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Original Contribution

SPACE SHUTTLE DROPPED DOWN THE TRAPPED PROTON DOSES AT INTERNATIONAL SPACE STATION

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Abstract: *The data from three Bulgarian build instruments on the International Space Station (ISS): Liuin-5 inside PIERS module of Russian segment, R3DE instrument outside at the European Technological Expose Facility (EuTEF) on the ESA Columbus module and R3DR instrument outside Russian "Zvezda" module shows that the docking of the Space Shuttle with the ISS decreased the trapped proton maximal doses in the region of the South-Atlantic Anomaly (SAA) by factor of 1.25 to 2 in dependence from the local shielding and the distance to the Space Shuttle. The analysis of the ascending/descending SAA dose rate maximums of the instruments shows that the effect can be simply explained by the additional shielding against the 30 to 150 MeV protons of the inner radiation belt in the region of the SAA, provided by the 78 tons Shuttle to the instruments and by changing of the ISS 3D mass distribution when the ISS rotates.*

Key words: *Space radiation, ISS, Space Shuttle*

I INTRODUCTION

The radiation field around the ISS is complex, composed of galactic cosmic rays (GCR), trapped radiation of the Earth radiation belts, solar energetic particles, albedo particles from Earth's atmosphere and secondary radiation produced in the shielding materials of the spacecraft and in biological objects.

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. Energetic ions and electrons within the Earth's radiation belts pose a hazard to both astronauts and spacecraft. The inner radiation belt, 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 ~ 100 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 ISS wall, but may deliver large additional doses to astronauts during extra vehicular activity [1] (Dachev et al., 2009). The main absorbed dose inside the ISS is contributed by the protons of the inner radiation belt. The South-Atlantic Anomaly (SAA) is an area where the radiation belt comes closer to the Earth surface owing to a displacement of the magnetic dipole axes from the Earth's center. The daily average absorbed dose rates reported by Reitz et al. (2005) [2] inside of the ISS vary in the range 74-215 μGy d^{-1}.

The GCR are not really rays at all, but charged particles that originate from sources beyond our solar system. They are thought be accelerated by high energetic sources like neutron stars, black holes and supernovae within our Galaxy. 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 [3]. Highly energetic particles in the heavy ion component, typically referred to as high atomic number Z and energy E (HZE) particles, play a particularly important role in space radiobiology [4]. Up to 1 GeV, the flux and spectra of GCR particles are strongly influenced by the solar activity and hence show modulation which is anti-correlated with solar activity. The GCR radiation in the *near – Earth free* space is approximately isotropic. However, because of the shielding effect of the Earth's magnetic field and the Earth itself, there is a lower limit of the cosmic ray particles energy to enter given points in low Earth orbit (LEO) from different locations - geomagnetic cutoff [5].

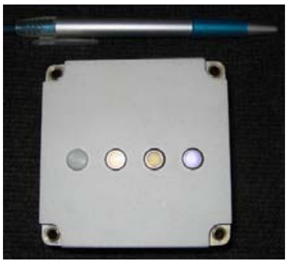

Fig. 1: External view of R3DE instrument. R3DR instrument is with very similar external view.

Because of the very low solar activity during the EXPOSE-E/R missions, solar energetic particles as well as significant fluxes of albedo particles from Earth's atmosphere were not observed. Therefore, they are not further described here.

II. INSTRUMENTATION

II.1 R3DE/R instruments

The (Radiation Risks Radiometer-Dosimeter (R3D) R3DE and R3DR instruments (Figure 1) are successors of the Liulin-E094 instrument, which was part of the experiment Dosimetric Mapping-E094 headed by Dr. G. Reitz that was placed in the US Laboratory Module of the ISS as a part of Human Research Facility of Expedition Two Mission 5A.1 in May-August, 2001 [2, 6].

The R3DE instrument for the EXPOSE-E facility on the European Technological Exposure Facility (EuTEF) worked outside of the European Columbus module of the ISS between 20th of February 2008 and 1st of September 2009 with 10 seconds resolution behind less than 0.4 $g.cm^{-2}$ shielding [7].

