Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 44 (2009) 1433–1440

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Relativistic electrons high doses at International Space Station and Foton M2/M3 satellites

T.P. Dachev [a,*], B. Tomov [a], Yu. Matviichuk [a], Pl. Dimitrov [a], N. Bankov [b]

[a] Solar-Terrestrial Influences Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str. Block 3, 1113 Sofia, Bulgaria
[b] Space Research Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str. Block 29, 1113 Sofia, Bulgaria

Received 30 November 2008; received in revised form 27 September 2009; accepted 29 September 2009

Abstract

The paper presents observation of relativistic electrons. Data are collected by the Radiation Risk Radiometer-Dosimeters (R3D) B2/B3 modifications during the flights of Foton M2/M3 satellites in 2005 and 2007 as well as by the R3DE instrument at the European Technology Exposure Facility (EuTEF) on the Columbus External Payload Adaptor at the International Space Station (ISS) in the period February 20 – April 28, 2008. On the Foton M2/M3 satellites relativistic electrons are observed more frequently than on the ISS because of higher (62.8°) inclination of the orbit. At both Foton satellites the usual duration of the observations are a few minutes long. On the ISS the duration usually is about 1 min or less. The places of observations of high doses due to relativistic electrons are distributed mainly at latitudes above 50° geographic latitude in both hemispheres on Foton M2/M3 satellites. A very high maximum is found in the southern hemisphere at longitudinal range 0°–60°E. At the ISS the maximums are observed between 45° and 52° geographic latitude in both hemispheres mainly at longitudes equatorward from the magnetic poles. The measured absolute maximums of dose rates generated by relativistic electrons are found to be as follows: 304 μGy h^{-1} behind 1.75 g cm^{-2} shielding at Foton M2, 2314 μGy h^{-1} behind 0.71 g cm^{-2} shielding at Foton M3 and 19,195 μGy h^{-1} (Flux is 8363 cm^{-2} s^{-1}) behind les than 0.4 g cm^{-2} shielding at ISS.

Keywords: Space radiation; Relativistic electrons; Dosimetry; ISS; Radiation measurements

1. Introduction

Relativistic electron precipitations (REP) are observed for many years. First reports are by (Brown and Stone, 1972, Imhof et al., 1986, 1991). Most comprehensive study of long term observations of REP is made by (Zheng et al., 2006), using the 2–6 MeV electron data from SAMPEX satellite during 1992–2004.

Understanding the dynamics of relativistic electrons in the inner magnetosphere is of significant importance from both a practical and space physics point of view. While it is known that relativistic electrons can have deleterious effects on space assets and humans in space, the highly complex behavior and the delicate balance between acceleration and loss processes of radiation belt electrons have not been fully resolved (Zheng et al., 2006).

In the United States report of the Committee on Solar and Space Physics (2000), the total dose of an astronaut, who is spending 6 h on Extra Vehicular Activity (EVA) inside of REP, is estimated. The conclusion is that the dose will be great enough and will exceed astronaut's short term limits for both skin and eyes. One of the recommendations (3b on p. 37) is: "As soon as possible, JSC should install an electron dosimeter and an ion dosimeter outside the ISS that can return data in real time to Space Radiation Analysis Group (SRAG) at the Johnson Space Center". As we know similar dosimeters are still not installed outside the ISS. There is another more disturbing fact that there is no active control of the doses accumulated by the American astronauts and Russian cosmonauts during EVA.

In this paper we report on the observations of REP at very low altitudes. For example on the Foton M3 space-

* Corresponding author. Tel.: +359 2 870 0307; fax: +359 2 870 0178.
E-mail address: tdachev@bas.bg (T.P. Dachev).

0273-1177/$36.00 © 2009 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2009.09.023

craft they are observed at 277 km altitude in the Northern hemisphere on the 18th of September 2007. On the International Space Station we see REP at the lowest altitude of 344 km again in the Northern hemisphere on the 17th of March 2008. It seems that our observations of REP at the ISS are the first really reported measurements there.

2. Instrumentation

R3D B2/B3 and R3DE are successors of the Bulgarian–Russian dosimeter-radiometer LIULIN and of the Liulin-E094 (Dachev et al., 2002) instrument. LIULIN was installed in the working compartment of the MIR space station in 1988. LIULIN measurements were carried out under a wide variety of solar and geomagnetic activity conditions from 1989 until the middle of 1994 (Dachev et al., 1989, 1999a, 1999b).

Liulin-E094 was part of the experiment Dosimetric Mapping-E094 headed by Dr. 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 (Reitz et al., 2005; Dachev et al., 2006; Wilson et al., 2007; Nealy et al., 2007).

The experiments with the R3D-B2/B3 and R3DE spectrometers are performed after successful participations in ESA Announcements of Opportunities, led by German colleagues Dr. Gerda Horneck and Prof. Donat Häder (Horneck et al., 1999). The spectrometers were mutually developed with the colleagues from the University in Erlangen, Germany (Streb et al., 2002; Häder et al., 2008; Häder et al., 2009).

