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HIGH ENERGY DEPOSITING EVENTS OBSERVED INSIDE AND OUTSIDE OF THE EARTHS MAGNETOSPHERE

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Abstract: *Three Liulin type spectrometers performed measurements of the energetic particles flux outside the International Space Station (ISS) in 3 long-term periods between 2008 and 2016. Very similar instrument was flown in the interplanetary space between the Earth and Moon and around the Moon on the Indian Chandrayaan 1 satellite in 2008-2009. All instruments are Bulgarian-built Liulin-type miniature spectrometer-dosimeters and acquired more than ten million energy deposited spectra from which the flux and absorbed dose rate were calculated with 10 s resolution behind less than 0.3 g cm^{-2} shielding. This paper analyses the high energy depositing events, which was observed in the 256th channel when the deposited in the detector energy is higher than the upper limit of the 256 channels spectrometer of 20.8 MeV. These events can be explained with registration of high charge and energy (HZE) ions (He^+, C^+, O^+, Ne^+, Mg^+ Si^+ and Fe^+) in the Galactic cosmic ray (GCR) source and with long path proton crossings of the detector in the region of the South Atlantic anomaly (SAA) and during solar energetic particles events (SEP). The paper analyses the global distribution of the high energy depositing events observed inside the Earths magnetosphere. The high energy deposition fluxes in the 256 channel of the spectrometer in GCR, observed by RADOM instrument, outside the Earth magnetosphere and atmosphere outside Chandrayaan-1 satellite, are 6.8 times more frequent than the average by R3D/E/R/R2 instruments outside ISS. The higher flux and the presence of high charge and energy (HZE) ions outside of the Earth magnetosphere and atmosphere poses higher health risks for the humans being on missions on the Moon or Mars surfaces or in the Solar system interplanetary space.*

СЪБИТИЯ С ВИСОКО ЕНЕРГИЙНО ОТДАВАНЕ, НАБЛЮДАВАНИ В И ИЗВЪН МАГНИТОСФЕРАТА НА ЗЕМЯТА

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Резюме*: Три спектрометри от типа "Люлин" проведоха измервания на потока от енергийни частици извън Международната космическа станция (ISS) в 3 дългосрочни периода между 2008 и 2016 г. Много подобен прибор работи в междупланетното пространство между Земята и Луната и около Луната на индийския спътник Chandrayaan 1 през 2008-2009 година. Тези прибори са спектрометри-дозиметри от типа "Люлин" и са разработени в секцията по „Слънчево-земна физика" на ИКИТ-БАН. Получените повече от десет милиона спектри на депозираната енергия са използвани да се изчислят потока и мощността на абсорбираната доза с разделителна способност от 10 s зад екранировка от 0.3 g cm^{-2}. Тази статия анализира потока на събития с висока депозирана енергия, които се наблюдават в 256-тия канал на спектрометъра, когато депозираната в детектора енергия е по-висока от горната граница на 256-тия канал на спектрометъра от 20,8 MeV. Тези събития могат да бъдат обяснени с регистриране на високоенергийни йони (He^+, C^+, O^+, Ne^+, Mg^+ Si^+ and Fe^+) с висока енергия и голям атомен номер (HZE) в галактическите космически лъчи (GCR) и с преминаване на протони надлъжно през детектора в региона на Южна-Атлантическата аномалия (SAA) и по време на слънчеви протонни събития (SPE). В статията се анализира глобалното разпространение на събитията с високо енергийно отдаване, наблюдавани в и извън земната магнитосфера. Потокът от събития в GCR с висока депозирана енергия в 256 канал на спектрометъра, наблюдавани от инструмента RADOM, извън земната магнитосфера и атмосферата извън спътника Chandrayaan-1, са 6.8 пъти по-голям от средните в приборите R3D/E/R/R2 извън ISS. По големият поток и наличието на високоенергийни йони създава по-високи рискове за здравето на хората, които са на мисии на повърхността на Луната или Марс или в междупланетното пространство на Слънчевата система.*

Introduction

There are three principal sources of primary ionizing radiation in low earth orbits (LEO): (1) galactic cosmic rays (GCR); (2) solar energetic particles (SEP), high fluxes of charged particles emitted during sporadic but intense solar flares and coronal mass ejections; (3) energetic electrons trapped in the outer radiation belt (ORB) and energetic protons trapped in the inner radiation belts (IRB). In LEO, a fourth source, albedo neutrons and protons, is also encountered [1]. Flux and dose characteristics in the near Earth space radiation environment depend on factors such as orbit parameters, solar cycle phase and current helio and geomagnetic conditions.

1. R3D and RADOM instruments

A total of fourteen successful space instruments were developed, qualified and used in numerous space missions between 1988 and 2018 [2, 3] by the scientist from the Solar-Terrestrial Physics Section of SRTI–BAS.

This paper analyze the high energy deposition events observed at three Liulin type spectrometers, which performed measurements of the energetic particles flux outside the International Space Station (ISS) in 3 long-term periods between 2008 and 2016. Very similar instrument was flown in the interplanetary space between the Earth and Moon and around the Moon on the Indian Chandrayaan 1 satellite in 2008–2009 [4].

The left part of Fig. 1 shows an external view of the R3D instruments (named R3D/E/R/R2) mounted on the 3 EXPOSE/E/R/R2 facilities outside ISS. The R3D instrument is a small-dimension (76x76x36 mm), low-mass (0.17 kg) automatic devices that measures solar electromagnetic radiation in four channels and ionizing radiation in 256 channels of a Liulin-type deposited energy spectrometer (DES) [2]. In left part of Fig. 1 small circles on the surface in the central portion of the R3D instrument show the four solar visible-and UV-radiation photodiodes, whose data are not addressed in this paper. The ionizing radiation detector (silicon PIN diode of Hamamatsu S2744-08 type) is located behind the aluminum wall of the instruments and are therefore not visible.

