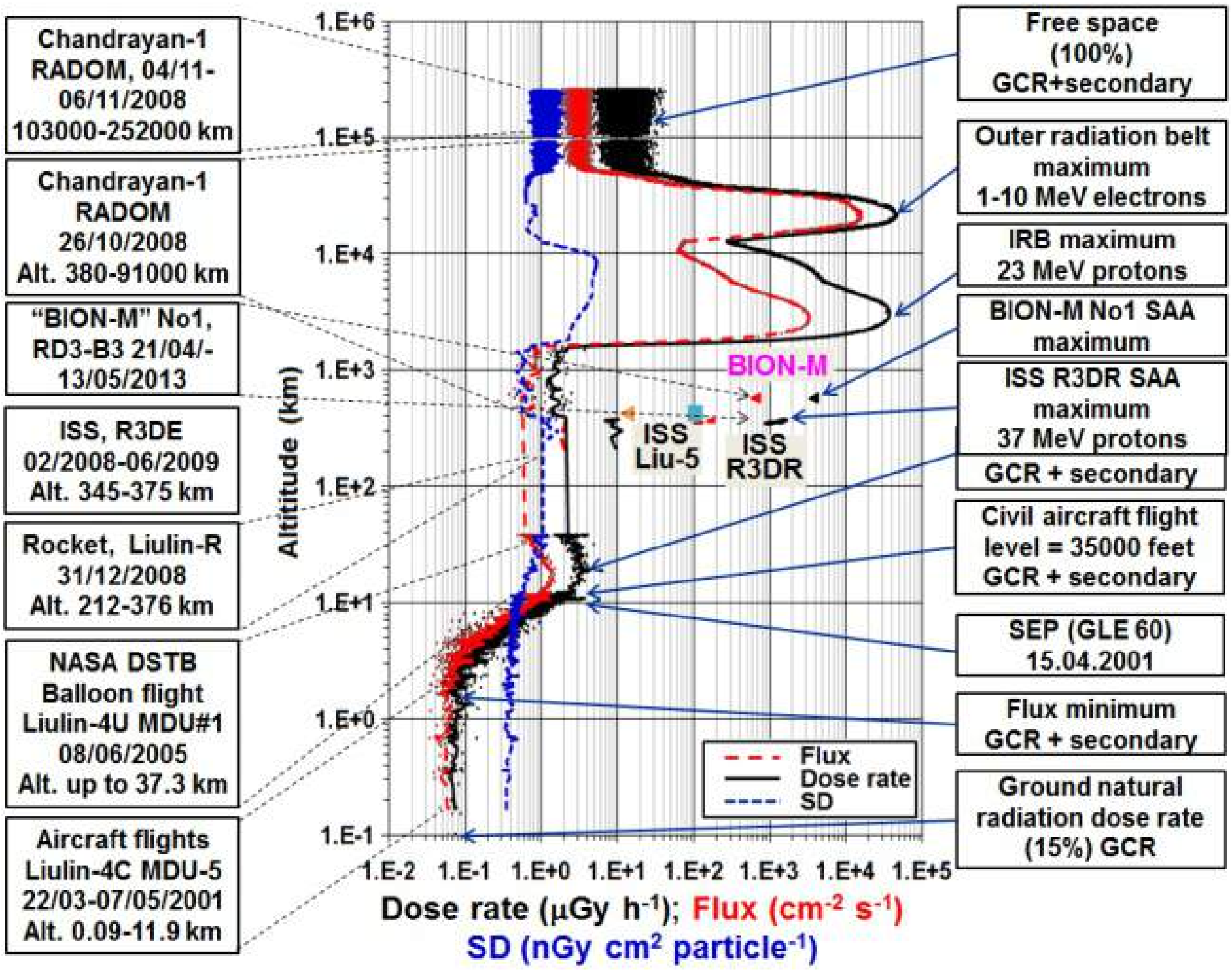

Fig. 17. Variations of the absorbed dose rate, flux and specific dose for altitudinal range from 0.1 to 250,000 km. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Conclusions

The Liulin type low mass, dimension and price instruments during the period 1989-2016 proved their ability to characterize the radiation environment at the ground, mountain peaks, aircraft, balloon, rocket and spacecraft.

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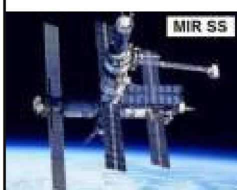
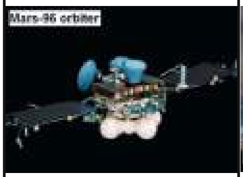
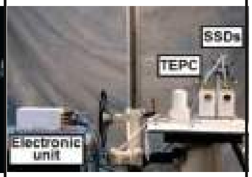
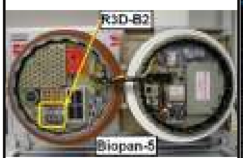
Table 1. (Part 1) Liulin type experiments performed during satellite missions.

Item No	Satellite Date begin-Date end Available number of measurements	Experiment name PI CoPI References	Instrument Size [mm]/Mass [kg] Place Shielding [g cm^{-2}] Resolution [sec]/[min]	Instrument Location image	External view of the instrument
1	MIR SS 04/1988-06/1994 >2,000,000 measurements	LIULIN V. Petrov, IMBP; Ts. Dachev, SRTI. Dachev, et al., 1989. [17]; Shurshakov et al., 1999. [54].	LIULIN 1 DU (109x149x40 mm, 0.45 kg); 1 MCU (300x220x187 mm, 6.5 kg) Inside different modules of MIR SS >5 g cm^{-2} 30 sec		

2	Mars-96 16/11/1996 (The satellite was lost because of rocket booster malfunctioning)	RADIUS-MD V. Petrov, IMBP; Ts. Dachev, SRTI. Semkova et al., 1994. [18].	2 Solid State Detectors (SSD) (154x80x70 mm, 0.38 kg) Outside and inside Mars-96 satellite >2 g cm-2; 10 min		
3	ISS 05/05/2001- 26/08/2001/ 1,267,200	Dosimetric Mapping G. Reitz, DLR; Ts. Dachev, SRTI. Dachev et al., 2002. [20]; Reitz et al., 2005. [10]; Nealy et al., 2007. [58]; Slaba et al., 2011. [59].	Liulin-E094 1 CIU (120x80x60 mm, 0.4 kg) 4 MDU (100x64x24 mm, 0.23 kg) Inside of the American Lab. and Node 1 of ISS >20 g cm^{-2}; 30 sec		
4	Foton M2 01/06/2005- 12/06/2005 17,280	Biopan 5 G. Horneck, DLR; D. Häder, UE; Ts. Dachev, SRTI. Häder et al., 2009. [70]; Dachev et al., 2009. [7].	R3D-B2 (57x82x24 mm, 0.12 kg) 1 DU outside of the satellite and inside of Biopan-5 facility 1.75 g cm^{-2}; 60 sec		
5	ISS Since Sept. 2005 13/08/2008- 29/08/2008 Service system in next 15 years 149,760 spectra	Liulin-ISS V. Petrov, IMBP; Ts. Dachev, SRTI. . Dachev, et al., 2005. [60].	Liulin-MKS 1 CIU (120x80x20 mm, 0.4 kg) 4 MDU (110x80x25 mm, 0.23 kg) Inside Russian segment of ISS >20 g cm^{-2}; 10-3599 sec		

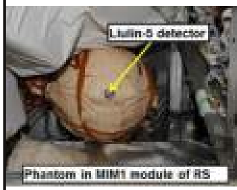
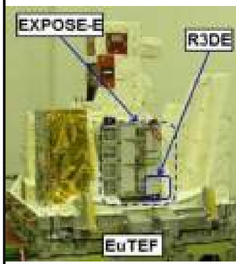
6	ISS 17/05/2007- 15/09/2015 . Data recorded on flash memory card >2,500,000 measurements	Matroska-R V. Petrov, IMBP; J. Semkova, SRTI. Semkova, et al., 2003. [21]; Semkova, et al., 2008. [22].	Liulin-5, Dosimetric telescope by 3 detectors (Φ50/30x191 mm, 0.4 kg) Electronic block (160x90x30 mm, 0.8 kg) Inside Russian segment of ISS >20 [g cm^{-2}]; 90 sec		
7	Foton M3 14/09/2007- 26/09/2007 18,720	Biopan 6 G. Horneck, DLR; D. Häder, UE; Ts. Dachev, SRTI. Damasso et al., 2009. [70a]; Häder et al., 2009. [70].	R3D-B3 1 DU (57x82x24 mm, 0.12 kg) outside of the satellite and inside of Biopan-6 facility 0.8 g cm^{-2}; 60 sec		

Table 1. (Part 2) Liulin type experiments performed during satellite missions.

Item No	**Satellite** **Date begin-Date end** **Number of measurements**	**Experiment name** **PI** **CoPI** **References**	**Instrument Size [mm]/Mass [kg]** **Place** **Shielding [g cm^{-2}]** **Resolution [sec]/[min]**	**Instrument Location image**	**External view of the instrument**
8	Foton M3 14/09/2007- 26/09/2007 27,360	PHOTO-II M.-T. Giardy, IC-AR, Rome, Italy; Ts. Dachev, SRTI. Damasso et al., 2009. [70a].	Liulin-Photo, 1 DU (57x82x24 mm, 0.5 kg) Above Photo instrument, inside of the satellite, >5.0 g cm^{-2}; 60 sec		

9	ISS, Columbus module 17/02/2008-03/09/2009 4,406,400	EXPOSE-E G. Horneck, DLR; D. Häder, UE; Ts. Dachev, SRTI. Häder and Dachev, 2003. [70] Dachev et al., 2012. [32]	R3DE 1 DU (76x76x36 mm, 0.19 kg) Outside of ISS in EXPOSE-E facility in EuTEF >0.6 g cm^{-2}; 10 sec		
10	Chandrayaan-1 satellite around the Moon 22/10/2008-29/09/2009 1,209,600 spectra	RADOM Ts. Dachev, SRTI Dachev et al., 2011. [34]; Dachev, 2013. [85].	RADOM 1 DU (110x40x20 mm, 0.098 kg) Outside of the Chandrayaan-1 satellite >0.6 g cm^{-2}; 10 and 30 sec		
11	ISS, Zvezda module 11/03/2009-20/08/2010 3,540,000	EXPOSE-R G. Horneck, DLR; D. Häder, UE; Ts. Dachev, SRTI. Dachev et al., 2013. [8] Dachev et al., 2015. [68]	R3DR 1 DU (76x76x36 mm, 0.19 kg) Outside of ISS in EXPOSE-R facility outside of Zvezda module >0.6 g cm^{-2}; 10 sec		
12	Phobos-Grunt 09/11/2011 (The satellite was lost because of rocket booster malfunctioning)	Liulin-Phobos V. Petrov, IMBP; J. Semkova, SRTI. Semkova, et al., 2008. [22].	Liulin-Phobos 2x2 dosimetric telescopes (172x114x45 mm 0.5 kg) Outside Phobos-Grunt satellite; >2 g cm^{-2} Dose and flux 60 sec Spectrum 60 min		
13	"BION-M" №1 19/04/2013-1305.2013 34,391 spectra	RD3-B3 V. Shurshakov, IMBP; Dachev et al., 2014. [71].	RD3-B3 (110x80x44 mm, 0.3 kg) 1 battery operated DU Inside "BION-M" №1 satellite/ >2 [g cm^{-2}]; 60 sec		

