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Time Profile of Cosmic Radiation Exposure During the EXPOSE-E Mission: The R3DE Instrument

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Abstract

The aim of this paper is to present the time profile of cosmic radiation exposure obtained by the Radiation Risk Radiometer-Dosimeter during the EXPOSE-E mission in the European Technology Exposure Facility on the International Space Station's Columbus module. Another aim is to make the obtained results available to other EXPOSE-E teams for use in their data analysis. Radiation Risk Radiometer-Dosimeter is a low-mass and small-dimension automatic device that measures solar radiation in four channels and cosmic ionizing radiation as well. The main results of the present study include the following: (1) three different radiation sources were detected and quantified—galactic cosmic rays (GCR), energetic protons from the South Atlantic Anomaly (SAA) region of the inner radiation belt, and energetic electrons from the outer radiation belt (ORB); (2) the highest daily averaged absorbed dose rate of 426 μGy d^{-1} came from SAA protons; (3) GCR delivered a much smaller daily absorbed dose rate of 91.1 μGy d^{-1}, and the ORB source delivered only 8.6 μGy d^{-1}. The analysis of the UV and temperature data is a subject of another article (Schuster *et al.*, 2012). Key Words: Ionizing radiation—R3D—ISS. Astrobiology 12, 403–411.

1. Introduction

1.1. Scientific background of the EXPOSE-E mission

The primary aim of astrobiological research is to investigate the processes of the origin, evolution, and dissemination of life on primordial Earth and possibly on other celestial bodies. In addition to laboratory investigations, space research poses the unique possibility for astrobiology *in situ* measurements under authentic space conditions. This research allows an investigation of the roles of extreme solar and cosmic radiation in prebiotic and biological evolution of life on Earth and, potentially, on other celestial bodies. It also allows investigators to test the panspermia hypothesis (Horneck *et al.*, 2001), which assumes that life can be distributed beyond its planet of origin.

The EXPOSE-E mission on board the International Space Station (ISS) was provided by ESA for astrobiological studies under space conditions as provided in low-Earth orbit outside the ISS. The radiation field encountered in this environment is of pivotal interest to astrobiology (Ferrari and Szuszkiewicz, 2009). To provide information about the diurnal variation of this radiation, the EXPOSE-E payload accommodated the Radiation Risk Radiometer-Dosimeter (R3D). R3DE is a low-mass and small-dimension automatic device that measures solar radiation in four channels and cosmic ionizing radiation as well. Its primary role was to monitor the time profile of cosmic radiation exposure during the EXPOSE-E mission.

1.2. Near-Earth radiation environment

The radiation field around the ISS is complex. It is composed of galactic cosmic rays (GCR), trapped radiation from Earth's 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 concentrations of the energetic electrons and protons trapped within Earth's magnetosphere. There are two distinct belts of toroidal shape that surround Earth in which the high-energy charged particles are trapped in Earth's magnetic field. Energetic ions and electrons within Earth's radiation belts pose a hazard to both astronauts and spacecraft. The inner radiation belt, located between about 0.1—2 Earth radii, consists of both electrons with energies up to 10 MeV and protons with

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energies up to $\sim$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 extravehicular activity (Dachev *et al.,* 2009, 2011c). 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 Earth's surface due to a displacement of the magnetic dipole axes from Earth's center. The daily average absorbed dose rates reported by Reitz *et al.* (2005) inside the ISS vary in the range of 74—215 μGy d^{-1}.

The GCR are not rays at all but charged particles that originate from sources beyond the Solar System. They are thought to be accelerated by high energetic sources, such as 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 (Simpson, 1983). Highly energetic particles in the heavy ion component, typically referred to as **h**igh atomic number ***Z*** and energy ***E*** (HZE) particles, play a particularly important role in space radiobiology (Horneck, 1994). Up to 1 GeV, the flux and spectra of GCR particles are strongly influenced by solar activity and hence show modulation that is anticorrelated with solar activity. The GCR radiation in the near-Earth free space is approximately isotropic. However, because of the shielding effect of Earth's magnetic field and Earth itself, there is a lower limit of the cosmic ray particles' energy to enter given points in low-Earth orbit from different locations—geomagnetic cutoff (Smart and Shea, 2005).

Because of very low solar activity during the EXPOSE-E mission, 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.

2. Materials and Methods

2.1. R3DE instrument description

The Radiation Risk Radiometer-Dosimeter for the EXPOSE-E facility (R3DE), which was mounted on the European Technology Exposure Facility (EuTEF) outside the European Columbus module of the ISS, is a Liulin-type miniature spectrometer-dosimeter (Horneck *et al.,* 1999; Dachev *et al.,* 2002; Häder and Dachev, 2003). Figure 1 presents the external view of the EXPOSE-E facility (Rabbow *et al.,* 2009, 2012) and the R3DE instrument (Dachev, 2009), which is situated in the bottom left corner of the picture. The four photodiodes of the solar irradiance spectrometer are well seen in the center of the R3DE. The ionizing radiation PIN