The R3DR spectrometer was launched inside of the EXPOSE-R facility to the ISS in December 2008 and was mounted at the outside platform of Russian Zvezda module of the ISS. The first data were received on March 11, 2009. Until 20th of August 2010 the instrument worked with 10 seconds resolution.

The exact mounting locations of the both instruments are seen in Figure 2. The figure is discussed comprehensively in the discussion part of the paper.

R3DE/R instruments are a low mass (~100 g), small dimensions (76x76x36 mm) automatic devices that measures solar radiation in 4 channels and ionizing radiation in 256 channels. The 4 solar UV and visible radiations photodiodes are seen in the center of the Figure 1, while the silicon detector is behind the aluminum box of the instrument; that is why is not seen in the picture. It is situated above the 4 photodiodes. They are Liulin type energy deposition spectrometers. The size of the aluminum box of the R3DR instrument is 76 x 76 x 34 mm.

The ionizing radiation is monitored using a semiconductor PIN diode detector (2 cm^2 area and 0.3 mm thick). Its signal is digitized by a 12 bit fast A/D converter after passing a charge-sensitive preamplifier. The deposited energies (doses) are determined by a pulse height analysis technique and then passed to a discriminator. The amplitudes of the pulses are transformed into digital signals, which are sorted into 256 channels by a multi-channel analyzer. At every exposure time interval one energy deposition spectrum is collected. The energy channel number 256 accumulates all pulses with amplitudes higher than the maximal level of the spectrometer of 20.83 MeV. The methods for characterization of the type of incoming space radiation are described in [7].

The total external and internal shielding in front of the detector of R3DE/R devices is 0.41 g cm^{-2}. The calculated stopping energy of normally incident particles to the detector is 0.78 MeV for electrons and 15.8 MeV for protons. This means that only protons and electrons with energies higher than the above mentioned could reach the detector.

II.2 Liulin-5 instrument

Liulin-5 [8] is an active experiment inside the Russian spherical tissue–equivalent phantom of the international project MATROSHKA-R

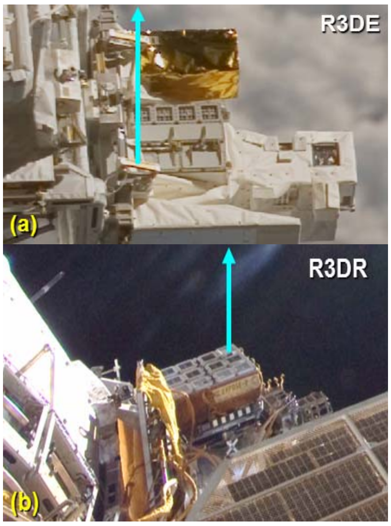

Fig. 2: Real photographs of the mounting positions of the EXPOSE-E/R facilities. The bases of the arrows show the exact places of R3DE/R instruments.

on ISS [9], which aims to study the depth-dose distribution at the sites of critical organs of the human body. The diameter of the phantom is 370 mm and the mass is 32 kg. Similar investigations on ISS are conducted by the ESA anthropomorphic phantom MATROSHKA [10].

Liulin-5 consists of two units: a detector module, placed inside the phantom and an electronic block outside. The detector module contains three silicon detectors D1, D2 and D3 arranged as a telescope and placed at different depths in the radial channel of the phantom, to measure the dose-depth distribution, and three charge-sensitive preamplifiers shaping amplifiers. The detectors axis is along the radial channel.

Fig.3 View of Liulin-5 inside the phantom during the tests of the instrument. In the center is seen the detector module mounted in the radial channel, while at the right side is the electronic block.