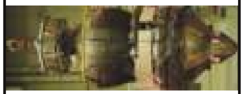
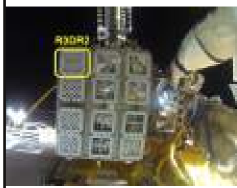
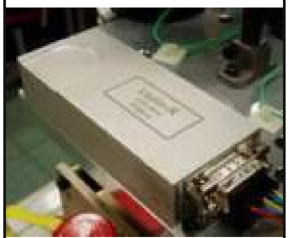
14	“FOTON-M” №4 08/09/2014- 20/10/2014 62,980 spectra	RD3-B3 V. Shurshakov, IMBP; Ts. Dachev, SRTI	Same as in previous row		Same as in previous row
15	ISS, Zvezda module 23/10/2014- 11/01/2016 4,210,500	EXPOSE-R G. Horneck, DLR; D. Häder, UE; Ts. Dachev, SRTI. Dachev et al., 2016. [92]	R3DR2 1 DU (76x76x36 mm, 0.19 kg Outside of ISS in EXPOSE-R2 facility outside of Zvezda module >0.6 g cm-2; 10 sec		
16	ExoMars 2016 Trace Gas Orbiter Launched 14/03/2016	FREND I. Mitrofanov, SRI J. Semkova, SRTI. Semkova et al, 2015. [49] Mitrofanov et al, 2016. [104] (in press)	Liulin-MO 1 (172x114x45 mm 0.7 kg) Outside of ExoMars 2016 >7 g cm-2; Dose and flux 60 sec Spectrum 60 min		

Table 2. Liulin type experiments at aircraft, balloon, rocket and mountains peaks.

Item No	Experiment description Date begin-Date end	Person performing the experiment References	Instrument Size [mm]/Mass [kg] Place Resolution [sec]	External view of the instrument
1	1. Balloon experiment at Gap-Tallard aerodrome, France, 14/06/2000; 2. NASA’s Lockheed ER-2 high altitude research aircraft, Oct.-Nov. 2000.	1. CNES balloon technological flight program, F. Spurny, NPI-CAS, Prague, Czech Republic; 2. Y. Uchihori, NIRS, Japan; Spurny, F., 2000. [72]. Uchihori et al., 2003. [73].	Liulin-4C/4J, MDU-2 (100x64x24 mm, 0.23 kg with rechargeable Li-Ion battery pack) Inside of the balloon gondola or the ER-2 cockpit, 60 sec.	

2	Long-term (>60 days) measurements at aircraft altitudes for different airlines. 28 V DC/DC converter. Since 2001 up to 2016.	F. Spurny and O. Ploc, NPI, Czech Rep; Ploc et al., 2013. [74] J.C. Saez Vergara and R. Dominguez-Mompell Roman, CIEMAT and IBERIA, Spain [76]. Hwang et al, KASI, Korea [77]	DU (110x100x45 mm, 0.48 kg including 2 D size Lithium-Ion batteries) Inside of the aircraft 300/600 sec.	
3	Deep Space Test Bed (DSTB) certification flight 8 June 2005 at Ft. Sumner, New Mexico, USA. ~10 hours	E. R. Benton, ERIL Research Inc. Benton, 2005. *http://wrmiss.org/workshops/tenth/pdf/08_benton.pdf*	3 Liulin MDU (100x64x24 mm, 0.23 kg with rechargeable Li-Ion battery pack) Inside of the balloon gondola 60 sec.	
4	Measurements at mountain peaks. The Liulin instrument contains Internet module to post, store and transmit the obtained results via FTP protocol in Internet.	Bern university, Jungfrau, Switzerland: *http://130.92.231.184/ 2005-2016* INRNE-BAS, BEO-Moussala: *http://beo-db.inrne.bas.bg/ moussala/2005-2014*	DU (84x40x40 mm, 0.12 kg. Internet module with 22 MHz microprocessor, 512K flash and 512K SRAM memory. 600 sec.	
5	Measurements at aircraft altitudes. A built in GPS receiver record: UT, Longitude, Latitude and Altitude, which together with the dose rate data are shown on the display.	I. Getley, University of New South Wales, Australia Getley et al., 2010. [44].	Spectrometer (110x55x45 mm; 0.38 kg); Display (115x40x20 mm; weight 0.12 kg; Rechargeable battery package (90x60x40 mm; 0.18 kg). Inside of the cockpit of Boeing 747-400 Qantas Airways flights.	

6	1. NASA balloon experiment for radiation studies. 2. RAZREZ system on ISS (The both systems are already delivered but both exp. are not performed.)	1. J. Adams et al., 2007. [79]. NASA/Marshall Space Flight Center, USA. 2. Petrov et al., 2009. [80] *http://wrmiss.org/workshops/fourteenth/Petrov.pdf*	4 DU (74x40x20 mm, 0.065 kg; 1 CIU (144x60x20 mm, 0.21 kg) Total 0.47 kg. Powered from 28 V DC, 0.72 mA. Data transmission trough RS485 interface.	
7	Under the HotPay2 project from Andoya Rocket Range, Norway was launched a rocket up to 380 km altitude on January 31, 2008.	Tomov et al., 2009. [82]. *http://www.stil.bas.bg/FSR/PDF/TOP5Tomov_Borislav2242058.pdf*	(110x40x20 mm, 0.098 kg) Inside of the rocket payload 60 sec.	
8	5 balloon flights up to 30 km altitude between July 2011 and August 2012	F.Wissmann et al., Physikalisch-Technische Bundesanstalt (PTB), Germany F.Wissmann et al., 2013. [83]	Liulin-RG4/5 2 DU (110x40x20 mm 0.092 kg). With serial readout of the data measured with the Si-detector. On the gondola of the balloon. 30 sec.	
9	Long-term measurements at aircraft altitudes. A built in GPS receiver records. Data are stored at SD card. Since 2005 up to 2016.	Green et al., Royal Military College of Canada, Canada. Green et al., 2005. [43]; Kitching, 2004. [84]. Meier et al., 2016 [93] DLR, Institute of Aerospace Medicine.	1 DU (110x100x45 mm, 0.48 kg including 2 D size Lithium-Ion batteries) inside of the aircraft 300/600 sec	
10	NASA RaD-X stratospheric balloon flight mission on 25 September 2015. >18 hours measurements.	Mertens et al, 2016. NASA Langley Research Center Mertens et al, 2016. [94] Meier et al., 2016 [96]	Liulin-6SA1 1 DU (110x40x20 mm 0.092 kg). With serial readout of the data measured with the Si-detector. On the gondola of the balloon. 60 sec.	

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БЪЛГАРСКИ ПРИБОРИ ЗА ИЗМЕРВАНЕ НА ЙОНИЗИРАЩАТА КОСМИЧЕСКА РАДИАЦИЯ

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Резюме. *Йонизиращата радиация създава здравни проблеми за хората на повърхността, на Земята в атмосферата в околоземното и междупланетното космическо пространство. Оценката на радиационното въздействие върху здравето изисква точно познаване на натрупаната погълната доза, която зависи от глобалното разпределение на космическата радиация, фазата на слънчевия цикъл и от локалните вариации на масата около точката на измерване. В статията е направен обзор на създадените в България спектрометри-дозиметри от типа „Люлин“ и основните научни резултати, които са получени с тях от 1988 г. досега (2016) на самолети, балони, ракети и спътници, включително станцията „Мир“ и международната космическа станция МКС.*

BULGARIAN ADDED VALUE TO ERA

MILESTONES OF BULGARIAN PHYSICS AFTER THE SECOND CONGRESS OF PHYSICAL SCIENCES

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Abstract. *In this paper we present the introductory talk at the III National Congress of Physical Sciences. In it we review the achievements in physical scientific research of colleagues, research teams and institutions for the period of 3 years after the previous Congress. These achievements are noticed and recognized in the national and international physics communities and corresponding awards and honors were given to their authors by the highest state institutions, foundations and scientific organizations. The role of the Union of physicists in Bulgaria in promoting them and developing and sustaining active national and international cooperation in the field of contemporary physical sciences and education is also noted. Hence the outlined achievements and the international cooperation of the Bulgarian scientists create the milestones and future prospective of the development of Bulgarian physical sciences.*

One of the goals before the Union of Physicists in Bulgaria (UPB) was to revive after 30 years pause the tradition of holding national congresses. 30 years after the First Congress we had the difficult task to review a long and difficult period of fundamental social and political changes. The review demonstrated that Bulgarian physics is alive, that its potential is still there, that its traditional directions are being successfully developed and that new ones have come to life which will influence its future.

In this paper we present the most successful Bulgarian physicists who are well placed on the national, European and world scientific scene. Our review of the achievements of our colleagues and research teams which have received peer recognition and honored by national and international institutions displays the milestones of Bulgarian physics and the prospects of its future development.

INTERNATIONAL RECOGNITION

The office of acad. Georgi Nadjakov – part of the European scientific heritage

In 2014 on the eve of May 24 – the day of Bulgarian alphabet, literacy and culture – the European physical society (EPS) honored the memory of the great Bulgarian physicist Georgi Nadjakov and designated its office in the Institute of Solid State Physics of the Bulgarian Academy of Sciences as a historic place belonging to the scientific and cultural heritage of the old continent. This is an international recognition not only of Bulgarian physics but of Bulgarian science as a whole.

Acad. Alexander Petrov was elected president of the Balkan Physical Union (BPU)

The IX International conference of the BPU took place on August 24 to 27 in Istanbul, where more than 700 scientist, teachers and students from all member states took part. During the conference the Council of the BPU elected a new governing body headed by acad. A. Petrov with a 3 year mandate.

Membership in international organizations

1. The UPB was designated a national representative of Bulgaria in IUVSTA (Intrnational Union for Vacuum Science, Technology and Application) at its Congress in Korea in 2016. Our compatriot Prof. Ivan Petrov is currently president of the American Vacuum Society and secretary of IUVSTA.