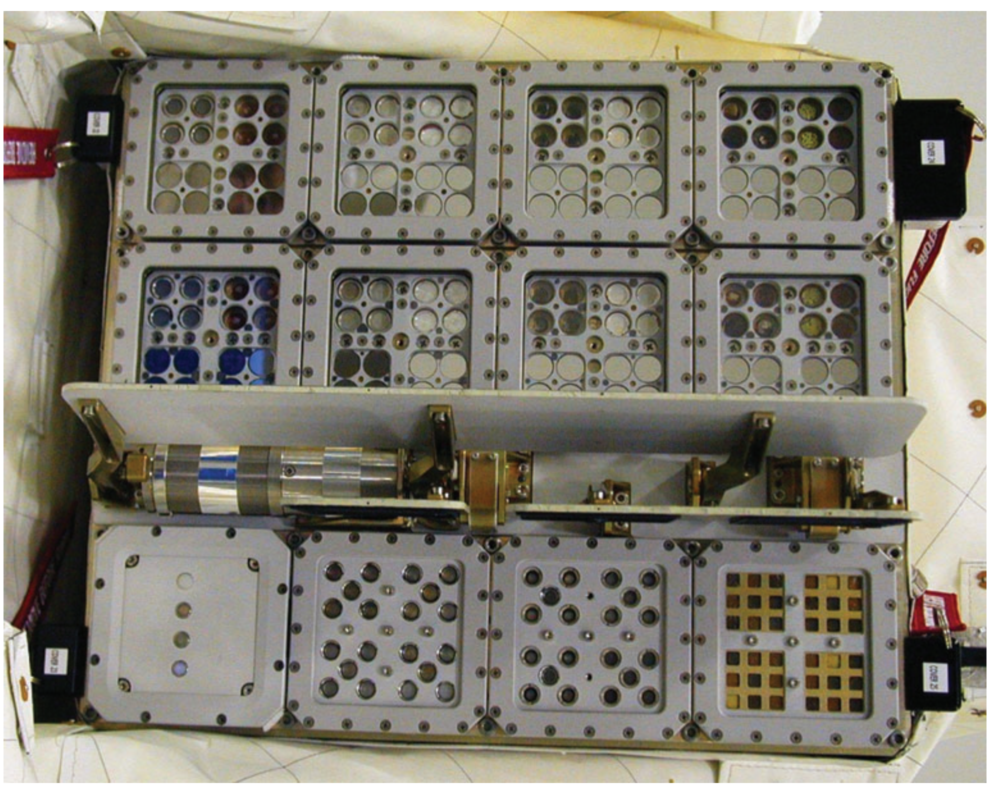

FIG. 1. External view of the EXPOSE-E facility and R3DE instrument, which is situated in the bottom left corner of the picture. The four photodiodes of the solar irradiance spectrometer can be clearly seen in the center of the R3DE. The ionizing radiation PIN diode with 2 cm^2 area is behind the aluminum cover and therefore not visible in the picture. Color images available online at www.liebertonline.com/ast

diode with 2 cm^2 area is behind the aluminum cover and therefore not visible.

The ionizing radiation detector of the R3DE instrument was about 3 mm below the aluminum 1 mm thick cover plate. Additionally, there was a technological shielding of 0.3 mm copper and 0.2 mm plastic materials. Altogether this produced less than 0.4 g cm^{-2} shielding. This allowed direct hits on the detector by electrons with energies higher than 0.78 MeV and protons with energies higher than 15.8 MeV (Berger *et al.*, 2009). The surface of the detector (2 cm^2 in size by 0.3 mm thickness) was orientated perpendicularly to the "+Z" axis of the ISS.

Figure 2 shows the block diagram of the R3DE instrument, whose size is 76×76×34 mm and weight about 0.12 kg. The instrument was mounted with 4 (4 mm) bolts in one of the corner pockets of the EXPOSE-E facility. From EXPOSE-E, the instrument obtained one fixed voltage, +12 V DC. The telemetry output from the instrument was arranged as an RS422 serial interface with a maximum rate of 19.2 kbps. The instrument was controlled by a master microprocessor that contained a 12-bit analog-to-digital converter (ADC) for the UV data channels and a multiplexer. The dose and flux measurements were arranged by a charge-sensitive preamplifier and another fast 12-bit ADC. The slave microcontroller determined the deposited energy spectrum, which was then transferred to the master microcontroller and to the telemetry system. The measurement cycle of the instrument was fixed at 10 s. During this time, 256 measurements of the UV and temperature channels were performed, and averaged values were transferred to the telemetry. In the same time interval, one energy deposition spectrum from the cosmic ionizing radiation channel was accumulated. Pulse height analysis technique was used for obtaining the deposited energy spectrum, which was further used for the calculation of the absorbed dose and flux in the silicon detector.

The analysis of the UV and temperature data obtained during the R3DE mission on EXPOSE-E are the subject of another paper (Schuster *et al.*, 2012).

2.2. Dose interpretation procedure

The main measurement unit in the ionizing radiation spectrometer is the amplitude of the pulse after the preamplifier generated by particles or quantums hitting the detector. It is proportional by a factor of 240 mV MeV^{-1} to the energy loss in the detector and respectively to the dose and linear energy transfer. By the 12-bit fast ADC, these amplitudes are digitized and organized in a 256-channel spectrum that uses only the first 8 bits of the ADC. The dose D(Si) [Gy] by definition is 1 J deposited in 1 kg. We calculate the absorbed dose (D(Si)) by dividing the summarized energy deposition in the spectrum in joules by the mass of the detector in kilograms:

$$D(Si) = K \sum_{i=1}^{255} ik_i A_i MD^{-1} \quad (1)$$

where MD is the mass of the detector in kilograms, $k_i$is the number of pulses in channel I, A_i is the amplitude in volts of