The thickness of the sensitive volume of each detector is 0.37 mm, and the detectors' diameter is 17.2 mm. Each detector records the amount of energy deposited in the detector and provides data for the dose rates and particle fluxes in them, evaluated for each 20-s period in SAA and each 90-s period outside SAA. The three detectors are placed at 40 mm, 60 mm and 165 mm distances from the phantom's surface. The first two detectors from the surface (D1 and D2) work in coincidence mode. When a particle enters the telescope within the 81.4^0 sensitivity cone with enough energy to make it through both detectors, it is considered a coincident event. The data for this event are recorded, and used to define the linear energy transfer (LET) spectrum.

The electronic block is mounted outside the phantom. It provides electric power to the detector module, controls the operation of the instrument, and accumulates the data from measurements in flash memory.

The instrument is built in collaboration between the Institute of Biomedical Problems - Moscow, Russia and SRTI-BAS. The Liulin-5 instrument was launched to the ISS in June 2007 and works successfully till now (March 2012) inside the Russian PIERS module.

III. DATA ANALYSIS

III.1. Long-term measurements of the ISS radiation environment by R3DE instrument

Some data from R3DE instrument connected with the decrease of the doses in SAA caused by the Space Shuttle docking were analyzed and already published in [11].

Figure 4 shows the R3DE measurements of the SAA: Incident energies in MeV, Maximal dose rates in μGy h^{-1} and daily dose rates in μGy d^{-1} for the time span between 22nd of March 2008 and 26th of June 2009. The SAA doses are separated from all R3DE data by two simple requirements. The first one is that the dose rate be larger than 200 μGy h^{-1}, which excludes the Galactic cosmic rays

(GCR) dose rates being usually below 50 μGy h^{-1}. The second one is that the dose to flux ratio has to be larger than 1 $nGy.cm^2.particle^{-1}$. This requirement excludes the parts of orbits with relativistic electrons precipitations (REP), in which the dose–to-flux ratio is less than 1 nGy cm^2 $particle^{-1}$ [7, 12].

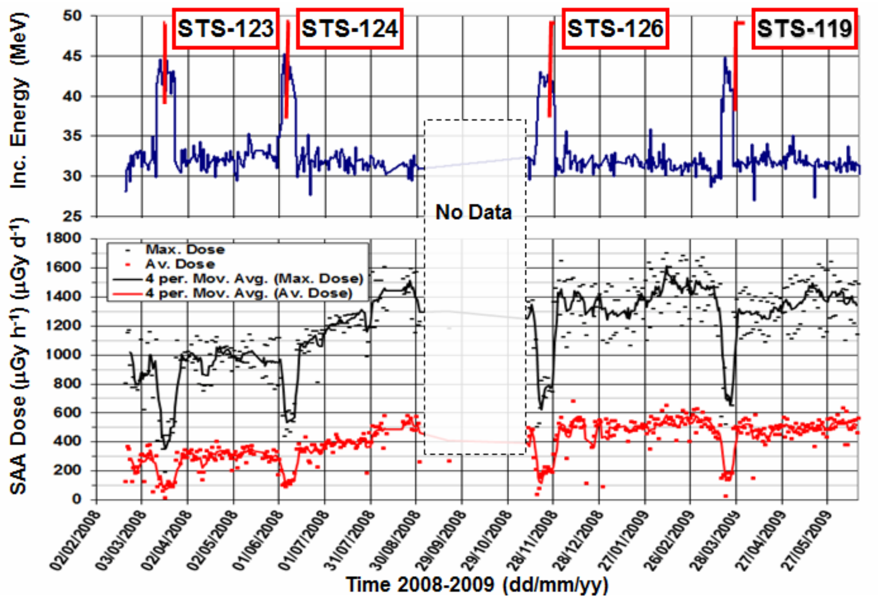

Fig. 4: Variations of SAA dose rate per day (μGy/day), maximum dose (□Gy/h), and Incident Energy from 22/02/2008 to 23/06/2009.