2. European Meteorological Society (EMS) has 37 national or regional members – two if those are from Bulgaria: Bulgarian Meteorological Society and Bulgarian Aviometeo Club. In 2015 they jointly organized the annual EMS&ECAM meeting with more than 490 scientists from over 40 countries.

3. 39-year old Bulgarian Prof. Tenio Popmintchev is among the ten most promising young scientists for 2016.

The rating is done by authoritative magazine “Science News” (Vol. 190, No. 7, October 1, 2016). The scientists under the age of 40 who are expected to make great contributions were nominated by Nobel Prize winners or by newly elected members of the US National Academy of Sciences.

NATIONAL AWARDS AND HONORS

1. Prof. T. Popmintchev was awarded the **presidential Badge of Honour** in May 2016 for his “exceptional scientific discovery and contribution to the development of science and technology and for promoting the image of Bulgaria worldwide”. The Sofia University graduate prof. Popmintchev has created the first of its kind “desktop” X-ray laser which allows us to “glimpse” into the fastest processes in atoms and to use it in biological and physical experiments. He is working on setting up of a Photonic Centre for nano and biotechnologies in Sofia.

2. “PYTHAGORAS” AWARDS FOR SUBSTANTIAL CONTRIBUTION TO THE DEVELOPMENT OF SCIENCE

2.1 In 2016 the Big Prize for

"Lifelong contribution to the development of science" was awarded to the physicist Acad. Peter Kralchevski, hwo has made essential and original contributions in the field of physical chemistry and colloids. He is an author of 197 publications with an impact in the international scientific literature.

2.2 In 2016 the Special Award for significant contribution of a Bulgarian scientist working abroad went to Prof. T. Popmintchev who was a team leader in the Joint Institute for Laboratory Astrophysics in Colorado, USA for his discoveries in quantum physics.

2.3 During the award ceremony Sofia University "St. Kliment Ohridski" received a citation from one of the leaders in scientometrics Thomson Reuters for the best performing Bulgarian institution in physics.

2.4 In 2015 Prof. Stoicho Yazadjiev from the Department of Physics of Sofia University received "PYTHAGORAS" for "Recognized researcher in natural sciences and mathematics". His activities are focused on General Theory of Relativity.

2.5 The same year Thomson Reuters Special Prize for publications with best "Essential Science Indicators for highly cited, top and hot papers" went to the Institute for Nuclear Research and Nuclear Energy at the Bulgarian Academy of Sciences.

2.6 The 2014 Young scientist "Pythagoras" award was shared by three nominees – one of them was Ass. Prof. Dr. Andon Rangelov from Department of Physics of Sofia University. His research is connected with finding analogues of quantum transitions in various branches of physics with applications in wireless transfer of energy.

2.7 In 2014, "Pythagoras" for "substantial interdisciplinary achievements" was awarded to Prof. Plamen Ivanov from the Institute of Solid State Physics of BAS. He is a pioneer in exploring systems of physiological organs as networks and has laid the foundations of a new direction called network physiology. His papers were published in very prestigious scientific journals. He was elected an honorary member of the American Physical Society and received the Harvard University Institute of biomedical research award for best researcher (2009–2010).

2.8 In 2013 Special "Phytagoras" prize for substantial contribution to natural sciences went to the leaders of two teams involved in the biggest scientific discovery of the 21-st century – the Higgs boson: Assoc. Prof. Dr. Leander Littov from Sofia University Department of Physics and Prof. Dr. Vladimir Genchev from the Institute for Nuclear Research and Nuclear Energy. The achievements of their teams received wide recognition at the highest level in CERN.

3. UNION OF SCIENTISTS IN BULGARIA COMPETITION

The annual completion for scientific excellence was won by:

3.1 In 2015 the physicist Corr. Member of BAS Angel Stefanov for his book "The riddles of the Universe and some reflections in dialogues" and five other papers in international journals.

3.2 In 2014 Assoc. Prof. Nickolay Minkov from Institute for Nuclear Research and Nuclear Energy of BAS for series of papers on deformed nuclei models, symmetries and fine structure of nuclear spectra.

4. BAS COMPETITION IN COMMEMORATION OF THE 145th ANNIVERSARY OF THE ACADEMY

The 2014 awards for scientific excellence went to:

4.1 Prof. Stefka Kartaleva et al. from the Institute of Electronics for their research in quantum optics and high definition laser spectroscopy based on nano and micro layers of alkaline metals vapors.

4.2 Assoc. Prof. Eugeny Semkov et al. from the Institute of Astronomy for their study of properties of newly formed stars.

5. MINISTRY OF EDUCATION AND SCIENCE DIPLOMAS AND PLAQUES

A number of research teams from BAS working on large (over 1 mil. BGN) projects within the seventh Framework programme of the European Union received diplomas and plaques from the Ministry of Education and Science:

- Team with project coordinator Acad. A. Petrov – Institute of Solid State Physics
- Teams from the National Institute for Meteorology and Hydrology lead by Prof. Dobri Dimitrov, Prof. Jordan Marinski, Prof. Veselin Aleksandrov, Assoc. Prof. Anna Korcheva, Assoc. Prof. Georgi Korchev, Assoc. Prof. Emilia Georgieva.
- Team lead by Prof. Peter Getsov and Dr. Alexei Stoev from the Institute for Space Research and Technology.

6. PHYSICISTS HONOURED BY BAS

6.1 Corr. members Chavdar Stoianov, Peter Atanasov, Prof. Petko Vitanov received the highest academy award “Marin Drinov with ribbon”.

6.2 Assoc. Prof. Lachezar Kostov, Prof. Rumen Kakanakov, Prof. Ekaterina Bachvarova and Prof. Veselin Kovachev (posthumously) received a Badge of Honor for Merit.

7. EVRIKA FOUNDATION GEORGI NADJAKOV SCOLARSHIP FOR ACADEMIC EXCELLENCE

The following students from the Sofia University Department of Physics received Georgi Nadvakov scholarship for their excellent academic record: Stanislav Hadjiski (2013-2014), Kalojan Genkov and Stanislav Hadjiski (2014-2015), Chavdar Dutzov (2015-2016).

8. BULGARIAN TRACE IN 2014 NOBEL PRIZE IN PHYSICS

Prof. Evgenia Valcheva from the Sofia University Department of Physics is a co-author with the Nobel Prize winners Acasaki and Amano in 13 papers connected with their discovery. Prof. Boris Petko Arnaudov from the same department was also very instrumental in the research that lead to the Nobel prize.

9. ACAD. ALEXANDER PETROV OPENS A PRESTIGIOUS SYMPOSIUM IN NIELS BOHR INSTITUTE IN COPENHAGEN

In august 2016 Acad. Petrov delivered the opening lecture of the First symposium on physics of exited membranes – "Bioflexoelectricity": an active interface between cell and ambient environment". The lecture is a summary of the discovery and explanation of a new phenomenon in electromechanical properties of biological membranes.

The conclusion of our review is that the UPB and Bulgarian physicists in general have achieved something to be proud of. Within a period of three years only at a time of an economic crisis, the enthusiasm and devotion of the scientific community bought about some remarkable results with a worldwide recognition. These results make us believe that there is a promising future before the Bulgarian physics.

ЖАЛОНИ НА БЪЛГАРСКАТА ФИЗИКА СЛЕД ВТОРИЯ КОНГРЕС ПО ФИЗИЧЕСКИ НАУКИ

Александър Г. Петров[1], Ана Георгиева[2], Пенка Лазарова[3]

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[2]зам.-председател
[3]член на УС

Резюме. *Статията представя доклад от откриването на III Национален конгрес по физически науки. В нея са представени серия успехи на български физици, научни колективи и организации през 3-годишния период след предходния конгрес. Тези постижения са забелязани и признати от национални и международни физични общества и съответните награди и отличия са присъдени от най-високи държавни институции, неправителствени и научни организации. Изтъкната е ролята на Съюза на физиците в България за подкрепата в изграждането на устойчиво и активно сътрудничество на национално и международно ниво в сферата на съвременните физически науки и образование. Отбелязаните постижения и международното сътрудничество на българските учени формират жалоните и бъдещата перспектива в развитието на физическите науки в България.*

MADE IN BULGARIA WITH EUROPEAN SUPPORT

INNOVATIVE NANOSTRUCTURED AND MULTILAYER MATERIALS FOR ADVANCED APPLICATIONS OBTAINED BY PVD TECHNIQUES

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Abstract. *The achievements of the researchers at the Central Laboratory of Applied Physics (CLAP), the Bulgarian Academy of Sciences, in the field of material science are presented by two recently developed advanced coatings, a TiAlSiN gradient nanocomposite coating and a low temperature deposited TiAlN multilayer coating. The coatings were developed, studied and adapt for technological transfer in the Centre for high technologies to CLAP, which was created and upgraded in the frames of two European and three national projects. The deposition technologies were optimized in respect to the structure and composition, which presume the mechanical and tribological properties required by the intended applications. Moreover, both coatings were successfully transferred in the innovative companies.Thus, in this article the realized relation research – development – industrial transfer done by the scientists at CLAP is illustrated.*

I. Introduction

The modern industry poses increased requirements to the mechanical and tribological properties, wear and corrosion resistance of the used materials.

The surface engineering is an advanced method allowing improvement of the material properties or achievement of quite new ones. Recently, the deposition of coatings with definite properties is recognized as a perspective approach for the surface modification. The coating composition and structure might significantly differ from these of the surface. Thus, completely new surface properties could be achieved, which is impossible with other methods. The surface engineering by coating deposition extensively stimulates the development of new materials with applications in the machining industry, automotive and aircraft industry, for implants and prostheses etc. Among the available technologies, PVD methods are widely applied techniques for deposition of coating variety such as monolayers, multilayers, gradient layers, and nanocomposites. Deposition of these coatings enhances the main surface parameters as hardness, wear resistance, corrosion resistance, and thermal stability.

The development of new coatings and deposition technologies, as well as the research and an innovative transfer of hard and superhard wear resistant coatings are the main activity at the Central Laboratory of Applied Physics. This scientific field was created and developed in the frames of two European and three national projects. The modern scientific infrastructure was built on the finances of these projects. It comprises multifunctional equipment for investigation of the mechanical and tribological properties of the coatings and completely automated high technological systems for coating deposition by both most perspective physical vapor deposition (PVD) techniques, cathodic arc evaporation and unbalanced magnetron sputtering in a close magnetic field. Last years many types of coatings intended for different applications were developed, studied and transferred by the CLAP's researchers.

In this article, the relationship between the scientific studies, innovative activities and industrial transfer is illustrated by two developed at CLAP coatings, a TiAlSiN gradient nanocomposite coating [1, 2] and a multilayer TiAlN coating [3].