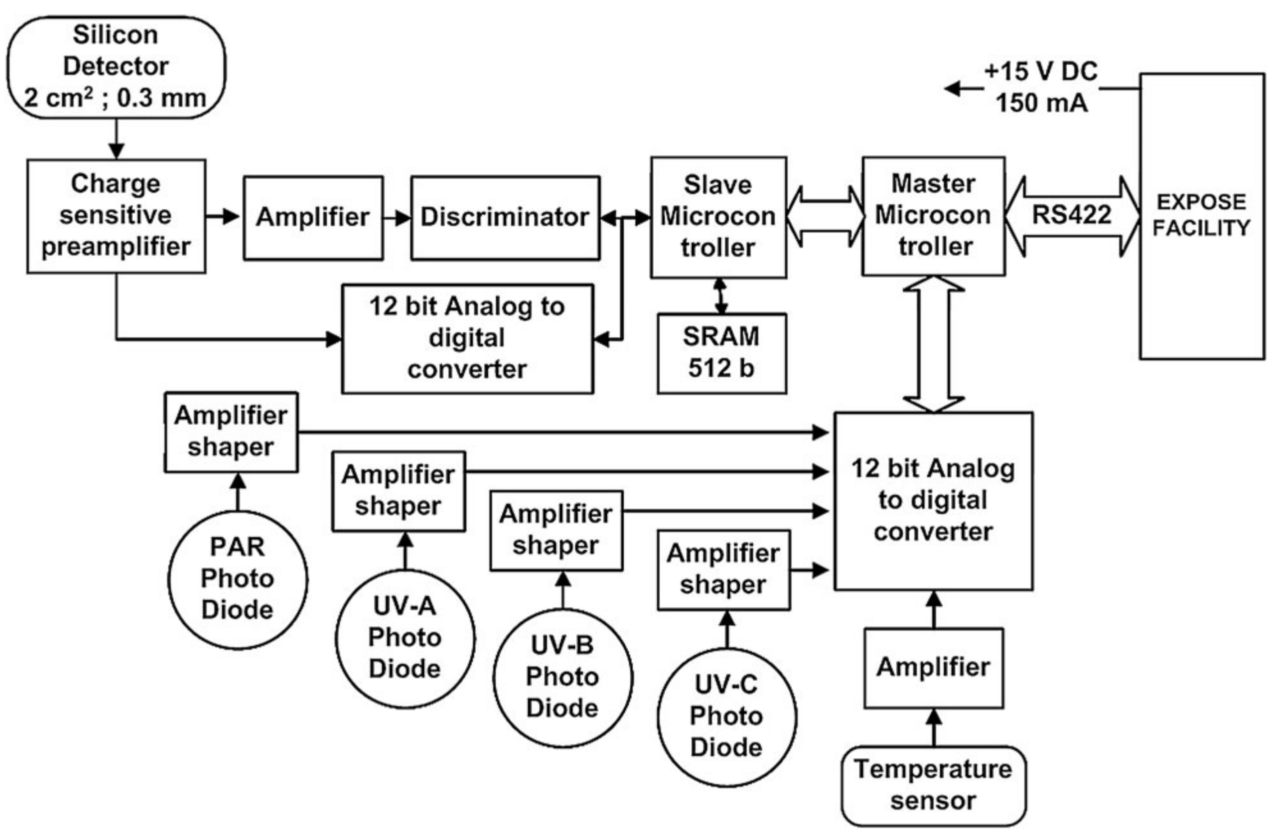

FIG. 2. Block diagram of the R3DE instrument. The upper part of the figure presents the ionizing radiation block scheme, while the bottom part shows the solar radiation and temperature block scheme.

pulses in channel I, $K \cdot i \cdot k_i \cdot A_i$ is the deposited energy (energy loss) in joules in channel i. K is a coefficient. All 255 deposited dose values, depending on the deposited energy for one exposure time, form the deposited energy spectrum.

2.3. Instrument calibrations

Liulin-type instruments were calibrated with high-energy fluxes of protons and heavy ions at different accelerators (Dachev *et al.*, 2002, 2011b; Uchihori *et al.*, 2002). The calibrations revealed that, except for charged energetic particles, the detector has high effectiveness for gamma rays (Spurný and Dachev, 2003). The high sensitivity toward gamma rays allows monitoring of the natural background radiation.

3. Results

3.1. Environmental history of the R3DE instrument

The temperature of the R3DE instrument was measured by a built-in thermometer. The R3DE was exposed to open space conditions from 7 February 2008 (upload), when the cargo bay doors of Space Shuttle Atlantis were opened, through 12 September 2009 (download), when the cargo bay doors of Discovery were closed. The total duration was 582 days. Over these 18 months, 10 high-temperature periods (maximum +40°C) were experienced, alternating with 10 cold periods (minimum −12°C), which were caused by gradual changes of the ISS orbital plane with respect to the Sun. Superimposed was a rapid temperature rhythm caused by the 91 min orbital loops across the dayside and nightside of Earth. Day/night variations spanned over 10°C during the hot periods and over 5°C during the cold periods. On 20 May 2009 an exceptional peak of 55°C was recorded by the R3DE when the ISS was temporarily placed in an attitude perpendicular to the Sun to facilitate the installation and testing of new solar panels.

3.2. Data selection procedure

The data selection procedure was established to select the three expected radiation sources: (i) GCR particles, (ii) protons with more than 15.8 MeV energy in the SAA region of the inner radiation belt, and (iii) relativistic electrons with energies above 0.75 MeV in the ORB. Different ways of characterization of the space radiation environment were treated comprehensively in Dachev (2009). The simplest method described in Dachev (2009) is based on the Heffner formulae (Heffner, 1971) and shows that the data can be simply split in two parts by the requirements of the value of the ratio dose to flux (D/F). When the ratio is less than 1 nGy cm^{-2} part^{-1}, the expected predominant type of radiation in a 10 s interval is electrons with energies above 0.75 MeV. When the ratio is greater than 1 nGy cm^{-2} part^{-1}, the expected type of radiation is protons with energies above 15.8 MeV. The GCR source, which has contributions in both ranges, will be divided between the two ranges; knowing that the GCR dose rates are within values below 50 mGy h^{-1}, it is easy to select them from the other two sources. The described selection in the next paragraph uses the results of the analysis of the dose-to-flux ratio and separates more precisely sources in the mixed radiation regions.