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

The main feature seen in Figure 4 is that during the Space Shuttle docking, the SAA maximal doses fell down by 600 μGy h^{-1} and reached an average level of 400-500 μGy h^{-1} for STS-123 and 124 missions. For STS-126 and STS-119 the drop down was also 600 μGy h^{-1} from an average level of 1400 μGy h^{-1}.

The analysis of the average SAA daily dose rate for the studied period shows that: before 21st of June 2008 it was around 300 μGy day^{-1}, after 21st of June 2008 it started to increase and on 31st of July reached a value of 500 μGy day^{-1}, which stead at this level till the end of the observations in June 2009. The dockings of the Shuttles decreased the average daily SAA dose rate by ~ 250 μGy day^{-1}. Similar reductions of the SAA dose rates are observed by Semones [13] with the Tissue Equivalent Proportional Counter (TEPC) in the Columbus module for the period 4-24 March 2008. Because of the larger shielding inside the Columbus module the dose rate reduction reported by Semones was less than measured in R3DE, namely from 120 to 97 μGy day^{-1} during the STS-123 docking time. Benghin et al. 2008 [14] also report about changes in the ratio of daily dose rates of the unshielded detectors numbers 2 and 3 of the DB-8 system during the dockings of the Shuttles.

The averaged incident energy of the protons in the SAA region is shown in the upper panel of Figure 5. It reveals that the dockings of the Shuttles increase this energy from about 32.5+15.8=48.3 MeV to

42.5+15.8=58.3 MeV. The energy of the protons incident normally to the detector is calculated by using the experimental formula described by Heffner, 1971 [12]. The exact formula used for calculating the proton energies from the measured dose to flux ratio has been recently shown in [7].

The increase of the averaged incident energy of the protons in the SAA region during the Shuttles dockings can be explained with the increase of the protons energy range caused by the stopping of the low energy protons by the mass of Shuttle.

III.II. Study of the ISS radiation environment close to STS-123 Space Shuttle mission in March 2008

Figure 5 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 5th – 31st of 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 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 5a 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 5th of March and 14:03:37 at 10th of March are from position SM-410, while second part till 31st of March is from position COL1A3. Data are obtained from http://cdaweb.gsfc.nasa.gov/ server. Figure 5b contains Liulin-5 [25] dose rate data from the first detector selected in same way as the TEPC data; Figure 5c contains R3DE dose rate data selected as the other 2 data sets. Only here the lowest dose rates are 200 μGy h^{-1}.

Because of the large time interval on the X axis in Figure 5 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 [15-17]. 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 [14].

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 labeled 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.

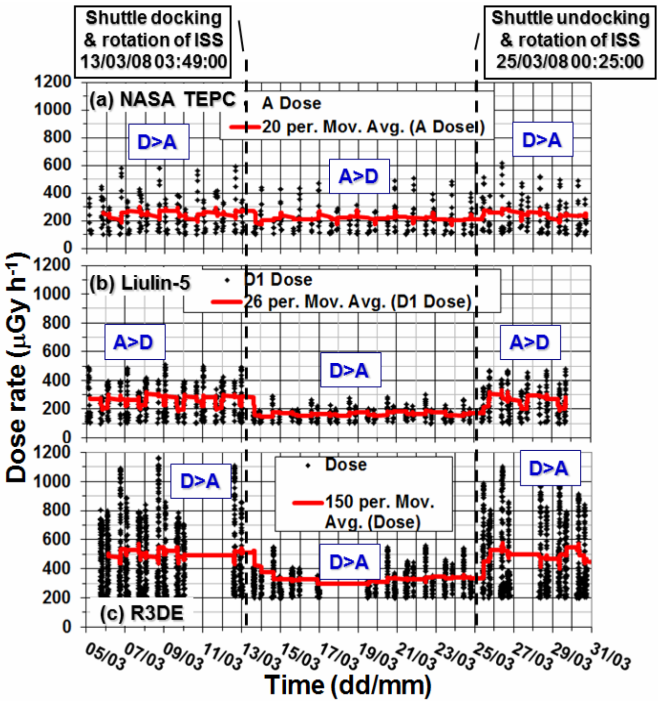

Fig. 5: Variations of the dose rates by NASA TEPC, R3DE and Liulin-5 instruments close to STS-123 docking in the time frame 5-31 March 2008.