II. TiAlSiN gradient nanocomposite coating

At present, the coatings, mostly applied as protective on metal-cutting tools, dies or presses, are based on nitrides of transition metals, and especially TiN and $Ti_xAl_{1-x}N$ [4–6]. The hardness of these coatings does not exceed 20 - 25 GPa and decreases rapidly when exposed at temperatures over 500 ^oC. Multicomponent coatings based on different metallic and nonmetallic elements have provided the benefit of individual components leading to a further improvement of coating properties. However, they cannot provide the coating features which could response to the needs of the modern industry. Nanocomposites have been developed as an alternative to binary and ternary phase materials, allowing for an increase to the hardness up to 70 GPa and an improvement of the thermal stability over 800 ^oC. Nanocomposite coatings being a next generation of multifunctional coatings with superhardness over 40 GPa at high temperatures, a low coefficient of friction, corrosion and wear resistance, are intensively developed and studied. These properties are achieved due to the specific coating structure, consisting of two immiscible phases, a nanocrystalline phase which is incorporated in a matrix phase. The nanocrystalline phase is formed by binary and ternary systems of nanocrystalline grains of nitrides, carbides, borides, oxides and silicides of the transition metals. The matrix phase can be either nanocrystalline (hard/hard structure) or amorphous (hard/soft structure) [7, 8]. The main part of the nanocomposites is formed of hard nitrides of transition metals with an optimal content of Si_3N_4 [7-12].

The TiAlSiN gradient nanocomposite coating was obtained by a cathodic arc evaporation technique where an electric arc is used to vaporize material from a cathode target.

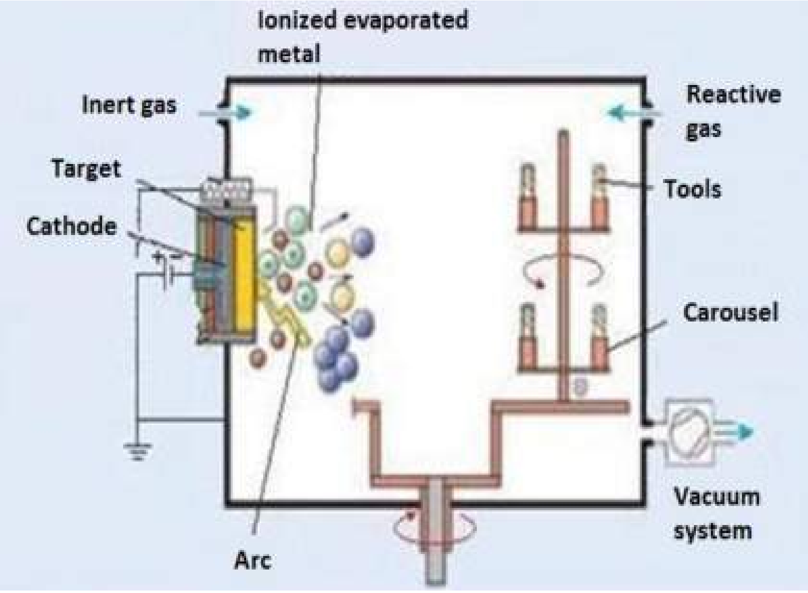

Fig. 1. A principal scheme of the cathodic arc evaporation process.

The vaporized material then condenses on a substrate, forming a thin film (Fig. 1). The cathodic arc deposition (CAD) technology for the TiAlSiN gradient nanocomposite coating was developed in the high technological equipment Platit π80+ (Platit AG, Switzerland) (Fig. 2). The machine is equipped with an innovative Lateral Arc Rotating Cathodes (LARC®) system (Fig. 2b), which allows enlarging and continuous refreshing the target surface during evaporation. Thus, the LARC® technology ensures the minimization of macroparticles generation during evaporation, and consequently significantly improves the coating structure and quality [13-15]. The three axis planetary system contributes to uniformity of the coating thickness. The contact layer, gradient and nanocomposite layers were obtained using titanium and Al+(18 wt.%)Si alloy LARC® cathodes in nitrogen ambient at a pressure of 9.0×10^{-3} mbar to 4.0×10^{-2} mbar depending on the required composition of an each nanolayer; the base pressure being lower than 5×10^{-6} mbar. The deposited gradient coating structure with a total thickness of 3.0 μm consists of consecutively deposited adhesion Ti, gradient TiN and Ti–Al–Si–N layers and a nanocomposite TiAlSiN layer. The X-ray diffraction (XRD) analysis of the developed coating revealed that it had a typical nanocomposite structure formed by TiN and AlN nanocrystals, which were incorporated in an amorphous matrix (Fig. 3). This structure was confirmed by the measurements performed on a 100 kV JEOL100CX

Fig. 2. Images of the common view of the Platit π80$^+$ equipment (a); LARC® cathodes (b) and a loaded chamber (c).

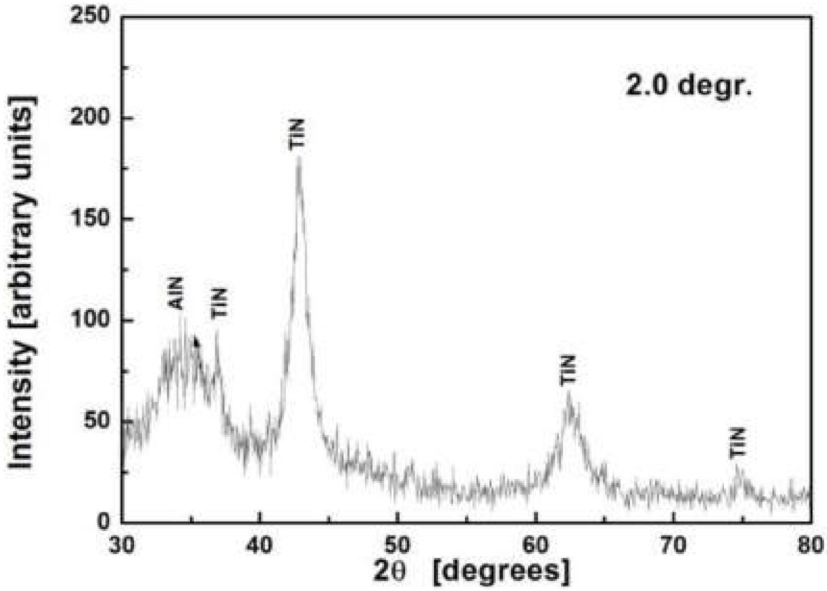

Fig. 3. XRD spectra of a TiAlSiN nanocomposite coating on a HSS substrate obtained at incidence angles of 2.0 degrees.

Transmission Electron Microscopy (TEM) (Fig. 4). The corresponding dark field (DF) image (Fig. 4a) shows a nanometer scale grain size. After measuring several of the as appearing crystals in the dark field image their average size was found to be 5-8 nm. From the corresponding diffraction pattern (ED) (Fig. 4b) two different phases were identified. Each of the rings corresponds to different Bragg reflections, i.e. different compounds. The identification of the rings revealed that the nanograins are (111), (200), (220) and (222) TiN Bragg reflections with fcc cubic structure and (100), (002), (110), (200) and (202) AlN Bragg reflections with hcp type structure (Fig. 4b) [16]. Rings corresponding to Si_3N_4 were not observed suggesting that either Si substituted Al/Ti in the AlN/TiN nano-crystallites, or that amorphous Si–N accumulated at the AlN/TiN nano-crystallite grain boundaries [17].

XPS depth analysis detected the binding energies corresponding to the Ti-N and Al-N bonds, which confirms the nanograin composition presumed by XRD and TEM measurements. The presence of an amorphous matrix was

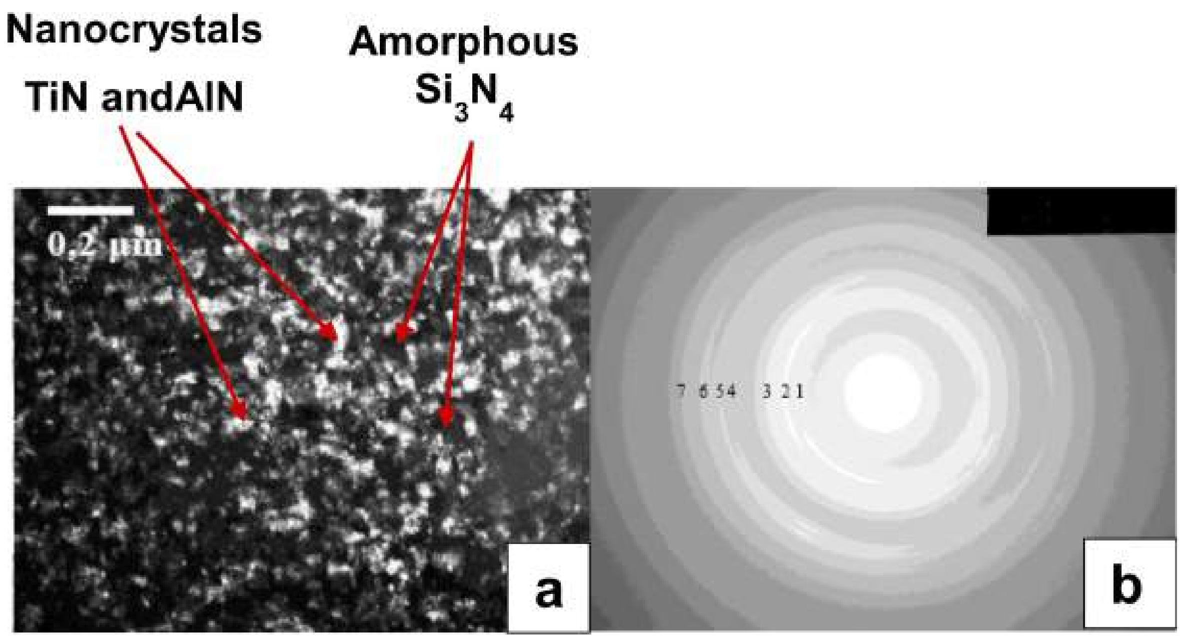

Fig. 4. TEM micrograph of the coating (a) and the corresponding diffraction pattern (b).

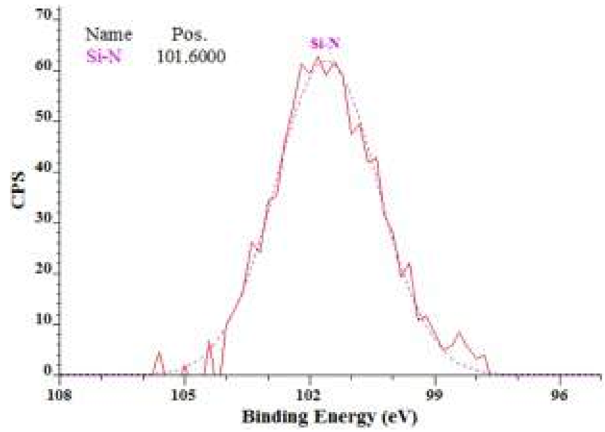

Fig. 5. XPS spectra of the Si 2*p* peak in the TiAlSiN nanocomposite coating.