Figure 3 presents the latitudinal distribution of the dose rates against McIlwain's L values (McIlwain, 1961; Heyndrickx *et al.*, 1996). [The ISS orbital data are calculated by using (Galperin *et al.*, 1980) algorithms.] On the x axis, the L value is plotted. On the y axis, the absorbed dose rate measured by the R3DE instrument is plotted. The figure covers data from 11/07/2008 to 21/07/2008 with 10 s resolution. Three different radiation sources separated by the heavy black line are easy to distinguish from the data. These sources are denoted on the figure as SAA, ORB, and GCR. From one 10 s spectrum of the R3DE instrument, we were able to decide only what the predominant radiation sources were, but we were not able to extract the exact doses of each source in those regions of mixed radiation sources with similar dose rates. This is why we specify, in the statistics of sources below, the number of measurements per day of the considered predominant source.

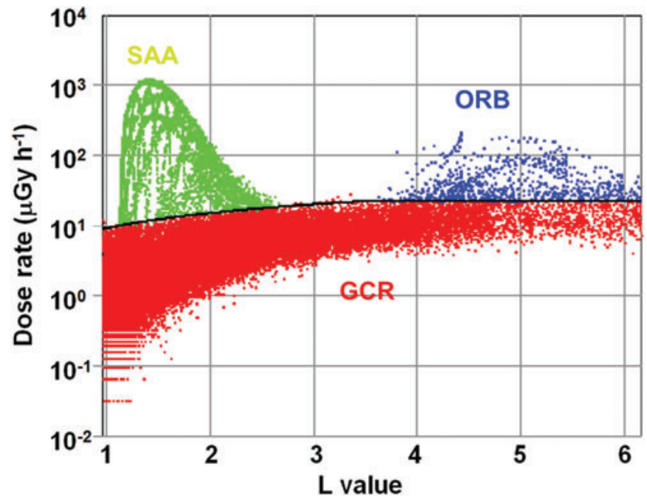

FIG. 3. Latitudinal distribution of the dose rates measured with the R3DE instrument against McIlwain's L values. The maximum in the upper left side of the figure denoted by SAA is created by high-energy protons when the ISS crosses the region of the SAA. The maximum in the right side is generated by sporadic high-energy electrons seen mainly at high geographic latitudes ($L > 3.5$). Galactic cosmic rays (GCR) are seen everywhere and at all times on the ISS. Their distribution is spread in the bottom side of the figure. Color images available online at www.liebertonline.com/ast

The black line on Fig. 3 consists of two parts. The left part up to $L = 3.5$ is obtained by mathematical methods as asymptote to the GCR values in the whole range of L values, which allows separation of GCR dose rates from trapped protons in the SAA region dose rates. The right part ($3.5 < L < 6.2$) is a horizontal line selected by the operator. The reason for this consideration is that in the high L-value region the GCR dose rate values are practically fixed because the ISS reached the open magnetic field lines. The ORB data are separated by the requirements to be above the line and the count rate in the first channel of the spectrum to be higher than 20.

The major amount of measurements is concentrated in the GCR points, which are seen as the area with many points in the bottom part of the figure in the whole L-value range between 0.9 and 6.2. The average number of GCR measurements per day with 10 s resolution for the whole period of available data (464 days) is 7142 with a maximal number of 8243 from a total possible 8640 measurements

(3600×24=86400/10=8640) per day. The covered dose rate range was between 0.03 and 20—25 μGy h^{-1}. The lowest dose rates were close to the minimal *L* values, for example, to the magnetic equator, while the highest were at high latitudes equatorward from both magnetic poles. Figure 3 also indicates the GCR latitudinal profile. These profiles were presented more precisely by Dachev *et al.* (2010).

The second source of radiation is the protons in the SAA region of the inner radiation belt, which are situated as a large maximum in the upper left part of Fig. 3. They cover the range in *L* values between 1.2 and 2.6. The structure seen inside the SAA maximum has to do with the different ways of crossing the anomaly by the ISS along its orbit. The maxima, which extend in a wide range of *L* values, were generated during the descending orbits. Their values were always higher than the spike-like maxima seen in the ascending orbits (Dachev *et al.*, 2010). The dose rates in the SAA region varied between 10—15 and 1208 μGy h^{-1}.

The wide maximum in *L* values between 3.5 and 6.2 has to do with the observations of sporadic relativistic electron (blue points) precipitations generated in the ORB (Dachev *et al.*, 2009, 2011c). Single 10 s ORB measurements can deliver a maximum of ISS dose rate values up to 20,000 μGy h^{-1}.

3.3. SAA daily doses

Figure 4 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 daily dose rates were obtained by first separation of all full-day (425 from 462 days of data) SAA 10 s doses. Next the obtained average dose was multiplied by the number of measurements per day, which varied between 318 and 667 in dependence of the exact path of the ISS per 24 h through the SAA. The average number of measurements in the SAA per day was 508 from 425 full days of measurements. The average SAA dose rate was 426 μGy d^{-1}, and the range was between 110 and 685 μGy d^{-1}. The SAA statistics for 425 full days of measurements is presented in Table 1.

The relatively low dose rates at the left side of Fig. 4 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 mGy h^{-1}.

The main feature seen in Fig. 4 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} (Dachev *et al.*, 2011a).