Both R3D B2/B3 spectrometers were placed inside of Biopan 5/6 facilities and used successfully during the flights of Foton M2/M3 satellites in June 2005 and September 2007 respectively (Häder et al., 2009; Damasso et al., 2009). R3DE spectrometer (Please see Fig. 1) was launched inside of the EXPOSE-E facility at the EuTEF platform of European Columbus module at the ISS in February 2008. The first data were received on February 17, 2008. Since that day until now (August 2009) the instrument has been working almost permanently with 10 s resolution (Dachev, 2009). Almost identical to R3DE but a 256 MB SD card allowing all data obtained for more than 1 year to be stored, is the R3DR spectrometer. It was launched at the Russian segment of ISS on the 26th of November, 2008.

Fig. 1. View of R3DE instrument, which is working on the EuTEF platform of the European Columbus module of the ISS since 20th of February 2008. The four solar UV and visible radiations photodiodes are seen in the centre of the figure.

Both modifications (R3D-B2/B3 and R3DE/R) are a low mass, small dimension automatic devices that measure solar radiation in four channels and ionizing radiation in 256 channels Liulin type energy deposition spectrometer. The four optical channels use four photodiodes with enhanced sensitivity in the following ultraviolet (UV) and visible ranges: UV–A (315–400 nm), UV–B (280–315 nm), UV–C (<280 nm) and Photosynthetic Active Radiation (PAR) (400–700 nm). They are constructed as filter dosimeters and measure the solar UV irradiance in W/m^2. Additional measurements of the temperature of UV photodiodes are performed for more precise UV irradiance assessments. The size of the aluminum box of R3DE/R instruments is $76 \times 76 \times 34$ mm (Dachev et al., 2005). The weight is 125 g. R3D B2/B3 instruments are with $53 \times 82 \times 28$ mm size of the boxes and 120 g wt. (Häder et al., 2009; Damasso et al., 2009).

The generalized block diagram of the instruments is shown at Fig. 2. Two microprocessors control the ionizing and the solar radiation circuitry, respectively, and the data are stored in a flash memory (2 MB) or transmitted to the ISS telemetry. The silicon detector and its circuitry are located above the photodiodes behind the aluminum box of the instrument and are not seen at Fig. 1. The photodiodes and the silicon detector are placed close to the preamplifiers to keep the noise level low. The signals from the solar radiation channels and the temperature sensor are digitized by a 12 bit A/D converter integrated in the microprocessor.

The ionizing radiation is monitored using a semiconductor detector (2 cm^2 area and 0.3 mm thick). Its signal is digitized by 12 bit fast A/D converter after passing a charge-sensitive preamplifier. The deposited energies

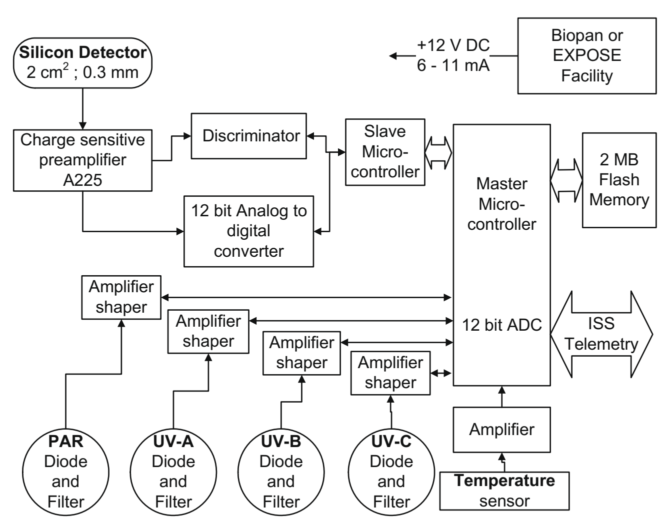

Fig. 2. Generalized block-diagram of the instruments on the Foton M2/M3 satellites and the ISS.

(doses) are determined by a pulse height analysis technique and then passed to a discriminator. The amplitudes of the pulses A [V] are transformed into digital signals, which are sorted into 256 channels by multi-channel analyzer. At every exposition 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 by (Dachev, 2009).

SI determination of the dose is used, in order to calculate the doses. SI determines that the dose is the energy in Joules deposited in 1 kg. The following equation is used:

$$D[Gy] = K\sum_{i=1}^{256}(EL_i i)[J]/MD[kg] \qquad (1)$$

where K is a coefficient, MD – the mass of the solid state detector in [kg] and EL_i the energy loss in Joules in channel i. The energy in MeV is proportional to the amplitude A of the pulse EL_i [MeV] = A [V]/0.24 [V/MeV]. 0.24 [V/MeV] is a coefficient depending on the preamplifier sensitivity used.

The construction of the R3D B2/B3 and R3DE/R boxes use in all cases 1.0 mm aluminum shielding before the detector. The total shielding of the detectors is formed by additional internal constructive shielding of 0.1 mm cooper and 0.2 mm plastic material. Thermo-luminescence detectors of the RADO experiment were mounted externally on the R3D B2/B3 instrument boxes on Foton M2/M3 satellites. The total external and internal shielding before the detectors of R3DE, R3D B3 and R3D B2 devices are 0.41, 0.81 and 1.75 g cm^{-2} respectively. The calculated stopping energy of normally incident particles to the detectors of the three instruments is 0.78, 1.4 and 2.81 MeV for electrons and 15.8, 23.7 and 35.6 MeV for protons (Berger et al., 2008). This means that only protons and electrons with energies higher than the above mentioned could reach the detectors.