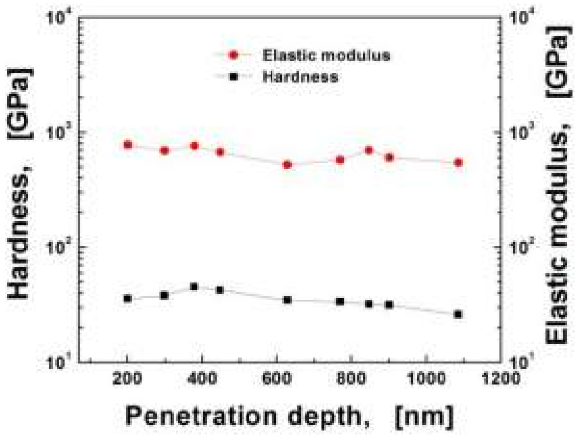

Fig. 6. Dependence of the nanohardness and elastic modulus on the penetration depth.

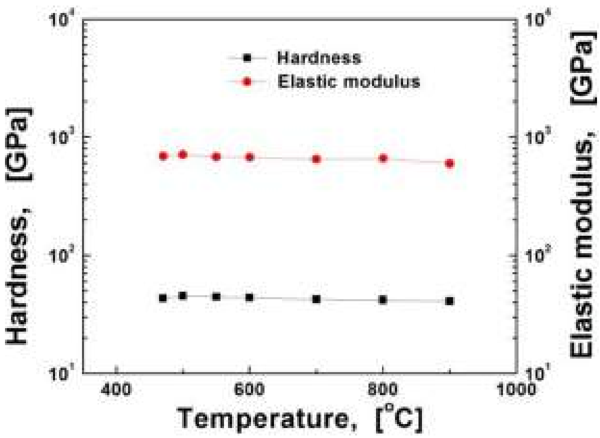

Fig. 7. Dependence of the coating hardness and elastic modulus on the heating temperature in air.

proved by the peak position of the Si2p spectrum at 101.6 eV which should associate with the Si_3N_4 compound (Fig. 5.) [18]. The Electron Dispersive Spectroscopy (EDS) revealed that the coating composition could be considered stoichiometric. Based on the EDS element analysis, the coating composition $Ti_{0.45}Al_{0.43}Si_{0.09}N_{1.02}$ was determined.

The nanocomposite structure and a high Si amount of the developed TiAlSiN nanocomposite coating result in improved mechanical and tribological properties. The Depth Indentation Sensing method at nanometer length scales [19] was applied and the Oliver & Pharr model was used to determine the coating hardness in the loading range from 30 mN to 500 mN. The dependence of the coating hardness on the penetration depth, loading respectively, presented in Fig. 6 implies that the coating is superhard. The maximum hardness of 45 GPa was determined at penetration depth lower than 400 nm, which implies that the influence of the substrate could be ignored. With an increase of the penetration depth the hardness decreases slightly but it remains higher 40 GPa up to 600 nm of penetration. After that it decreases smoothly due to the increased influence of the substrate. It should be notted that all of the measured load/displacement curves (of the as-deposited and heated samples) are smooth and have not features which could suppose any surface demages during indentation such as cracking, chipping or delamination. This is an indirect evidence for the good mehanical properties and adhesion of the coating developed.

The developed coating demonstrated excellent thermal stability at temperatures as high as 900 °C. Fig. 7 presents the coating behaviour during the thermal treatment at temperatures ranging from 500 °C to 900 °C in air for 6 hours at each temperature. Because the coating deposition temperature is 470 °C, the hardness after heating at 500 °C did not differ notably from this one measured for the as-deposited coating. Increase of the heating temperature up to 700 °C causes negligible decrease of the hardness and after this temperature no significant changes were observed. This effect is attributed to the oxidation of the coating surface. When the oxide thickness reached a certain value, it started to act as a mask for further oxidation and the hardness was stabilised.

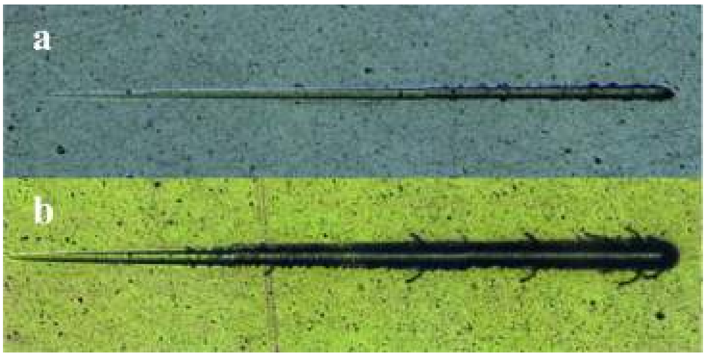

Fig. 8. Scratch tracks of: (a) as-deposited sample; (b) sample heated at 900 °C.

The friction coefficien and adherence strength of the gradient TiAlSiN nanocomposites were examend by a scratch test performed on as-deposited sampleas and after each heating at temperatures of 500 °C, 600 °C, 700 °C, 800 °C, and 900 °C. Different types of adhesive layer/substrate failures are possible under strong plastic deformation conditions depending on the heating temperature. The optical images of scratch tracks of the as-deposited and heated at 900 °C samples measured at a load progressive increasing from 1 N to 30 N, are shown in Fig. 8. No failures in the coating were found in both samples. In this track region a friction coefficient of 0.07 and 0.06 was determined for the as-deposited and heated at 900 °C coatings, respectively. Besides, no delamination of the coating was observed.

III. Low temperature deposited TiAlN multilayer coating

TiAlN coatings have been developed as an alternative to TiN to overcome its shortcoming of instability at high temperatures. A fundamental advantage of TiAlN films is that during heating they demonstrate high oxidation resistance up to 800 °C. Over this temperature they form a highly adhesive, dense protective Al_2O_3 film on the surface preventing further inward diffusion of oxygen into the coated material [20]. Furthermore, these films have enhanced hardness (30–35 GPa) and higher corrosion resistance [20-25]. It is known that protective hard TiAlN coatings are generally deposited at temperatures of 400-500 °C which provide high adhesion of the coatings to the substrate, but could lead to structural changes and worsen the substrate material properties. Thus, some instrumental materials such as carbon tool steel (U12) have low thermal resistance (≤ 200 °C), which requires low-temperature deposition of the coatings to protect the instruments from overheating. The requirement for a low temperature during deposition of the TiAlN coatings complicates the technological process. Hence, the establishment of optimal technological regimes providing stable and high functional properties of the system “tool-coating” is necessary.

The TiAlN multilayer coating was obtained by closed-field unbalanced magnetron sputtering (CFUBMS) technique in high technological equipment UDP 850-4 (Teer Coatings Ltd., UK).

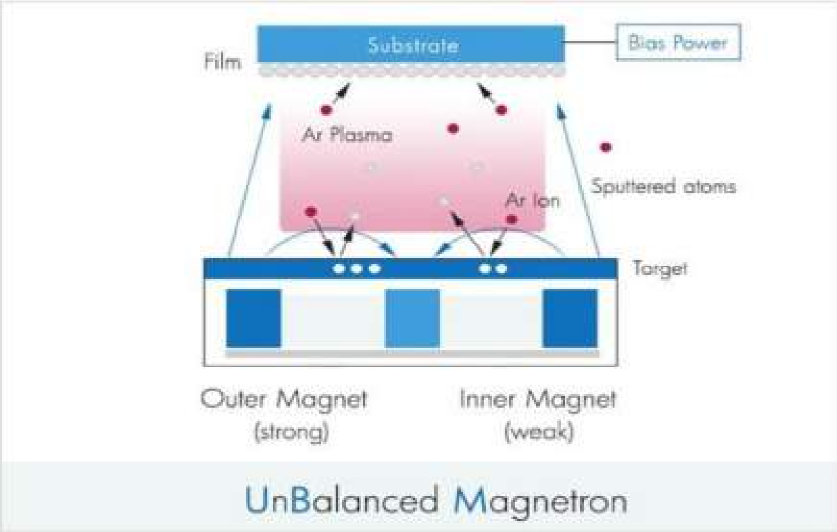

Fig. 9. A scheme of the UBMS process.

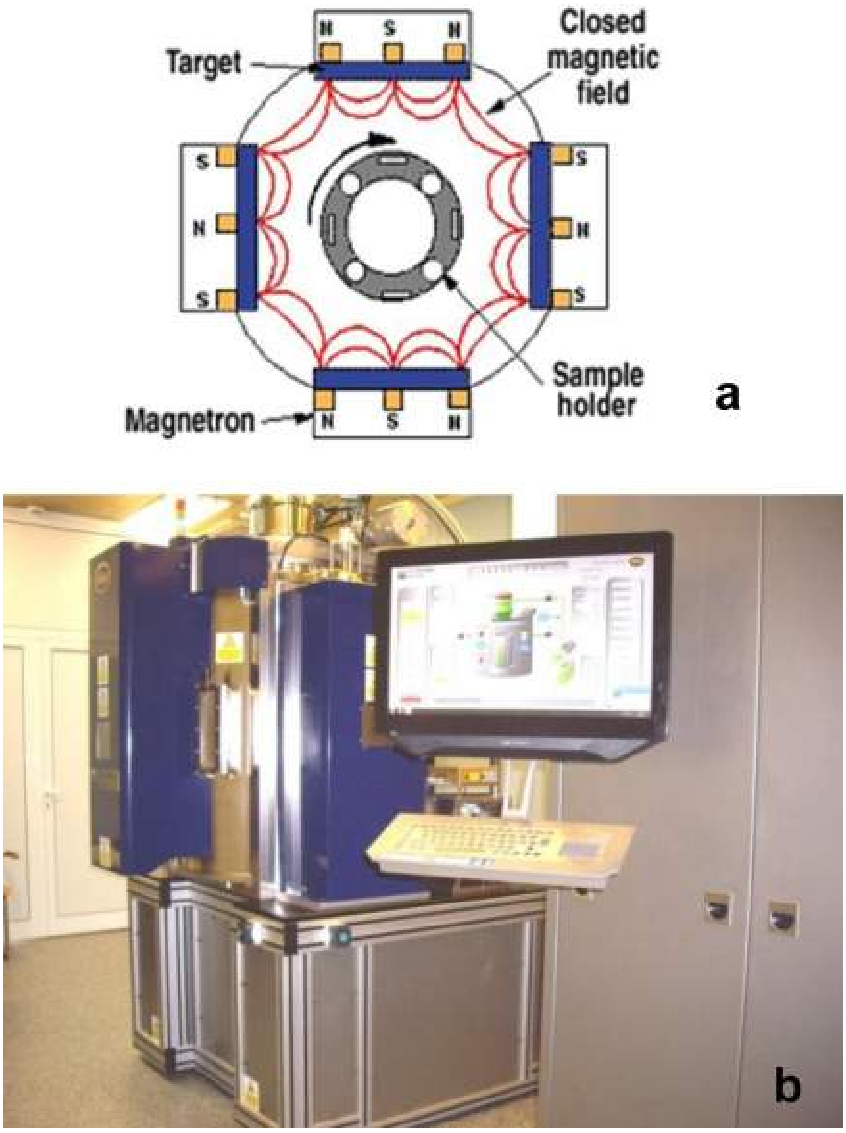

Fig. 10. A scheme of the equipment chamber (a) and a photo of the equipment UDP-850 (b).