At any time the descending dose rate value was greater than the ascending one. This behavior can be explained by the position of the R3DE instrument on the top of Eu-TEF 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 13^{th} 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 $\mu Gy\ h^{-1}$ or about 40% from the value before the docking. The Liulin-5 data decreased from 300 to 180 $\mu Gy\ h^{-1}$ or again about 40% from the value before the docking. TEPC dose rates obtain the smallest decrease from 280 to about 200 $\mu Gy\ h^{-1}$, 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 25^{th} of March, when the undocking of Space Shuttle occurred.

III.3 Study of the ISS radiation environment close to STS-119 Space Shuttle mission in March 2009

Figure 6 is very similar to Figure 5 and shows the dose rate dynamics observed by 4 different instruments around the time of Space Shuttle (STS-119) docking and undocking in the time frame 11^{th} – 31^{st} of March 2009. The 4 panels contain data as follows: In Figure 6a there are the NASA TEPC absorbed dose rate data, which by the selection to be higher than 200 $\mu Gy\ h^{-1}$ present only the SAA maximums. First part of the data between 11^{th} of March and 23:59:43 at 30^{th} of March are from position SM-327, while second part till 31^{st} of March is from position JEM-1FD3. Data are obtained by the http://cdaweb.gsfc.nasa.gov/ server; Figures 6b-6d contain Liulin-5, R3DE and R3DR dose rate data selected in same way as the TEPC data.

The analysis of the 4 panels shows that the highest measured SAA dose rates are seen in the R3DR data (Figure 6d) reaching values up to 2500 $\mu Gy\ h^{-1}$.

Next are the increases in the R3DE dose rates. These both instruments are outside of the ISS at less than 0.5 g cm^{-2} shielding; therefore it is understandable that their SAA dose rates are higher than the dose rates measured by the other 2 instruments, Liulin-5 and TEPC, being inside of Russian PIERS and the US laboratory module respectively. Liulin-5 data were a bit higher than TEPC data, probably because the shielding in the PIERS module is less than the TEPC shielding in the US laboratory module.