3. Data obtained and analysis

3.1. Foton M2/M3 satellite data

Our first observations of relativistic electrons in the outer radiation belt were on Foton M2 satellite in June 2005. Unfortunately the maximum dose rate was not greater than 304 μGy h^{-1} mainly because the shielding in this case was 1.75 g cm^{-2}. We will not describe comprehensively the obtained data on the Foton M2 satellite because the data obtained on the Foton M3 satellite have almost the same features with much greater fluxes and doses.

Foton M3 is a Low Earth Orbit (LEO) satellite that orbited the Earth with a period of 89.9 min, an inclination of 62.8° with respect to the Earth's equator (highly inclined orbit), and with an altitude above the Earth surface in the range 263–302 km. During the mission the satellite completed 190 orbits. In this study the orbital parameters used are calculated by KADR-2 software (Galperin et al., 1980).

Fig. 3 illustrates the observations of the Foton M3 radiation environment by the R3D B3 instrument. Data started at 22:00:50 h on September 17, 2007 and finished at 07:51:50 h on September 18, 2007 presenting 591 measurements with 60 s resolution. On the figure there are two panels. The lower panel present with linear vertical black bars the total number of events (particles) reaching the detector per each 1 min measurement cycle in logarithmic scale on the Y axis. The upper panel is 3D spectra time diagram up to the first 64 channels of the total of the 256 channels spectrum of the instrument.

On the lower panel the moments when the satellite encounters REP are well seen with peaks of count rate above 3×10^3 particles per minute. The smooth meander with amplitude from tens to 3×10^2 particles is formed by the variations of the Galactic cosmic rays (GCR) when the satellite crosses the high and low latitudes. The high latitude crossings of Northern and Southern hemisphere are mentioned on the upper panel with “N” and “S” letters respectively. The three crossings of the region of the South Atlantic Anomaly (SAA), marked on the upper panel with the same abbreviation, are seen on the lower panel with peaks not higher than 2×10^3 particles per minute. The SAA crossings on the upper panel are well recognized by counts above the 32nd channel, while the REP crossings do not extend to the 24th channel. The accumulated counts in the first 12 channels of the spectrum with number 384 are more than 120,000. With this spectrum, the dose rate reaches the absolute maximum of 2314 μGy h^{-1} and the flux reaches 1032 cm^{-2} s^{-1} for the entire Foton M3 data. This point is at 04:24:50 UT on 18/09/2007 and is situated in the peak of the outer radiation belt in the Southern hemisphere at 295 km altitude with coordinates 24°E, 63°S and L = 4.36. This is the highest peak on Fig. 3, bottom panel.

The global distribution of dose rates, obtained by the R3D B3 instrument when the lid of Biopan 6 facility on Foton M3 satellite was open (between 17:13 UT on September 14 2007 and 17:02 UT on September 24, 2007) is presented in Fig. 4 as a surface map in coordinates geographic longitude and latitude. On the Z coordinate are the averaged dose rates in μGy h^{-1} in bins of 10° longitude and 5° latitude.

Fig. 4 reveals that dose distribution has three well formed maxima. The SAA region maximum, which is situated in the Southern hemisphere in longitudinal range 70°W–0° is with average dose rate of 150 μGy h^{-1}. The Southern hemisphere relativistic electrons maximum is situated closely to the predicted by AE-MIN model outer radiation belt maximum place (Vette, 1991; Heynderickx et al. 1996a) and reached an average value close to 300 μGy h^{-1}. The Northern hemisphere REP maximum is much smaller than the Southern and reached an averaged value of few tens of μGy h^{-1}.