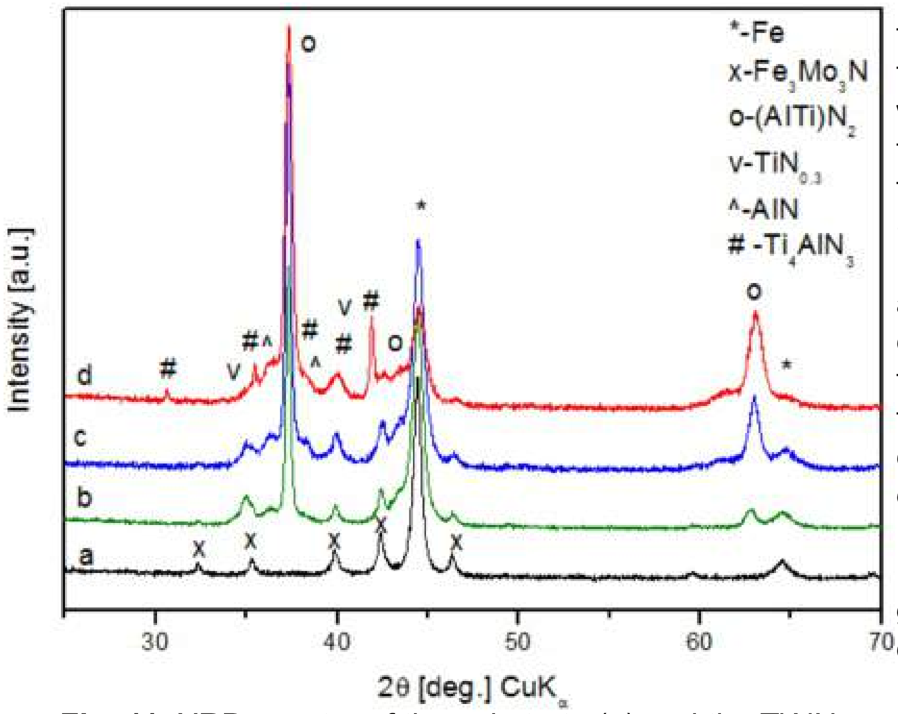

Fig. 11. XRD spectra of the substrate (a) and the TiAlN multilayer coating at incidence angles of 90° (b), 10° (c) and 5° (d).

CFUBMS (or UBMS) is an exceptionally versatile technique, suitable for the deposition of high-quality, well-adhered films of a wide range of materials at commercially useful rates. An unbalanced magnetron possesses stronger magnets on the outside resulting in the expansion of the plasma away from the surface of the target towards the substrate. The effect of the unbalanced magnetic field is to trap fast moving secondary electrons that escape from the target surface. These electrons undergo ionizing collisions with neutral gas atoms away from the target surface and produce a greater number of ions and further electrons in the region of the substrate considerably increasing the substrate ion bombardment. Effectively secondary plasma is formed in the region of the substrate. When a negative bias is applied to the substrate, ions from this secondary plasma are accelerated to the substrate and bombard it. This ion bombardment is used to control the many properties of the growing film (Fig. 9). The multilayer TiAlN coating was deposited at a temperature of 200 °C from two titanium (99,99 %) and two aluminium (99,99 %) rectangular targets in a closed-field configuration (Fig. 10). Prior to the deposition, the vacuum chamber was evacuated to a base pressure of 5×10^{-6} mbar. Two extra purity gases were used in the deposition process, an inert Ar with a flow rate of 25 sccm controlled by a mass flow controller, and a reactive N_2, which flow was controlled by an Optical Emission Monochromator (OEM). The deposition of the multilayer TiAlN coating started with a Ti adhesion layer of 100 nm, which was followed by two TiN interlayers, graded and stoichiometric, with a total thickness of 250 nm. After that the Al content was increased gradually forming a graded TiAlN transition layer. The structure was completed with a TiAlN layer. Graded interfaces are routinely formed to ensure the minimisation of the stress induced at the coating - substrate interface. The total thickness of the coating was 1.8 µm. All the films were deposited at a bias voltage of -70 V, a pulsed regime of the Al cathodes and DC regime of the Ti ones.

In contrast to the nanocomposites, the TiAlN multilayer coating grows in a columnar structure. This structure be due to the low deposition temperature and an absence of Si contamination in the coating composition. The XRD analysis revealed that the coating itself comprises mainly the $(AlTi)N_2$ phase,

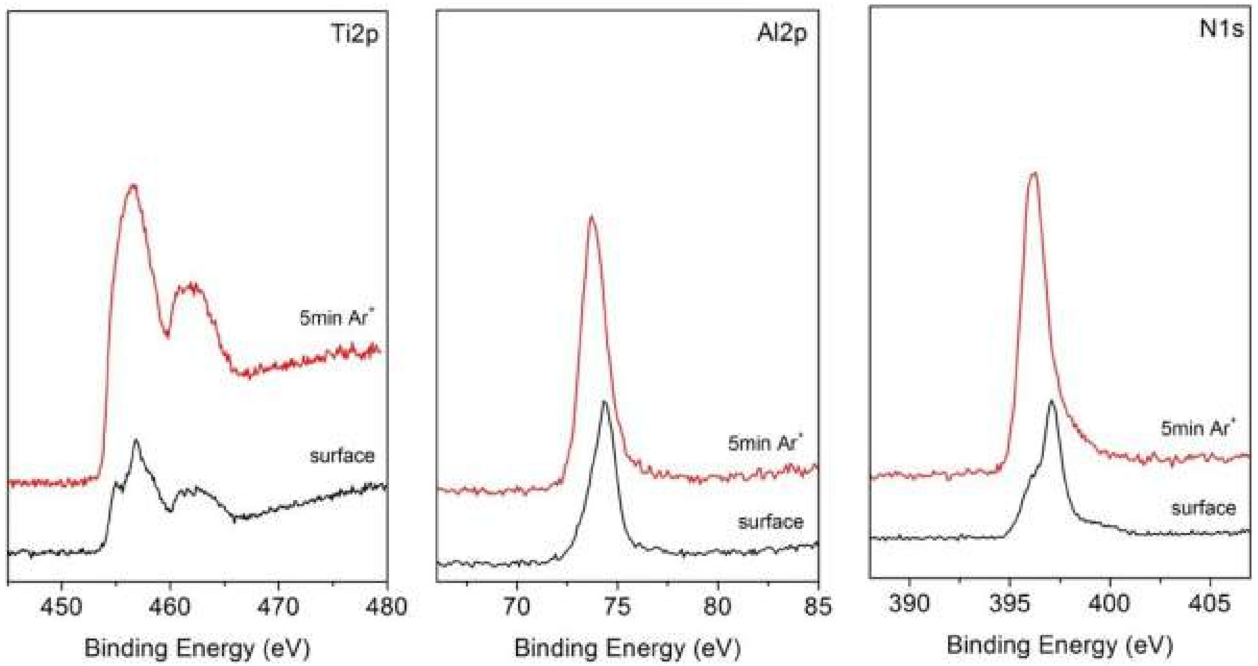

Fig. 12. XPS spectra of the TiAlN coating measured on the surface and in the coating depth after 5 min etching.

which crystallizes in the cubic Fm-3m space group with an unit cell parameter a= 4.175 Å close to the value 4.172 Å given in ICDDPDF2 #71-5864. The mean crystallite size of the $(AlTi)N_2$ phase was 44 nm. The spectrum measured at a lowest incidence angle indicated the presence of $TiN_{0.3}$, AlN and Ti_4AlN_3 phasses as local contaminations of the coating layer (Fig. 11). The binding energies of the Ti2p, Al2p and N1s peaks as determined by XPS analysis are assigned to Ti-N and Al-N chemical bonding state within the coating [26] (Fig. 12). The concentrations of titanium, aluminium and nitrogen in the coating calculated from the XPS spectra were 24,1 at.%, 33,2 at.% and 42,7 at.%, respectively, presuming the coating composition $Ti_{0.24}Al_{0.33}N_{0.43}$.

Despite the columnar structure, the developed TiAlN multilayer coating demonstrated very good mechanical properties. Values of 38 GPa and 418 GPa were determined for the coating hardness and elastic modulus, respectively. It should be noted that the achieved hardness is very close to the superhardness and extremely high for the low temperature deposited coatings with a columnar structure. Besides the valuable hardness, the TiAlN multilayer coating showed a perfect adhesion to the substrate and a friction coefficient as low as 0.09. As can be seen in Fig. 13 no cracks, cheeping and delamination were detected within the whole loading interval of the scratch track.

Fig. 13. A scratch track in the TiAlN coating at loading in the interval 1-10 N.

IV. Conclusion

CAD and UBMS technologies were developed for deposition of the TiAlSiN gradient nanocomposite coating and a multilayer TiAlN coating, respectively. The deposition techniques were selected based on the requirements to the coating properties determined by the intended application. For instance, the enlargement of the life-time of the tools used in the machining industry demands of enhanced hardness, a low friction coefficient and thermal stability. The TiAlSiN nanocomposite coating was developed to response these needs. Because the nanocomposite structure forms at high temperatures, these coatings are deposited on tools of high temperature materials such as stainless steel, tungsten carbide etc. However, for some applications low-temperature materials are used. Therefore a special UBMS technology for low-temperature deposition of the multilayer TiAlN coating was developed.

The detailed study of the structure and composition of both coatings enabled explaining their mechanical and tribological properties. Moreover, based on the results from these investigations the developed technologies were optimized, which allowed the realization of the transfer to the industry. Fig. 14 presents different applications of the TiAlSIN nanocomposite coating currently used in several industrial companies.