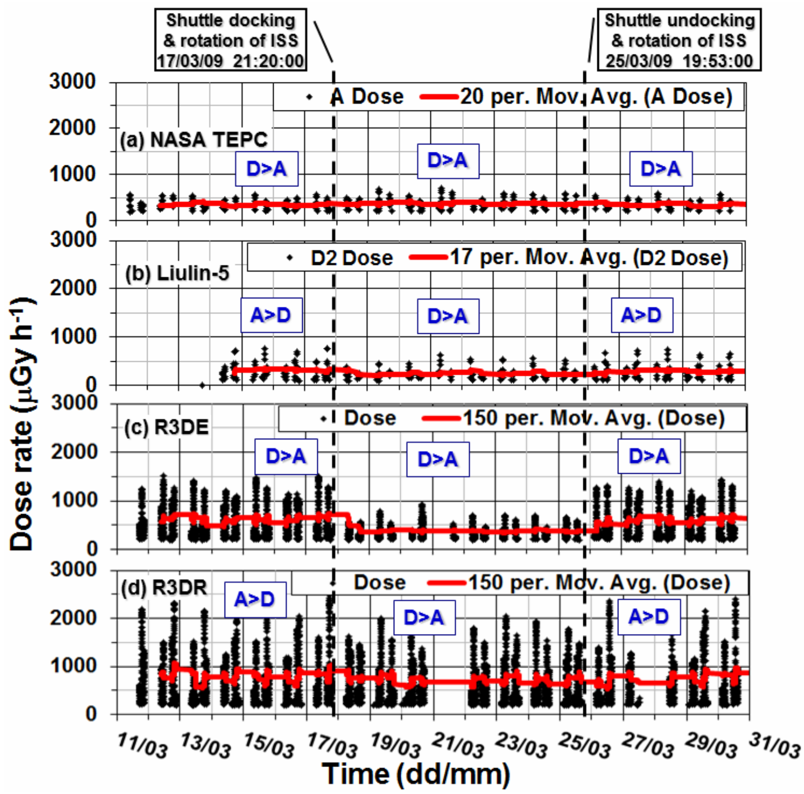

Fig. 6. Variations of the dose rates measured by NASA TEPC, Liulin- 5, R3DE and R3DR instruments close to STS-119 docking in the time frame 11-31 March 2009.

The reason of R3DR SAA dose rates being higher than the R3DE dose rates is seen in Figure 2 and 7. The 2 photographs on Figure 2 present the surrounding of the R3DE and R3DR instruments on ISS. As mentioned before, R3DE was located at the top of the EuTEF platform outside the European Columbus module (Figure 7). In Figure 2a, the lower end of the heavy arrows pointing "up" in the R3DE photograph shows the exact place of the instrument. It is seen that it was surrounded by different constructive elements of the EuTEF platform, which produced additional shielding of the instrument. In addition being on the top of EuTEF module R3DE was practically not shielded by the Columbus module body from the SAA drifting protons coming from west and up. That is why always the descending dose rates in this instrument were higher than the ascending ones. The R3DR position presented in Figure 2b shows that this instrument is far from the Zvezda module at the end of the EXPOSE-R facility and is practically shielded from below only.

IV. DISCUSSIONS

We interpret the dose rate decreases measured in the ISS instruments to be generated by 2 factors – a static one and a dynamic one. The static factor is connected with the presence of the Space Shuttle body in the angle of view of the instruments, which leads to the decrease of flux of the SAA protons. The dynamical factor is connected with the attitude of ISS, which usually rotates [14] at 180° before Space Shuttle docking

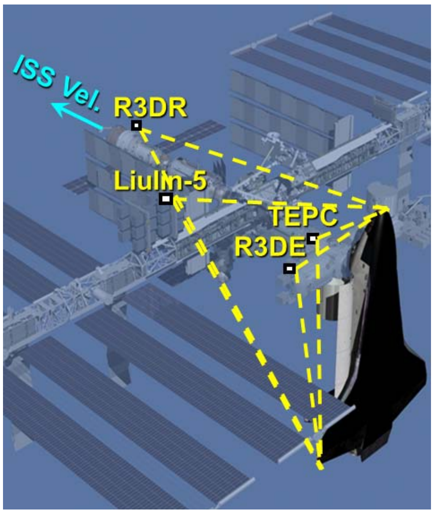

Fig. 7. Variations of the dose rates by NASA TEPC, R3DE and R3DR instruments close to STS-119 docking in the time frame 11-31 March 2009.

and reverses again after the undocking.

The decreases of the dose rates, observed by the R3DE and Liulin-5 instruments, when the Space Shuttle was docked with the station can be explained by the additional shielding to the instruments inside and outside of the ISS against the SAA 30 to 150 MeV proton drifts, provided by the 78-tons shuttle body. Qualitatively this is shown in Figure 7 where the Space Shuttle and the major part of ISS are schematically presented. The places of the R3DE, R3DR, TEPC and Liulin-5 instruments in this schema are marked by black rectangles and the corresponding labels. It is seen that the large and heavy body of the Shuttle covers a wide angle of view (shown with light and dashed lines) of the R3DE and TEPC instruments. R3DR and Liulin-5 being away from Shuttle were less shielded by the Space Shuttle body. This fact describes the relatively small decrease in the R3DR dose rates presented in Figure 7. The relatively low energy inner radiation belt protons were stopped in the Shuttle body and did not reach the instruments thus producing a decrease in the measured dose rates.