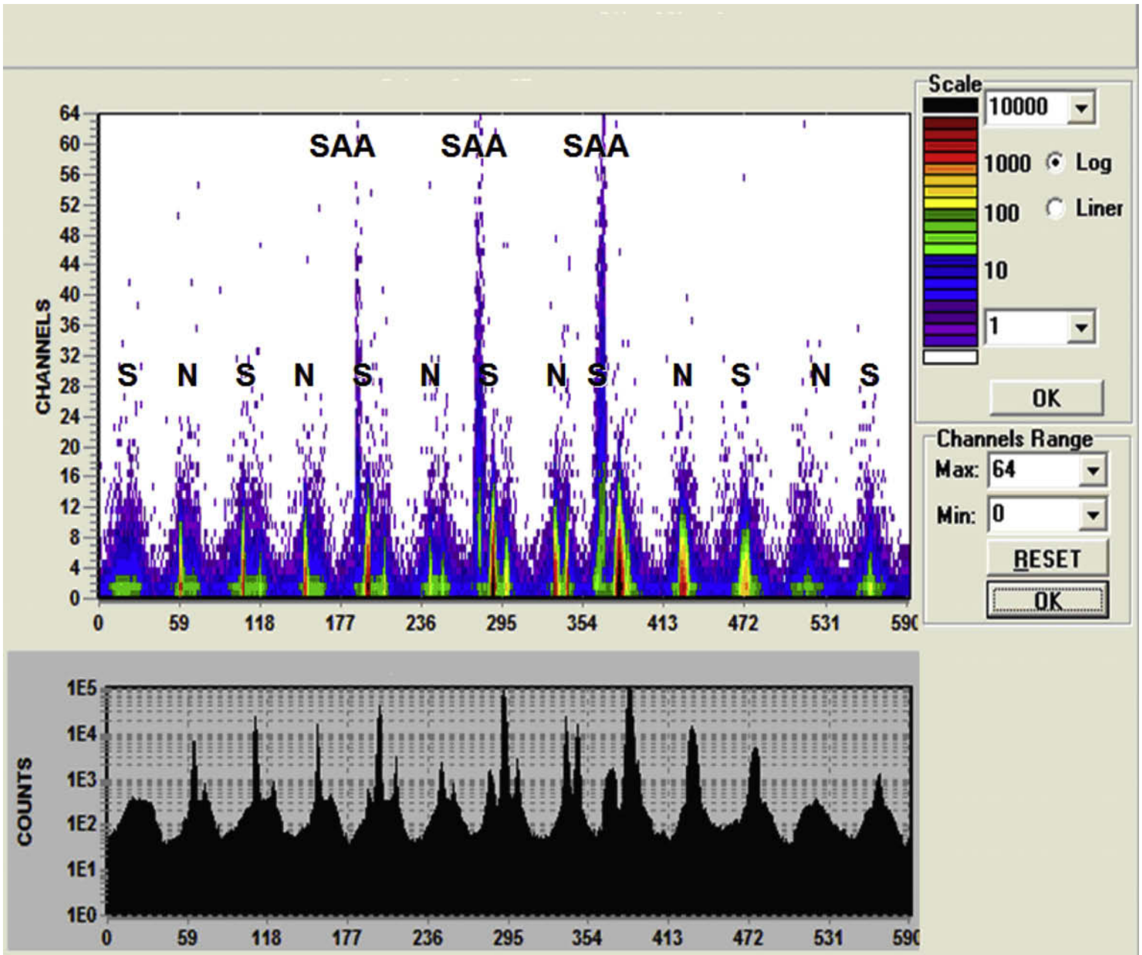

Fig. 3. Upper panel: 3D presentation of the counts in 1–64 channels of the spectrometer by relativistic electrons precipitations; Lower panel: Counts per minute observed by the R3D B3 instrument on the Foton M2 satellite. All except three mentioned in the upper panel as SAA spikes above 3×10^2 are generated by REP.

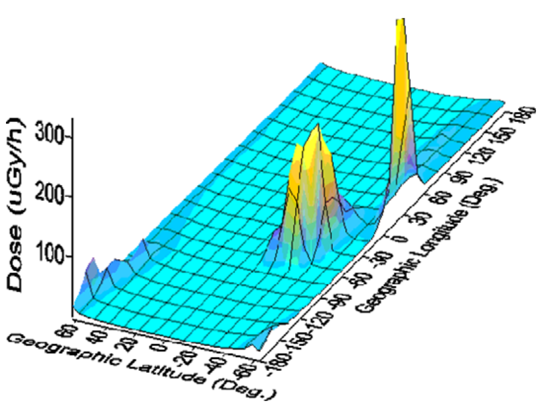

Fig. 4. Surface map presentation of the global distribution of Foton M3 dose rate data.

3.2. International Space Station data

ISS is a LEO satellite that orbits the Earth with a period of 91.2 min, an inclination of 51.6° with respect to the Earth's equator, and an altitude above the Earth's surface in the range 345–365 km for the period February–April 2008. The orbital parameters used in this study are calculated by KADR-2 software (Galperin et al., 1980).

Fig. 5 presents a case of REP, observed on ISS on March 5, 2008 from 14:27 to 14:46 UT, with 10 s resolution. This is the example when the absolute maximum of the observed dose rate at three satellites has reached – 19,194.6 μGy h^{-1} at 14:34:41 UT (Spectrum with number 45 on Fig. 5). Similar panels as in Fig. 3 are used. On the Y axes of the upper panel the first 32 channels of 116 spectra are presented with color codes. The two maxima seen there are created during one transit of ISS through the Southern hemisphere high latitude region. The first maximum is with coordinates 87.07°E, 51.65°S, L = 5.16 at 360.6 km altitude, while the second one is at 125.9°E, 46.33°S, L = 4.00, 358.3 km altitude. During the first maximum 167,264 relativistic electrons (19,194.6 μGy h^{-1}) are counted for 10 s, reaching the absolute flux maximum of 8363 cm^{-2} s^{-1}, that we have ever observed in space. The whole first REP takes 27 spectra or 4.5 min (Points 32 to 58 in the figure). The second enhancement's (points 58–81) maximal dose rate is only 667 μGy h^{-1} and 278 cm^{-2} s^{-1}.