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 mGy d^{-1}, the level at which the daily average SAA dose rate stayed until the end of the

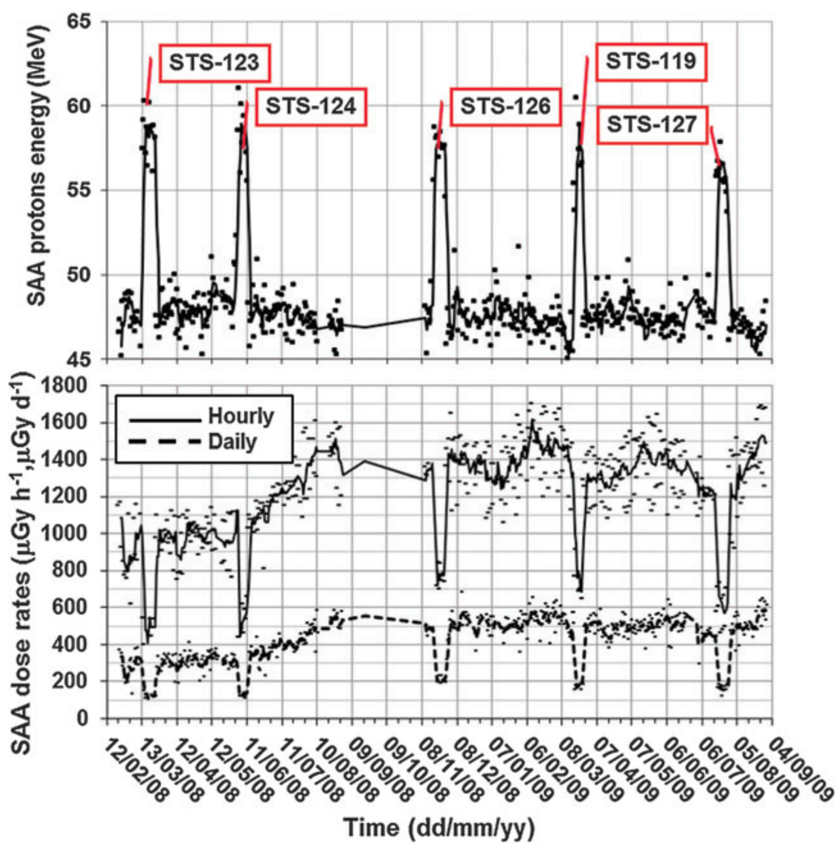

FIG. 4. Daily and hourly SAA dose rates and SAA proton energies measured with the R3DE instrument during the EXPOSE-E mission. The space shuttle dockings at the ISS create strong decreases in the hourly and daily dose rates due to the additional shielding effect of the space shuttle body on the R3DE 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. Color images available online at www.liebertonline.com/ast

Table 1. Statistics of SAA Parameters, as Measured with the R3DE Instrument during the EXPOSE-E Mission

Parameter	*Minimum*	*Average*	*Maximum*	*Accumulated for 425 days*
Hourly averaged absorbed dose rate (in Si) (μGy h^{-1})	116	296	399	
Daily averaged absorbed dose rate (in Si) (μGy d^{-1})	110	426	685	181.1 mGy
Averaged proton energy (MeV)	43	49	61	

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) 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 by Semones (2008) was from 120 to 97 μGy d^{-1} during the STS-123 docking time. Benghin *et al.* (2008) 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.

The investigation of the averaged energy of the protons in the SAA region is shown in the upper panel of Fig. 4, 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). The exact formula used for calculating the proton energies from the measured dose-to-flux ratio was recently shown by Dachev (2009).

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.

3.4. GCR daily doses

Figure 5 shows the daily dose rate history of the GCR component of the space radiation in the period from 22/02/2008 to 01/09/2009. There are two parameters in the graphic: daily GCR absorbed dose rates presented with asterisks and daily averaged Oulu neutron monitor (NM) count rates divided by 60.

The daily absorbed dose rates are obtained by first separation of all full-day GCR 10 s doses. The full days of data are 432 from 462 real days. One day of data is considered to be a full day if there are more than 4000 measured values from a maximum observed 8243. The daily number of GCR measurements is formed as the difference between the maximum possible number of measurements (8400) and the sum of the SAA and ORB measurements. Next the obtained average hourly dose rate is multiplied by 24 (hours) to calculate the daily dose. This is reasonable because GCR are constantly present at the orbit of the ISS. The average per day number of measurements in GCR is 7408 from 432 full days of