Fig 14. Industrial tools with a TiAlSiN nanocomposite coating deposited at CLAP.

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ИНОВАТИВНИ НАНОСТРУКТУРИРАНИ И МНОГОСЛОЙНИ МАТЕРИАЛИ С МНОГОФУНКЦИОНАЛНИ ПРИЛОЖЕНИЯ, ПОЛУЧЕНИ ЧРЕЗ PVD ТЕХНИКИ

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Резюме. *Постиженията на учените в Централната лаборатория по приложна физика при Българската академия на науките (ЦЛПФ) в сферата на материалознанието са представени чрез две новоразработени и усъвършенствани покрития: TiAlSiN градиентно нанокомпозитно покритие и нискотемпературно TiAlN многослойно покритие. Покритията са разработени, проучени и адаптирани за технологичен трансфер в Центъра за върхови технологии към ЦЛПФ, който е създаден и модернизиран в рамките на два европейски и три национални проекта. Технологиите на отлагане са оптимизирани по отношение на структурата и състава, които определят механичните и трибологични свойства, изисквани от предвижданите приложения. Освен това, двете покрития са трансферирани в иновативни компании. В статията е илюстрирана осъществената от учените в ЦЛПФ връзка научни изследвания – развойна дейност – индустриален трансфер.*

EQUAL IN EUROPEAN RESEARCH AREA

AWARDS

PYTHAGORAS AWARDS ‘2016 FOR SIGNIFICANT CONTRIBUTIONS TO SCIENCE*

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Under the motto of Pythagoras’s thought that ***science is the love of wisdom and the yearning to reach the truth*** has passed the 8th official ceremony of handing the Pythagoras awards ‘2016 for significant contributions to science in the period of 2013 – 2015 to individual scientists, research teams and organizations.

The ceremony, which was held on May 19, 2016 in Sheraton Sofia Hotel Balkan, was opened by the Deputy Prime Minister and Minister of Education and Science Ms. Meglena Kuneva. She expressed confidence that the phrase “And we have also given something to the world” (from the Ivan Vazov’s *Epic of the Forgotten*) can be filled with new content. In the globalized world in which we live, we need of advanced knowledge and technology to overcome the growing social and economic challenges. Minister Kuneva said, that for the finding of solutions politicians must rely on science and expresses her hope among this year’s laureates of the highest Bulgarian science award “to be the next Nobel laureate”.

Just before announcement of the awards the authoritative jury was presented. It was composed by holders of the Pythagoras awards in 2015, as follows: Assoc. Prof. Milen Geor-

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giev, Ph.D., from the Institute of Microbiology at the Bulgarian Academy of Sciences (BAS) – chairman, and members: Assoc. Prof. Georgi Yordanov, Ph.D., from the Faculty of Chemistry and Pharmacy at the Sofia University “St. Kliment Ohridski”; Prof. Dorotey Getov, Ph.D., from the Institute of literature at the BAS; Prof. D.Sc. Galya Angelova, head of section “Linguistic Modelling” in the Institute of Information and Communication Technologies at the BAS; Prof. D.Sc. Stoycho Yazadzhiev from the Department of Theoretical physics in the Faculty of Physics at the Sofia University “St. Kliment Ohridski”; Assoc. Prof. Neli Koseva, Ph.D., Director of the Institute of Polymers at the BAS; Assoc. Prof. Dr. med. Radka Kaneva, Ph.D., head of Molecular Medicine Center in the Medical University – Sofia.

For this year’s Pythagoras awards, based on scientometric indicators – publications and citations in the period of 2013 – 2015, represented in the international databases of Web of Science and Scopus – over 47 scientists from higher educational institutions in Bulgaria and abroad have been nominated. Three new categories of the awards have been established, as follows: (1) for research team with a successful exploitation and commercialization of scientific results, (2) for scientific book and (3) for a company that most invests in research. This year “Grand Prize for successful manager of international projects” and “Prize for popular science book for children” have not been handed.

The Deputy Prime Minister and Minister of Education and Science Ms. Meglena Kuneva awarded the **Big Prize for Lifetime Achievement in the Development of Science**, restored this year, to two eminent scientists: Academician Peter Kralchevski and Corresponding Member of BAS Elka Bakalova-Lazarova. Each of them received money prize of 5000 BGN.

Academician Peter Kralchevski works in the field of Physical and Colloid Chemistry. He is holder of high awards of the Sofia University “St. Kliment Ohridski”, the BAS and the Ministry of Education and Science. Acad. Kralchevski is vice chairman of European COST action for application of colloidal chemistry in nanotechnologies and secretary of the European Colloid and Interface Society. He is author of 197 papers, which has found a wide resonance in the international scientific literature. In the period of 2013 – 2015 he is head of 14 industrial projects, whose outcomes are used to development of industrial designs and products. Acad. Kralchevski has significant and original contributions to physical chemistry of liquid surfaces, as well as to mechanics and thermodynamics of distorted interphase borders and membranes taking into account the presence of surface moments.

Corresponding member Elka Bakalova-Lazarova dedicated all of her scientific, teaching and public activity to the research of medieval Byzantine and Bulgarian art and the protection of cultural monuments of that period. She is the author of 198 publications cited over 500 times in national and international issues. Corresponding member Bakalova-Lazarova holds the Honorary Sign of BAS "Marin Drinov" for outstanding contribution to the humanities. She is an expert of ICOMOS on the UNESCO for more than 10 years and performs missions related to the inclusion of important monasteries in the List of World Heritage. She also has recognized contribution to the development of the Bulgarian medieval art on modern methodological foundations.

Academician Stefan Vodenicharov, Chairman of the BAS, handed Pythagoras statuette and money prize of 10 000 BGN in the category BIG PYTHAGORAS AWARD FOR YOUNG SCHOLAR to Assist. Prof. Antonia Toncheva, Ph.D. and expressed his satisfaction that young scientists from the BAS continue the traditions of their teachers.

Assistant Professor Antonia Toncheva, Ph.D., works on implementation-oriented research in the Laboratory of "Biologically active polymers" at the Institute of Polymers – BAS. In the last three years her studies are focused on the manufacturing of micro- and nanofibrous of biocompatible material and absorbable polymers for use in medicine and pharmacy. She has specialized in the Laboratory of Polymer and Composite Materials at the University of Mons, Belgium, within the program BEWARE Fellowships Academia, funded by Horizon 2020, Program Marie Skłodowska-Curie actions. In the period 2013 – 2015 she has 9 scientific publications in international journals with impact factor and more than 90 citations. She participated in numerous national and international scientific projects and forums with oral presentations and posters or as invited presenter. She was awarded the prize "Prof. Ivan Shopov" for prominent young scholar in the field of polymers by the Union of Chemists in Bulgaria. Assist. Prof. Toncheva is member of the team headed by Corresponding Member of BAS Iliya Rashkov, which received in 2014 the prize for creation of new generation micro- and nanostructures polymeric materials through development of the advanced technology of "electrospinning"; this award was handed in a contest for excellence of scientists and collectives, dedicated to the 145th anniversary of the BAS.

Professor Luben Totev, Ph.D., Rector of the University of Mining and Geology "St. Ivan Rilski" and Chairman of the Board of Rectors of the higher education institutions in Bulgaria, handed the PYTHAGORAS AWARD FOR ESTABLISHED SCHOLAR IN THE FIELD OF NATURAL AND ENGINEERING SCIENCES to Professor D.Sc. Vladimir Bozhinov, Ph.D., head of Department "Organic synthesis and fuels" at the University of Chemical Technology and Metallurgy – Sofia. His researches are focused on the functional fluorescent compounds. Prof. Bozhinov held for the first time in Bulgaria studies related to the ability of molecules to perform logic operations in binary system. In the period 2013 – 2015 he has 20 publications in international journals with high impact factor, which are cited 838 times. In the last three years he led 5 projects with national and international significance. In 2014, on the First International Caparika Conference on Chromogenic and Emissive Materials, Caparika-Almada, Portugal, Prof. Bozhinov and his team are awarded first prize for the best work.

The PYTHAGORAS AWARD FOR ESTABLISHED SCHOLAR IN THE FIELD OF HEALTH AND MEDICAL SCIENCES was handed by Professor D.Sc. Venelin Enchev, Chairman of the Union of the Scientists in Bulgaria, to Professor D.Sc. Ivailo Tournev and Professor D.Sc. Irini Doychinova.

Professor D.Sc. Ivailo Tournev, Ph.D., for the first time in the world described two new hereditary diseases – autosomal dominant spinal muscular atrophy and a new form of autosomal dominant "Cone-rod" dystrophy. He creates and manages the Expert Centre for Hereditary Neurological and Metabolic Diseases at the Alexandrovska Hospital in Sofia. In the last three years he established cooperation with a number of international authoritative scientific institutions; introduces and carries out selective screening programs for rare diseases; creates Bulgarian school for clinical neurogenetics and raises the clinical neurogenetics in our country to European and Global level. He introduces and confirms the profession "Health Mediator" in Bulgaria and prepares medical staff from the Roma community. Currently, under his leadership work 195 health mediators in more than 110 municipalities in Bulgaria. Through organized by him preparatory courses and mentorship 106 Roma students are studying in medical universities. In the last three years he has 25 publications in international journals with high impact factor. He's also a winner of many prestigious awards, including "Gold Coin: Script" of the Council of the European Scientific and Cultural Community for significant contribution to the Bulgarian science.

Professor D.Sc. Irini Doychinova, Ph.D., is lecturer of physical chemistry and pharmacokinetics in the Pharmaceutical Faculty of the Medical University – Sofia. Her scientific interests are in the field of drug design, bioinformatics and computational chemistry and biology. Among her main contributions in the last three years are the designs of new structures active against tuberculosis and Alzheimer's disease, as well as the definition of major structural fragments and physicochemical properties, influencing the distribution and elimination of drugs. In the period of 2013 – 2015 Prof. Doychinova has 21 publications in foreign journals with impact factor. She is co-author of two textbooks and two monographic series. Prof. Doychinova also participates in numerous national and international research projects and is a member of the editorial boards of six foreign journals. In 2011 she was awarded the prize "Golden Panacea" for special contributions in realization of teaching, research and expert work in the medical and biological field.

Professor Ivan Dimov, Deputy Minister of Education and Science, handed the PYTHAGORAS AWARD FOR ESTABLISHED SCHOLAR IN THE FIELD OF HUMANITIES AND SOCIAL SCIENCES to **Professor D.Sc. Veselin Petrov**, from the Institute for Study of Societies and Knowledge at the BAS, Executive Director of the Board of the International Organization for process philosophy and co-founder of the European Organization for process philosophy. He received Pythagoras statuette and money prize of 5000 BGN.