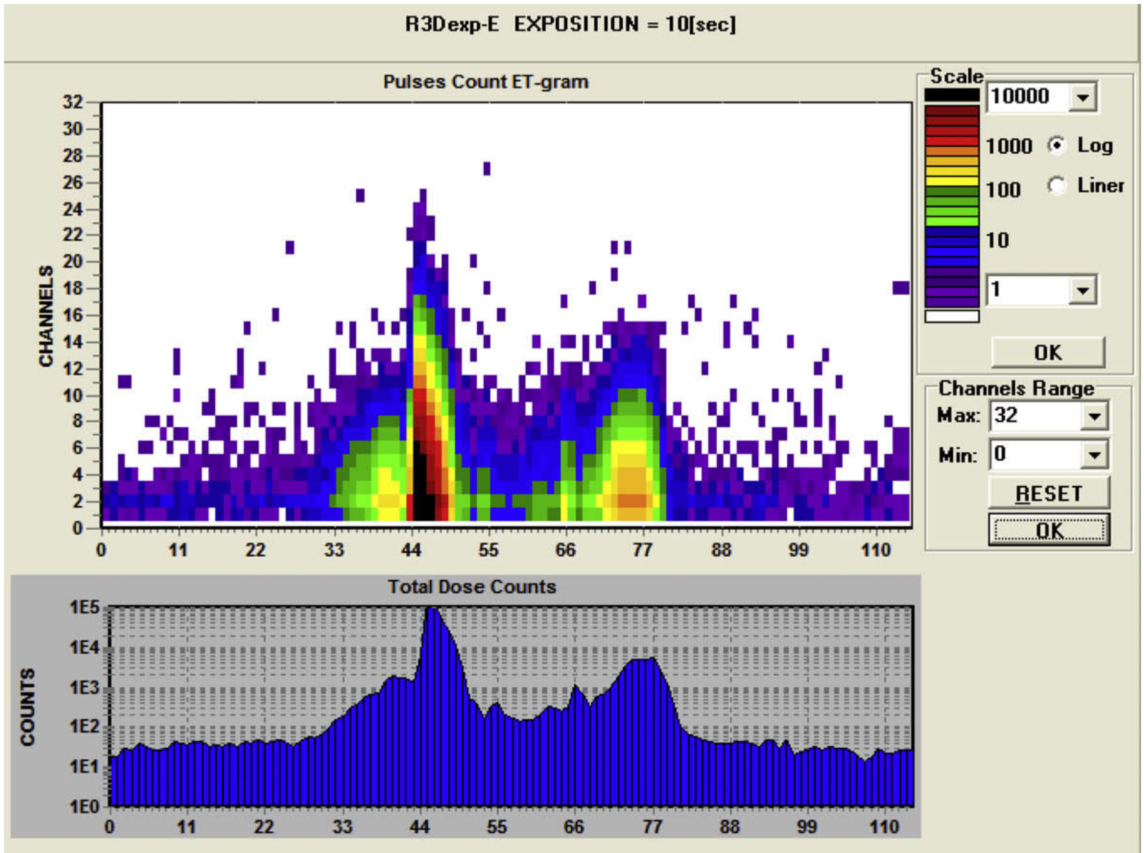

Fig. 5. 3D presentation of relativistic electrons precipitations observed by the R3DE instrument on the ISS.

Fig. 6 presents the radiation environment of ISS in the period 20 February–20 March 2008. Only cases with dose rates above 100 μGy h^{-1} are selected. Geographic longitude is on the X axis.

The bottom panel (of four) shows the dose rates separated for ascending and descending orbits of the station. The interval of longitude between 120°W and 75°W is populated by relativistic electrons in the Northern hemisphere (Latitudes between 45°N and 52°N as seen on the third panel from the bottom). The deposited dose rates reached a maximum of 2000 μGy h^{-1}. This is about 10 times lower than analogical maximum in the Southern hemisphere seen in the longitude range 60°E–120°E on the bottom panel. The small altitudinal difference between Northern hemisphere (347 km) and Southern hemisphere 360 km (seen on the top panel) is not the reason for the difference. The main reason is the asymmetry of both hemispheres caused by the angle between the axes of geographic and geomagnetic poles that leads to larger magnetic latitude values in the Southern hemisphere region equatorward from the magnetic pole. That is why the maximum McIlwain's – L-parameter value (McIlwain, 1961; Heynderickx et al. 1996b) reached by the station in the Southern hemisphere is 6.2, while in the Northern is only 4.75.

Very special features of the radiation environment are seen in the second panel from bottom. Both regions with relativistic electrons population in the Northern and Southern hemispheres are plotted against the left side axes of the panel, i.e. the specific energy of the particles in nGy cm^{-2} $particle^{-1}$. It is seen that both regions shows similar specific energies with an average value about 0.65 nGy cm^{-2} $particle^{-1}$, which is about 0.2 higher than the value of 1–10 MeV electrons according to (Haffner, 1971; Dachev, 2009). The higher values are explained by the way of calculation of the specific energy. The latter uses the whole spectrum of the instrument, while the relativistic electrons are really seen up to channel 24. All other channels, up to 256, collect higher specific energy particles thus enlarging the average value.