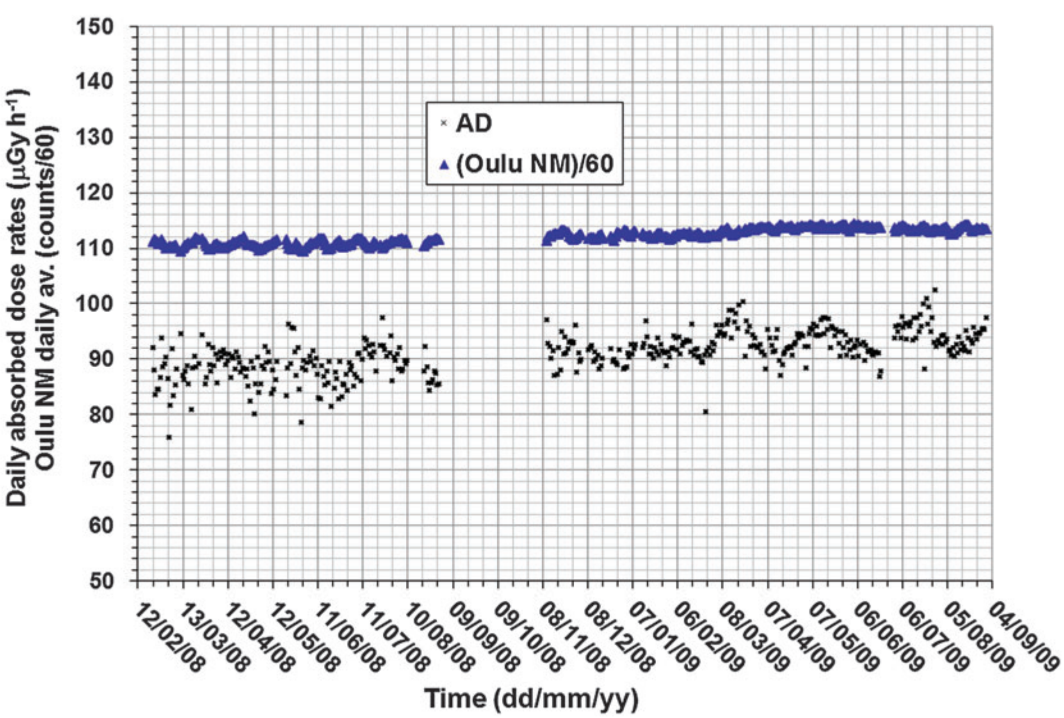

FIG. 5. Daily GCR dose rates measured with the R3DE instrument during the EXPOSE-E mission are denoted on the figure by AD. The small positive trend of the GCR doses is compared with the trend in the daily averaged Oulu neutron monitor (NM) counts divided by 60 to be in the same linear scale as the GCR data. Color images available online at www.liebertonline.com/ast

Table 2. Statistics of GCR Parameters as Measured with the R3DE Instrument during the EXPOSE-E Mission

Parameter	*Minimum*	*Average*	*Maximum*	*Accumulated for 432 days*
Hourly averaged absorbed dose rate (μGy h^{-1})	3.158	3.796	4.263	
Daily averaged absorbed dose rate (μGy d^{-1})	76.792	91.104	102.312	39.4 mGy

measurements. More details about the GCR statistics are shown in Table 2.

The data in Fig. 5 are separated into two periods: 22/02/2008 to 31/08/2008 and 11/11/2008 to 01/09/2009. The main feature seen in Fig. 5 is the relatively constant values of the daily dose rates in the first period and rising values in the second. The explanation of these variations has to do with the solar modulation of the GCR flux (Usoskin *et al.,* 2011). From Fig. 5 it can be seen that the daily GCR dose rate data sets correlate well with the "(Oulu NM)/60" curve. (The Oulu neutron monitor count rate is available online from http://cosmicrays.oulu.fi). In general, the enhancement of the daily GCR dose rates in the second period of the observations measured with the R3DE instrument was produced by the decrease of the interplanetary magnetic field caused by low solar activity at the end of the 23rd cycle. The decreased interplanetary magnetic field allowed a higher amount of GCR particles to reach the orbit of the ISS.

3.5. ORB daily doses

The daily ORB dose rates (Fig. 6) are obtained by first separation of all full-day (374 from 462 days of data) 10 s doses. Because of the very sporadic character of the ORB electron fluxes, we considered only those days as full days when at least 10 observations were made. Next the obtained average dose is multiplied by the number of measurements per day, which varied between 10 and 218 in dependence of the geomagnetic activity. The average number of measurements from the ORB per day was 44 from 374 full days of measurements. The average ORB dose rate is 8.64 μGy d^{-1}, and the range is between 0.25 and 212 μGy d^{-1}. More details about the ORB statistics are seen in Table 3.

Figure 6c (bottom panel) shows clearly a gradual decrease of the daily ORB dose rates in the whole period of observations. This again has to do with the decrease of solar activity with respect to the geomagnetic activity (see Fig. 6a). The daily ORB dose rate correlates well with more than 2 MeV electron fluence presented in Fig. 6b.

4. Discussion

Here, the major concern is how the obtained daily dose rates can be used by scientists from other EXPOSE-E experiments. The detector of the R3DE instrument, as mentioned, is behind 0.4 g cm^{-2} shielding at the level of the first samples (see Fig. 1). Figure 1 also shows the position of the instrument in the frame of EuTEF and the Columbus module when looking down (to Earth) in the most-used orientation of the ISS. In this frame, the EuTEF base and the Columbus module are at the left side of the instrument and the whole EXPOSE-E facility, respectively. It is expected that samples that are in