Prof. Petrov is member of the editorial boards of two foreign scientific journals. For the last three years his main achievements are in the field of contemporary process ontology and its applications. His publications in the period 2013 – 2015 are the first comprehensive study of the process ontology in the Bulgarian literature and philosophy and one of the first monographic researches in the particular field of applied process ontology. The studies of Prof. Petrov are focused on the development of the theory of dynamic and process-relational ontology, on the philosophical sense of the idea, as well as on the application of these ontologies in philosophy itself and in different field of science.

Mr. Krasimir Kiryakov, Deputy Minister of Education and Science, handed the PYTHAGORAS AWARD FOR RESEARCH TEAM WITH SUCCESSFUL EXPLOITATION AND COM-

MERCIALIZATION OF SCIENTIFIC OUTPUTS to **Collective under the leadership of Associate Professor Georgi Nekhrizov, Ph.D.**, from the National Archaeological Institute with Museum at the BAS. The winners received a plaque and a money prize of 8000 BGN.

The collective headed by Assoc. Prof. Georgi Nekhrizov develops and successfully implements the project “Development of Archaeological Map of Bulgaria and Improvement of non-destructive research methods using Geographic Information Systems”. In connection with the assignation of new layouts of the municipalities in Bulgaria arises the need for providing updated information about localizations and characteristics of archaeological objects on their territory. Since 2013 the team of Assoc. Prof. Nekhrizov has prepared reports for 103 municipalities, which include detailed information for more than 7000 archaeological sites; so are provided conditions for effective conservation, research and future socialization of archaeological sites in Bulgaria. As a result of this project the municipalities receive data about localization, borders, chronology and type of all known archaeological sites on their territory.

THE PYTHAGORAS AWARD in the category “SCIENCE BOOK”, plaque and money prize of 1000 BGN, was handed by Mrs. Zlatina Karova, Director of the Directorate of Science at the Ministry of Education and Science, to **Associate Professor Alexander Kuymdzhiev, Ph.D.**, author of “The Murals in the Main Church of the Rila Monastery”, 720 pages, issued in 2015 by the Institute of Art Studies at the BAS. The book is fundamental research in which for first time is presented the history of the building and painting of the main church in the Rila Monastery. Studied are a lot of new documentary evidences, through which is restored the overall picture of events, surrounding the building and painting of the most representative monument of Bulgarian Revival art. The book contains a number of new hypotheses related to the monastery’s history from earlier centuries. Corrected are many errors and inaccuracies that received public distribution and create inaccurate picture of actual events in the monastery in the 19th century. The book has won competitions organized by the National Science Fund of the Ministry of Education and Science and by the program “Support for the book” of the Ministry of Culture.

An award for A COMPANY WITH MOST RESEARCH INVESTMENTS – plaque and money prize of 1000 BGN – was handed to **Comac Medical Ltd.**, founded in 1997 by Dr. Milen Vrabevski, owner and CEO. The company is specialized contract research organization in the field of clinical research and innovation in medicine, operating in 18 countries in Central and Eastern Europe and participant in project of "Horizon 2020" – the small and medium enterprises initiative. The award was handed by Mrs. Daniela Vezieva, Deputy Minister of the Ministry of Economy.

The Deputy Prime Minister Ms. Meglena Kuneva handed A SPECIAL AWARD FOR SIGNIFICANT CONTRIBUTION OF BULGARIAN SCIENTIST WORKING ABROAD – plaque and money prize of 5000 BGN – to Professor Tenio Popmintchev for his discoveries in the field of quantum physics.

Professor Tenio Popmintchev, Ph.D., is an established and leading expert in the field of attosecond quantum physics and extreme non-linear optics. He discovered and patented a new system for efficient coherent conversion of ultraviolet laser light in attosecond X-ray light, published in 2015 in the authoritative journal "Science". In the last years he is author of 12 papers, featured in prestigious international scientific journals as "Nature Photonics", "Physical Review Letters", "PNAS" etc. At the time of submission of applications for the award he has 73 peer-reviewed articles with more than 2600 citations. At the same time Prof. Popmintchev has presented five papers at international conferences, two presentations in highly selective conferences, a key presentation with essential significance for the modern science and one prestigious plenary report. The publications of Prof. Popmintchev in "Science" are cited as one of the fundamental motivations in the draft programs for the development of sources of coherent X-ray beam by scientific foundations and military departments in the United States and Europe (DARPA, MURI, NSSEFF).

Prof. Popmintchev, who heads a research team in the JILA Institute, Colorado, USA, said, that the excitement of returning to Bulgaria is bigger than the excitement from the arrival on the stage. He said also that he would like Bulgarian scholars and research teams to work with his findings and will be happy to work with Bulgarian students. He dedicated his award to his teacher Mr. Teodosi Teodosiev and to his lecturers in the Faculty of Physics at the University of Sofia.

This year for second time are handed awards for high performance in science by the partners of Bulgaria in scientometrics – the company THOMSON REUTERS and the scientific publisher ELSEVIER.

The award for scientific organization with highest number of scientific results in the past year, according to data from Web of Science, was awarded to “St. Kliment Ohridski” Sofia University.

The publisher Elsevier, which takes into account the number of publications of scientific organizations as shown in SCOPUS and follows the trend of significant growth in this indicator for the past five years, handed award for most successful research team to the University of Chemical Technology and Metallurgy – Sofia.

The awarding of the most prestigious awards for science in our country on the eve of May 24 – the feast of Bulgarian education and culture – is an act of homage and recognition to the Bulgarian scientists, but also – after the words of Deputy Minister Prof. Ivan Dimov – of hope that Bulgaria has a future. Let’s hope that among the winners of Pythagoras awards is a future Nobel laureate, as wished in her speech at the opening ceremony Minister Kuneva!

EVENTS

EUROPEAN CULTURAL AND HISTORICAL HERITAGE: THE 12-TH NATIONAL STUDENTS' SCIENTIFIC CONFERENCE IN PLOVDIV

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On May 28 and 29, 2016, the 12th National Students' Conference took place in the city of Plovdiv under the motto "European Cultural and Historical Heritage. It was organized by the Students' Club of History and Archaeology named after Prof. Velizar Velkov at the Department of History and Archaeology of the Faculty of Philosophy and History at the Paisii Hilendarski University of Plovdiv. The scientific forum for students and PhD candidates coincided with the twentieth anniversary of the foundation of the students' club. The young historians and archaeologists gathered in one of the largest and most beautiful houses in the Old Town of Plovdiv – the house of Veren Stambolyan also known as the "House of the Artists". It was provided by courtesy of the Ancient Plovdiv Municipality Institute.

The conference was opened by a welcoming speech by the Dean of the Faculty of Philosophy and History at the *Paisii Hilendarski* University of Plovdiv, Assoc. Prof. Krasimira Krastanova PhD. The official part also included award giving and other welcome addresses. The *Prof. Velizar Velkov* Students' Club of History and Archaeology, a student organization already well established in the field of the humanities, introduced a badge of honour to be awarded annually to people with serious achievements in their scientific fields and contribution to the development of the club's activity. The first winners of that award chosen were Assoc. Prof. Ivan Dzhambov PhD and Assoc. Prof. Georgi Mitrev PhD – Head of the History and Archaeology Department for many years and at present, the two of them also being the ideologists and founders of Prof. Velizar Velkov Students' Club of History and Archaeology.

The opening day, 28th May, coincided with Armenia's national holiday (the Day of the Republic). That is why we were especially honoured to have as our guest His Excellency Armen Sargsyan, Ambassador Extraordinary and Plenipotentiary of the Republic of Armenia in the Republic of Bulgaria. His Excellency greeted the participants in the forum and delivered a plenary report on the role and place of Armenia in the European cultural and historical heritage.

In relation to the 20th anniversary of *Prof. Velizar Velkov* Students' Club of History and Archaeology, a contest for secondary school students was organized in relation to writing an essay on the following subject: „Plovdiv as part of the history and culture of Europe". The contest's purpose was to encourage the studies of Local History and involve students in history. The reward fund provided by the Department of History and Archaeology included money awards and books. The student ranked first by the contest's evaluation panel was Mina Panayotova from the *Ivan Vazov* Foreign Language School, Plovdiv who was also granted the opportunity to read her essay before the audience of the opening. The second place was for Bozhidara Atanasova from *Acad. Kiril Popov* Secondary School of Mathematics, Plovdiv, and the third-ranked student was Mariya Shtarbeva from the National Secondary School of Commerce, Plovdiv. They all received honorary diplomas and their essays will be included in the collection of reports from the scientific conference.

The presentation of the collection book with results from the eleventh students' scientific conference held last year caused great excitement and each guest and participant received one copy of it. Many promising young scientists have had their first publications in the collections issued by *Prof. Velizar Velkov* Students' Club of History and Archaeology on a regular basis.

During the working sessions of the scientific forum, about 40 university students and PhD candidates presented their research. Among them, there were colleagues from six Bulgarian universities: the *Paisii*

Hilendarski University of Plovdiv, *St. Clement of Ohrid* University of Sofia, *St. Cyril and St. Methodius* University of Veliko Tarnovo, Neofit Rislki Southeastern University, *Bishop Constantine of Preslav* University of Shumen and the New Bulgarian University along with one participant from abroad – from the University of Pardubice, Czech Republic. According to the established tradition, all of them received working materials provided by the Student Council o the University of Plovdiv. This year, participants also received four books on subjects from the realm of history provided by Ivrai Publishing House and the Department of History and Archaeology.

The 12th Students' Scientific Conference was an event for an entire generation of alumni of the Department of History and Archaeology of the University of Plovdiv. A major aspect of the jubilee conference was the Round Table on the following topic: "Problems and Challenges before the Education in History in Bulgarian Universities", which closed the programme for the first day. Present and former members of the *Prof. Velizar Velkov* Students' Club of History and Archaeology, from its very establishment 20 years ago until nowadays, took part in the round table. A peculiar meeting of 20 alumni of young historians and archaeologists among whom there was a large number of specialists with established careers and others who in spite of their professional realization in other fields have preserved a dear memory from the years spent in the University.

This event, which is a special celebration for the *Prof. Velizar Velkov* Students' Club of History and Archaeology, was also attended by respected professors like Assoc. Prof. Simeon Katsarov PhD, Assoc. Prof. Dimitar Dimitrov PhD, Assistant Professor Bozhidar Draganov PhD, and Assistant Professor Stanislav Boyanov PhD who is the scientific adviser of the club at present.

The 12th National Students' Conference finished with an exciting visit of the restored Small Basilica in Plovdiv. Under the expert guidance of Assist. Prof. B. Draganov PhD, the participants in the forum were acquainted with one of the recently exposed Late Antiquity archaeological sites in the city and with the interesting floor mosaics preserved in it.

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