The specific energies of relativistic electrons and of high energy protons inside of the South Atlantic Anomaly (SAA) are plotted in the second panel of Fig. 6. The relativistic electrons specific energies have values about 0.65 nGy cm^{-2} $particle^{-1}$. Protons' specific energies are presented with many points forming a heavy black patch rising from about 2 to 6 nGy cm^{-2} $particle^{-1}$ in longitudes 67°W–0°. Applying a formula calculating the relation between specific and incident energies cited by Haffner (1971) and Dachev (2009) we have calculated the incident energy of the SAA protons. The result is presented in the second panel against the right side axes as another patch falling from about 70 MeV to 10 MeV. These values well

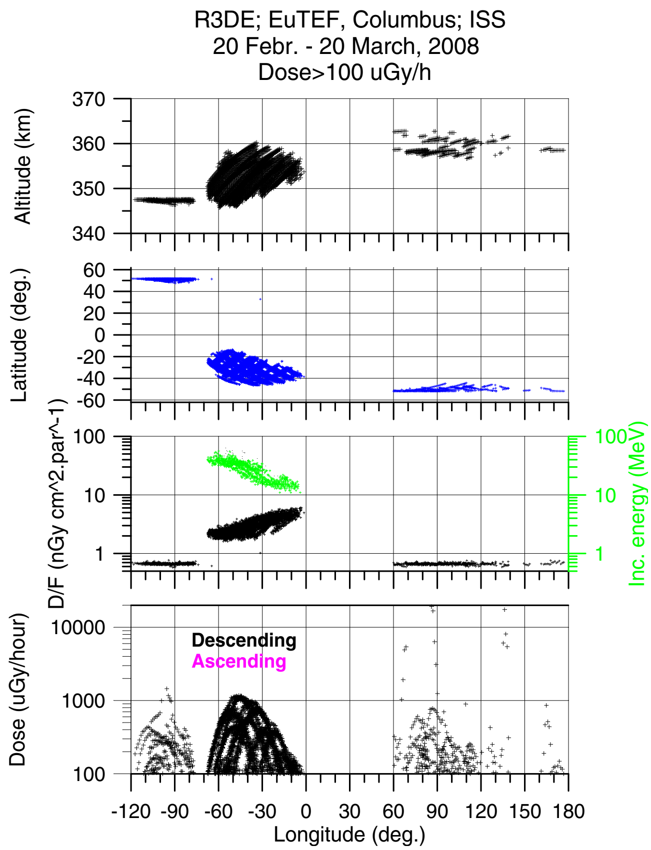

Fig. 6. Characterization of the ISS radiation environment with more than 100 μGy h^{-1} deposited dose rates.

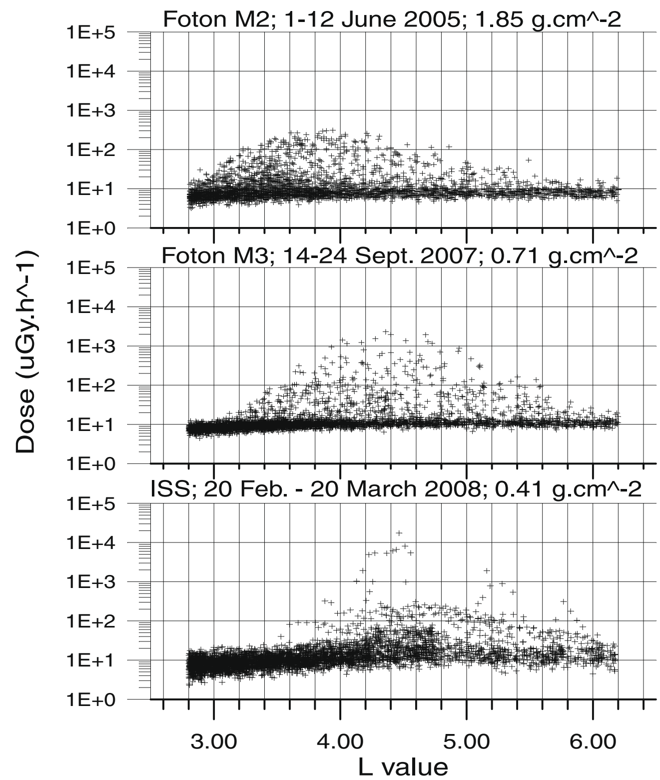

Fig. 7. Comparison of REP data obtained on the ISS and the Foton M2/M3 satellites at high latitudes.

correspond to the values in the AP-8 MIN model published in (WDC-A-R&S, 76-06, 1976 http://www.ccmc.gsfc.nasa.gov/modelweb/magnetos/AP-8-min-max-76-6.pdf.

There is no well seen anisotropy in REP dose rates for the ascending and descending orbits of the ISS in Fig. 6, while in the region of the SAA (bottom panel of Fig. 6) the descending orbit doses are 15% higher. This is due to the higher shielding of the R3DE detector from the different segments of the station during the ascending parts of the orbits.

3.3. Comparison of all data

Comparison of all data obtained at high latitudes by the three different satellites is presented in Fig. 7. The X axis is the McIlwain's – L-parameter (McIlwain, 1961) in the range between 2.5 and 6.5 (Heynderickx et al., 1996b), because, according to Zheng et al., (2006), this is the range where more often REP is observed. On the Y axes in three panels the dose rates obtained on ISS, Foton M3 and Foton M2 satellites are presented.

The points, organized as heavy black lines, in the lower part of all panels are generated by measurements of the dose rates from GCR particles. For L-values greater than 4.0, the dose rates are below 10 μGy h^{-1} on Foton M2 in 2005, equal to 10 μGy h^{-1} on Foton M3 in 2007 and tend to be above 10 μGy h^{-1} on ISS in 2008. This follows the well known anticorrelation of GCR flux and solar activity (O'Neill, 2006). It is hard to separate the spectra with mixed radiation of REP and GCR but we consider that all dose rates above 20 μGy h^{-1} originate by relativistic electrons in the outer radiation belt.