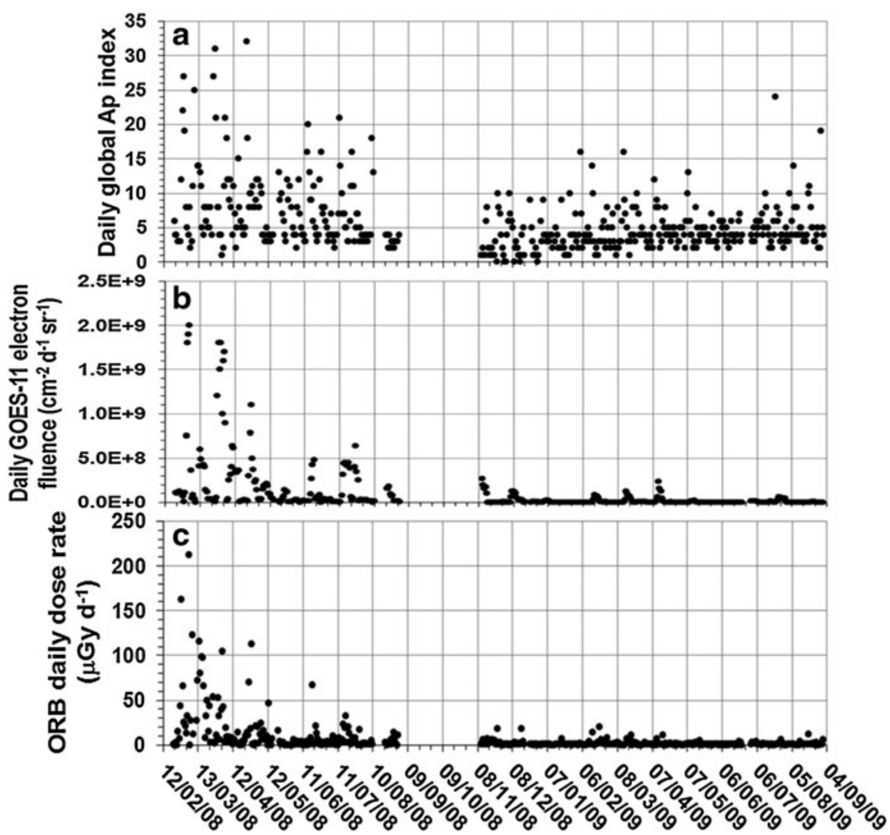

FIG. 6. ORB dose rates measured with the R3DE instrument during the EXPOSE-E mission (**c**) are compared with the GOES-11 daily more than 2 MeV electron fluence (**b**) and global daily Ap index (**a**). The data for GOES energetic electrons and Ap indexes are taken from the 2008/2009_DPD.txt and 2008/2009_DGD.txt files prepared by the U.S. Department of Commerce, NOAA, Space Weather Prediction Center, available online from http://www.swpc.noaa.gov/ftpmenu/index.html.

Table 3. Statistics of ORB Parameters, as Measured with the R3DE Instrument during the EXPOSE-E Mission

Parameter	*Minimum*	*Average*	*Maximum*	*Accumulated for 374 days*
Hourly averaged absorbed dose rate (μGy h^{-1})	17	42	15,841	
Daily averaged absorbed dose rate (μGy d^{-1})	0.25	8.64	212	3.2 mGy

the left-hand side of EXPOSE-E (see Fig. 1) close to the R3DE instrument will have daily doses close to the ones obtained by it (see Tables 1—3). The farther the samples are to the right-hand side of the EXPOSE-E facility, the more the SAA and ORB doses will rise. Also the SAA doses in the samples will decrease with increasing thickness of the shielding as shown in Nealy *et al.* (2007, Fig. 13).

The daily average global GCR dose rate is valid for almost all depths and positions of the EXPOSE-E samples. To obtain the total accumulated dose from GCR, it is necessary to multiply the average daily dose rate by the number of exposition days. Some small increase of the GCR doses can be expected behind thicker shielding because additional doses from secondary particles will be generated in the shielding (Nealy *et al.*, 2007, Fig. 14).

The SAA proton and ORB electron daily dose rates are valid behind less than 0.4 g cm^{-2} shielding. Some increasing SAA doses have to be expected, which depends on the position of the samples. Samples, which are far from the body of the Columbus module, have to have larger doses. ORB doses that have less penetration decrease rapidly with the depth of the samples, and the calculated values account only for the first few millimeters' thickness.

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Author Disclosure Statement

No competing financial interest exists for Tsvetan Dachev, Gerda Horneck, Donat-Peter Häder, Martin Schuster, Peter Richter, Michael Lebert, or Rene Demets.

Abbreviations

ADC, analog-to-digital converter; EuTEF, European Technology Exposure Facility; GCR, galactic cosmic rays; ISS, International Space Station; ORB, outer radiation belt; R3DE, Radiation Risk Radiometer-Dosimeter for the EXPOSE-E facility; SAA, South Atlantic anomaly.

References

Benghin, V.V., Petrov, V.M., Drobyshev, S.G., Panasyuk, M.I., Nechaev, O.Yu., Miasnikov, A.G., and Volkov A.N. (2008) Results of the radiation monitoring system onboard the service module of ISS. In *13th Workshop on Radiation Monitoring for the International Space Station (WRMISS)*, Krakow, Poland, September 8–10, 2008. Available online at http://wrmiss.org/workshops/thirteenth/Benghin.pdf.

Berger, M.J. (2009) Stopping-power and range tables for electrons, protons, and helium ions. NIST Standard Reference Database 124, National Institute of Standards and Technology (NIST), Gaithersburg, MD. Available online at http://physics.nist.gov/PhysRefData/Star/Text/contents.html.

Dachev, T.P. (2009) Characterization of the near Earth radiation environment by Liulin type spectrometers. *Adv Space Res* 44:1441–1449.

Dachev, Ts., Tomov, B., Matviichuk, Yu., Dimitrov, P., Lemaire, J., Gregoire, G., Cyamukungu, M., Schmitz, H., Fujitaka, K., Uchihori, Y., Kitamura, H., Reitz, G., Beaujean, R., Petrov, V., Shurshakov, V., Benghin, V., and Spurný. F. (2002) Calibration results obtained with Liulin-4 type dosimeters. *Adv Space Res* 30:917–925.

Dachev, T.P., Tomov, B.T., Matviichuk, Yu.N., Dimitrov, P.G., and Bankov, N.G. (2009) Relativistic electrons high doses at International Space Station and Foton M2/M3 satellites. *Adv Space Res* 44:1433–1440.

Dachev, Ts., Plock, O., Tomov, B., and Spurný, F. (2010) Analysis of the GCR dose rate increase onboard spacecraft and aircraft in the declining phase of the 23rd solar cycle. In *Fundamental Space Research*, supplement of *Comptes Rendus de l'Académie Bulgare des Sciences*, ISBN 987-954-322-409-8, pp 139–143. Available online at http://www.stil.bas.bg/FSR2009/pap139.pdf.

Dachev, T.P., Semkova, J., Tomov, B., Matviichuk, Yu., Dimitrov, Pl., Koleva, R., Malchev, St., Reitz, G., Horneck, G., De Angelis, G., Häder, D.-P., Petrov, V., Shurshakov, V., Benghin, V., Chernykh, I., Drobyshev, S., and Bankov. N.G. (2011a) space shuttle drops down the SAA doses on ISS. *Adv Space Res* 11:2030–2038.