The ISS attitude change was performed in preparation of the Shuttle docking. The rotation of the ISS at 180° against the velocity vector led to both, decreasing dose rates in detectors on ascending orbits and changing the places of the maximum doses on

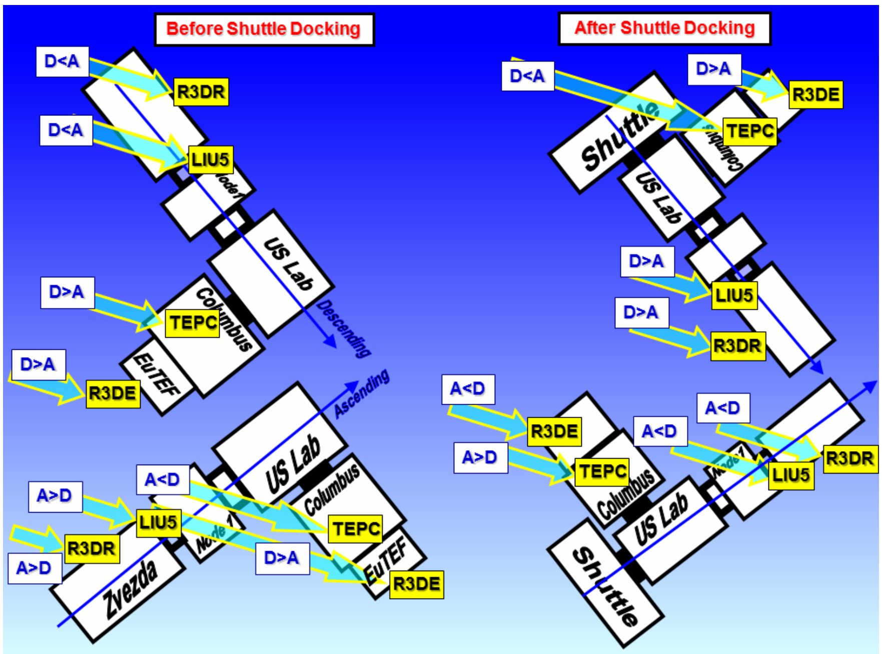

Fig. 8: Sketch of the situations between different instruments placed on ISS and their interaction with the west-east direction of the SAA ion drift velocity.

ascending and descending SAA crossings because of the East-West asymmetry. This dynamical effect on the dose rates depends by the place and shielding distribution around the instrument. Exact quantitative modeling of the passive and dynamical ISS dose rates changes connected with the Shuttle docking are in progress and the results will be presented in future.

Figure 8 is a sketch, attempting to explain how the ascending/descending orientation and Shuttle docking affects the dose rates values measured by the different instruments. In the left part of the figure the situation is shown before Shuttle docking when the ISS is in the nominal "XVV" orientation http://spaceflight.nasa.gov/station/flash/iss_attitude.html and when the US Laboratory module is leading the station along the velocity vector. Upper-left part of the figure presents the situation in descending parts, and the ascending parts are presented in the down-left corner. Major station modules as US laboratory module (US lab), European Columbus module (Columbus), European Technologically Expose Facility (EuTEF), Node 1 module and Russian Zvezda module are shown with black rectangles. The Zvezda module is not directly connected to Node 1, but here, for simplicity reasons, we accept that it is so. Different instruments are presented with yellow filled blocs with labels as: R3DE, R3DR, NASA TEPC and Liulin-5 instrument (LIU5). They are situated in their positions respectively in the left or right side of the station axes, which is along the velocity vector shown with blue arrows.

The SAA proton drift velocity is presented with heavy semitransparent yellow/sky blue arrows oriented to the down-right i.e. from up to down and from west to east. The white rectangles on the drift velocity vectors summarize the observed in Figures 6 and 7 ascending/descending dose rate amplitude relationships.

It can be seen that higher ascending/descending amplitudes are seen at the side of ISS complex, which is rotated to the drift velocity vectors and in reverse lower amplitudes are seen at the other side of the station body. Only R3DE instrument as described before stays at fixed D>A relationship.

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