The maximum dose rates depend strongly on the shielding before the detector (Fig. 7). On Foton M2 (upper panel), where the shielding is a maximum in comparison with other two satellites, the maximum dose rates do not exceed 300 μGy h^{-1}. The position of the maximum is shifted toward lower L values due to higher shielding and respectively higher energies of the electrons reaching the detector.

The Foton M3 distribution (middle panel) is symmetrical to $L = 4.4$ and coincides well with the observations in Zheng et al. (2006). Lower shielding, in comparison with Foton M2 satellite, brings about one order of magnitude higher doses. REP is seen very regularly in Southern hemisphere maximum in the data of Foton M2/M3 satellites (Fig. 4).

REP observations on ISS (bottom panel, Fig. 7) give the highest dose rates because of the lowest shielding. They are rare and very sporadic as the ISS never reaches the REP maximum in the Southern hemisphere. This is due to the lower inclination of the ISS compared to the inclinations of both Foton satellites. Only eight events with dose rates above 2000 μGy h^{-1} were observed during the entire operation period of the R3DE instrument on the ISS between February and July 2008.

4. Conclusions

Relativistic electrons are observed by the R3D B2/B3 instruments during the flights of the Foton M2/M3 satellites in 2005 and 2007 and by the R3DE instrument at the EuTEF facility of the European Columbus module of the International Space Station (ISS) in the period February 20–April 28, 2008.

On the Foton M2/M3 satellites relativistic electrons are observed more frequently than on the ISS because of the higher (62.8°) inclination of the orbit. At both satellites usual duration of the observation is a few minutes. On the ISS the duration usually is about 1 min or even less.

The places of the observations of high doses are distributed for the Foton M2/M3 satellites mainly at latitudes above 50° geographic latitude in both hemispheres. A strong maximum is found in the Southern hemisphere in the longitudinal range 0°–60°E. At the Columbus module of the ISS the maxima are observed between 45° and 51.6° geographic latitude in both hemispheres at longitudes equatorward from the places of magnetic poles.

The measured absolute maxima of dose rates generated by relativistic electrons are as follows: 304 μGy h^{-1} behind 1.75 g cm^{-2} shielding at Foton M2, 2314 μGyh^{-1} behind 0.71 g cm^{-2} shielding at Foton M3 and 19,195 μGy h^{-1} (Flux is 8363 cm^{-2} s^{-1}) behind less than 0.4 g cm^{-2} shielding at the ISS.

If we will consider that the danger for the astronauts being on EVA relativistic electrons events are with dose rate above 500 μGy h^{-1} than for the period February 22–March 18, 2008 we have collected 132 intervals of 10 s each, which is only 22 min separated in different days and orbits. From the point of view of astronauts' radiation protection this does not result in a dangerous increase of the radiation doses. On the other hand, these observations are made during very low solar activity. Long period observations with SAMPEX satellite (Zheng et al., 2006) have shown an increase of the REP observations when the solar activity is higher. This confirms once again the necessity of permanent active monitoring of the radiation doses of astronauts during EVA.

Acknowledgements

The authors are thankful to German colleagues: G. Horneck, D.-P. Häder and G. Reitz, principal investigators of the experiments with R3D type instruments on Foton M2/M3 satellites and on ISS. This work was partially performed in the frame of the Bulgarian Science Fund project No НЗ-1511/2005.

References

WDC-A-R&S report, AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum, WDC-A-R&S, 76-06, pp 71–78, 1976. http://www.ccmc.gsfc.nasa.gov/modelweb/magnetos/AP-8-min-max-76-6.pdf.

Berger, M.J., Coursey, J.S., Zucker, M.A., Chang, J., Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions, NIST Standard Reference Database 124, December, 2008.http://www.physics.nist.gov/PhysRefData/Star/Text/contents.html.

Brown, J.C., Stone, E.C. High-energy electron spikes at high latitudes. J. Geophys Res. 77, 3384–3391, 1972.

Committee on Solar and Space Physics and Committee on Solar-Terrestrial Research, National Research Council, Radiation and the International Space Station: Recommendations to Reduce Risk, ISBN: 0-309-51536-X, pp 37, 2000.

Dachev, Ts.P., Matviichuk, Yu.N., Semkova, J.V., Koleva, R.T., Boichev, P., Baynov, B., Kanchev, N.A., Lakov, P., Ivanov, Ya.J., Tomov, P.T., Petrov, V.M., Redko, V.I., Kojarinov, V.I., Tykva, R. Space radiation dosimetry with active detections for the scientific program of the second Bulgarian cosmonaut on board the MIR space station. Adv. Space Res. 9 (10), 247–251, 1989.

Dachev, Ts.P., Tomov, B.T., Matviichuk, Yu.N., Koleva, R.T., Semkova, J.V., Petrov, V.M., Benghin, V.V., Ivanov, Yu.V., Shurshakov, V.A., Lemaire, J. Detailed study of the SPE and their effects on the dose rate and flux distribution observed by Liulin instrument on MIR space station. Radiat. Meas. 30 (3), 317–325, 1999a.