Dachev, Ts.P., Tomov, B.T., Matviichuk, Yu.N., Dimitrov, Pl.G., Spurný, F., Ploc, O., Brabkova, K., and Jadrnickova. I. (2011b) Liulin-type spectrometry-dosimetry instruments. *Radiat Prot Dosimetry* 144:675–679.

Dachev, Ts.P., Tomov, B.T., Matviichuk, Yu.N., Dimitrov, Pl.G., Bankov, N.G., Reitz, G., Horneck, G., Häder, D.-P., Lebert, M., and Schuster, M. (2011c) Relativistic electron fluxes and dose rate variations during April–May 2010 geomagnetic disturbances in the R3DR data on ISS. *Adv Space Res* doi:10.1016/j.asr.2012.03.028, in press.

Ferrari, F. and Szuszkiewicz, E. (2009) Cosmic rays: a review for astrobiologists. *Astrobiology* 9:413–436.

Galperin, Yu.I., Ponamarev, Yu.N., and Sinizin, V.M. (1980) Some algorithms for calculation of geophysical information along the orbit of near Earth satellites. Report No 544, Space Research Institute, Moscow. In Russian.

Häder, D.-P. and Dachev, T.P. (2003) Measurement of solar and cosmic radiation during spaceflight. *Surveys in Geophysics* 24:229–246.

Heffner, J. (1971) *Nuclear Radiation and Safety in Space*, Atomizdat, Moscow. In Russian.

Heynderickx, D., Lemaire, J., and Daly, E.J. (1996) Historical review of the different procedures used to compute the L-parameter. *Radiat Meas* 26:325–331.

Horneck G. (1994) HZE particle effects in space. *Acta Astronaut* 32:749–755.

Horneck, G., Win-Williams, D.D., Mancinelli, R.L., Cadet, J., Munakata, N., Ronto, G., Edwards, H.G.M., Hock, B., Waenke, H., Reitz, G., Dachev, T., Haeder, D.P., and Briollet, C. (1999) Biological experiments on the EXPOSE facility of the International Space Station. In *Proceedings of the 2nd European*

Symposium: Utilisation of the International Space Station, European Space Agency, ESTEC, Noordwijk, the Netherlands, pp 459–468.

Horneck, G., Rettberg, P., Reitz, G., Wehner, J., Eschweiler, U., Strauch, K., Panitz, C., Starke, V., and Baumstark-Khan C. (2001) Protection of bacterial spores in space, a contribution to the discussion on panspermia. *Orig Life Evol Biosph* 6: 527–547.

McIlwain, C.E. (1961) Coordinates for mapping the distribution of magnetically trapped particles. *J Geophys Res* 66:3681–3691.

Nealy, J.E., Cucinotta, F.A., Wilson, J.W., Badavi, F.F., Zapp, N., Dachev, T., Tomov, B.T., Semones, E., Walker, S.A., De Angelis, G., Blattnig, S.R., and Atwell, W. (2007) Pre-engineering spaceflight validation of environmental models and the 2005 HZETRN simulation code. *Adv Space Res* 40:1593–1610.

Rabbow, E., Horneck, G., Rettberg, P., Schott, J.-U., Panitz, C., L'Afflitto, A., von Heise-Rotenburg, R., Willnecker, R., Baglioni, P., Hatton, J., Dettmann, J., Demets, R., and Reitz, G. (2009) EXPOSE, an astrobiological exposure facility on the International Space Station—from proposal to flight. *Orig Life Evol Biosph* 39:581–598.

Rabbow, E., Rettberg, P., Barczyk, S., Bohmeier, M., Parpart, A., Panitz, C., Horneck, G., von Heise-Rotenburg, R., Hoppenbrouwers, T., Willnecker, R., Baglioni, P., Demets, R., Dettmann, J., and Reitz, G. (2012) EXPOSE-E: an ESA astrobiology mission 1.5 years in space. Astrobiology 12:374–386.

Reitz, G., Beaujean, R., Benton, E., Burmeister, S., Dachev, Ts., Deme, S., Luszik-Bhadra, M., and Olko, P. (2005) Space radiation measurements on-board ISS—the DOSMAP experiment. *Radiat Prot Dosimetry* 116:374–379.

Schuster, M., Dachev, T., Richter, P., and Häder, D.-P. (2012) R3DE: Radiation Risk Radiometer-Dosimeter on the International Space Station—optical radiation data recorded during 18 months of EXPOSE-E exposure to open space. *Astrobiology* 12:393–402.

Semones, E. (2008) ISS TEPC measurement results. In *13th Workshop on Radiation Monitoring for the International Space Station (WRMISS),* Krakow, Poland, September 8–10, 2008. Available online from http://wrmiss.org/workshops/thirteenth/Semones_TEPC.pdf.

Simpson, J.A. (1983) Elemental and isotopic composition of the galactic cosmic rays. *Annu Rev Nucl Part Sci* 33:323–382.

Smart, D.F. and Shea, M.A. (2005) A review of geomagnetic cutoff rigidities for Earth-orbiting spacecraft. *Adv Space Res* 36:2012–2020.

Spurný, F. and Dachev, Ts. (2003) Long-term monitoring on the onboard aircraft crew exposure level with a Si-diode based spectrometer. *Adv Space Res* 32:53–58.

Uchihori, Y., Kitamura, H., Fujitaka, K., Dachev, Ts.P., Tomov, B.T., Dimitrov, P.G., and Matviichuk, Y. (2002) Analysis of the calibration results obtained with Liulin-4J spectrometer-dosimeter on protons and heavy ions. *Radiat Meas* 35:127–134.

Usoskin, I.G., Bazilevskaya, G.A., and Kovaltsov, G.A. (2011) Solar modulation parameter for cosmic rays since 1936 reconstructed from ground-based neutron monitors and ionization chambers. *J Geophys Res* 116, doi:10.1029/2010JA016105.

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