Dachev, Ts.P., Tomov, B.T., Matviichuk, Yu.N., Koleva, R.T., Semkova, J.V., Petrov, V.M., Benghin, V.V., Ivanov, Yu.V., Shurshakov, V.A., Lemaire, J. Solar cycle variations of MIR radiation environment as observed by the Liulin dosimeter. Radiat. Meas. 30 (3), 269–274, 1999b.

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

Dachev, Ts., Dimitrov, Pl., Tomov, B., Matviichuk, Yu., New Bulgarian build spectrometry-dosimetry instruments – short description. In: Proceedings of 11th International Science Conference on Solar-Terrestrial Influences, pp 195–198, Sofia, November 23–25, 2005. http://www.stil.bas.bg/11conf/Proc/195-198.pdf.

Dachev, T., Atwell, W., Semones, E., Tomov, B., Reddell, B. ISS observations of SAA radiation distribution by Liulin-E094 instrument. Adv. Space Res. 37, 1672–1677, 2006.

Dachev, T.P. Characterization of the near earth radiation environment by Liulin type spectrometers. J. Adv. Space Res., doi:10.1016/j.asr.2009.08.007, 2009.

Damasso, M., Dachev, Ts., Falzetta, G., Giardi, M.T., Rea, G., Zanini, A. The radiation environment observed by Liulin-photo and R3D-B3 spectrum-dosimeters inside and outside Foton-M3 spacecraft. Radiat. Meas. 44 (3), 263–272, 2009.

Galperin, Yu.I., Ponamarev, Yu.N., Sinizin, V.M. Some Algorithms for Calculation of Geophysical Information Along the Orbit of Near Earth Satellites, Report No 544. Space Res. Inst., Moscow, 1980 (in Russian).

Häder, D.P., Richter, P., Schuster, M., Dachev, Ts., Tomov, B., Georgiev, Pl., Matviichuk, Yu. R3D-B2 – measurement of ionizing and solar radiation in open space in the BIOPAN 5 facility outside the FOTON M2 satellite. Adv. Space Res. 43 (8), 1200–1211, 2009.

Häder, D.P., Strauch, S.M., Schuster, M., Dachev, Ts., Tomov, B., Georgiev Pl., Matviichuk, Yu., R3D-B3 – measurement of ionizing and solar radiation in open space in the BIOPAN 6 facility outside the FOTON M3 satellite. J. Microgravity Sci. Technol., submitted for publication.

Haffner, J. Nuclear Radiation and Shielding in Outer Space. Atomizdat, Moscow, p. 115 (in Russian), 1971.

Heynderickx, D., Lemaire, J., Daly, E.J., Evans, H.D.R. Calculating Low-altitude trapped particle fluxes with the NASA models AP-8 and AE-8. Radiat. Meas. 26, 947–952 (see also)http://www.spenvis.oma.be/spenvis/help/background/traprad/traprad.html, 1996a.

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

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., Häder, D.P., Briollet C. Biological experiments on the expose facility of the International Space Station. In: Proceedings of the 2nd European Symposium – Utilisation of the International Space Station, ESTEC, Noordwijk, 16–18 November 1998, SP–433, pp. 459–468, 1999.

Imhof, W.L., Voss, H.D., Datlowe, D.W., Gaines, E.E., Mobilia, J., Evans, D.S. Relativistic electron and energetic ion precipitation spikes near the plasmapause. J. Geophys. Res. 91, 3077–3088, 1986.

Imhof, W.L., Voss, H.D., Mobilia, J., Datlowe, D.W., Gaines, E.E. The precipitation of relativistic electrons near the trapping boundary. J. Geophys Res. 96, 5619–5629, 1991.

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

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., Atwell, W. Pre-engineering spaceflight validation of environmental models and the 2005 HZETRN simulation code. Adv. Space Res. 40 (11), 1593–1610, 2007.

O'Neill, P.M. Badhwar–O'Neill galactic cosmic ray model update based on advanced composition explorer (ACE), energy spectra from 1997 to present. Adv. Space Res. 37 (9), 1727–1733, 2006.

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

Streb, C., Richter, P., Lebert, M., Dachev, T., Häder D.-P. R3D-B, Radiation risk radiometer-dosimeter on biopan (Foton) and expose on International Space Station. In: Proceedings of the Second Exo-Astrobiology workshop, Graz, Austria, 71–74, ESA SP-518, November, 2002.

Vette, J.I. The AE-8 Trapped Electron Model Environment, NSSDC/WDC-A-R&S 91-24, 1991.

Wilson, J.W., Nealy, J.E., Dachev, T., Tomov, B.T., Cucinotta, F.A., Badavi, F.F., de Angelis, G., Leutke, N., Atwell, W. Time serial analysis of the induced LEO environment within the ISS 6A. Adv. Space Res. 40 (11), 1562–1570, 2007.

Zheng, Y., Lui, A.T.Y., Li, X., Fok, M.-C. Characteristics of 2–6 MeV electrons in the slot region and inner radiation belt. J. Geophys. Res. 111, A10204, doi:10.1029/2006JA011748, 2006.