On the right part of Fig. 1 the external view of RADOM instrument is shown. The dimensions of the instrument are size of 120x40x20 mm and mass of 0.098 kg. It contains the same ionizing radiation detector as R3D instruments but don’t have solar electromagnetic radiation spectrometer.

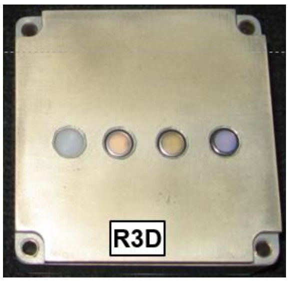

Fig. 1. External view of the R3D and RADOM instruments

The R3D and RADOM instruments [2, 4] contain: one semiconductor detector (Hamamatsu (S2744-08) PIN diode 2 cm^2 area, 0.3 mm thick), one charge-sensitive preamplifier, 12 bit analogue to digital converter (ADC), 256 channels multichannel analyzer and serial interface of RS422 toward the EXPOSE facility. Pulse analysis technique is used to obtain the deposited energy spectrum, which further is used for the calculation of the absorbed dose and the flux in the silicon detector. The two microcontrollers, through specially developed firmware, manage the measurements and communications of the instrument.

The main measurement unit in the R3D and RADOM instrument is the amplitude of the pulse after the preamplifier, generated by particles or quanta, hitting the detector [2]. The amplitude of the pulse is proportional by a factor of 240 mV MeV^{-1} to the energy loss in the detector and respectively to the dose. By 12 bit analogue to digital converter (ADC) these amplitudes are digitized and organized in a 256-channel deposited energy spectrum. The dose in the silicon detector D_{Si} [Gy] by definition in System international (SI) is one Joule deposited in 1 kg of matter. The absorbed dose is calculated by dividing the summarized in 256 channels energy depositions in the spectrum in Joules to the mass of the detector in kilograms.

The semiconductor detector of the R3D instruments was mounted approximately 7 mm below the 0.8 mm thick aluminum cover plate. Furthermore, there was shielding from 0.07 mm copper and 0.2 mm plastic, which provided 0.3 g cm^{-2} of total shielding from the front side. The calculated required kinetic energy of particles arriving perpendicular to the detector was 0.835 MeV for electrons and 19.5 MeV for protons. This means that only electrons and protons with energies exceeding the values listed above can cross the R3DR2 shielding materials and reach the detector surface. The detector shielding, being larger from the sides and from behind (Fig. 1), stops all ORB relativistic electrons, attenuates the lower energy IRB protons, but practically does not change the flux of the primary GCR particles.

2. Observations

The current paper analyses the high energy deposition events obtained with 3 R3D instruments on ISS and with RADOM instrument on the Indian Chandrayaan-1 lunar satellite:

- R3DE instrument was installed in Expose-E facility outside ESA Columbus module of the ISS. The R3DE data covered the time interval between February 22, 2008 and September 1, 2009 [5];

- Expose-R facility mounted outside of the Russian “Zvezda” module hosted the R3DR instrument [6] in the period from March 11, 2009 to August 20, 2010 outside of the Russian “Zvezda” module;

- R3DR2 was installed in the same place as R3DR instrument from October 24, 2014 to January 10, 2016 [7, 8];

- RADOM instrument was mounted outside of the Indian Chandrayaan-1 satellite launched to the Moon on 22 October 2008 and injected into a 255 x 22,860 km orbit. After separation from the launcher, the spacecraft rose to moon rendezvous orbit by five consecutive in-plane perigee maneuvers to achieve the required 386,000 km apogee that placed it in a lunar transfer trajectory. Here we use the data obtained between 29 October and 9 November 1988 when the satellite was in the interplanetary GCR source at altitudes between 90,000 and 360,000 km, far away from the bodies of Earth and Moon.

The different radiation sources, named GCR, SAA, SEP and outer radiation belt (ORB), are separated using the selection procedure described recently by Dachev et al. in [7] and some additional requirements. Finally, the SAA source is selected by the following requirements: Dose rate>15 μGy h^{-1}, D/F ratio>1.12 nGy cm^2 particle^{-1}, L-value<3; B<0.23 Gauss. The GCR source: Dose rate<15 μGy h^{-1}, B>0.23. The ORB source: Dose rate>15 μGy h^{-1}, D/F ratio<1.12 nGy cm^2 particle^{-1}, B>0.23.; (2) Larger amount of them 677 counts are in the SAA source. The SEP source: Dose rate>15 μGy h^{-1}, D/F ratio>1.12 nGy cm^2 particle^{-1}, B>0.23. Only in the data of the R3DR2 instrument were found and selected SEP particles.

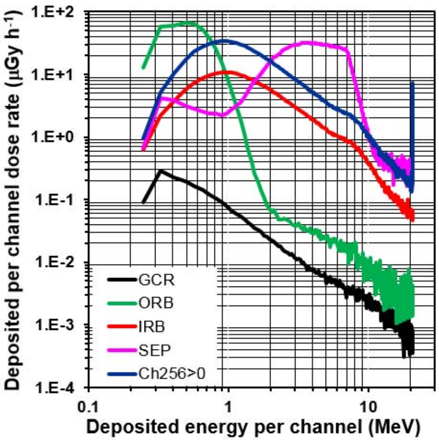

Fig. 2. Deposited energy spectra from different radiation sources

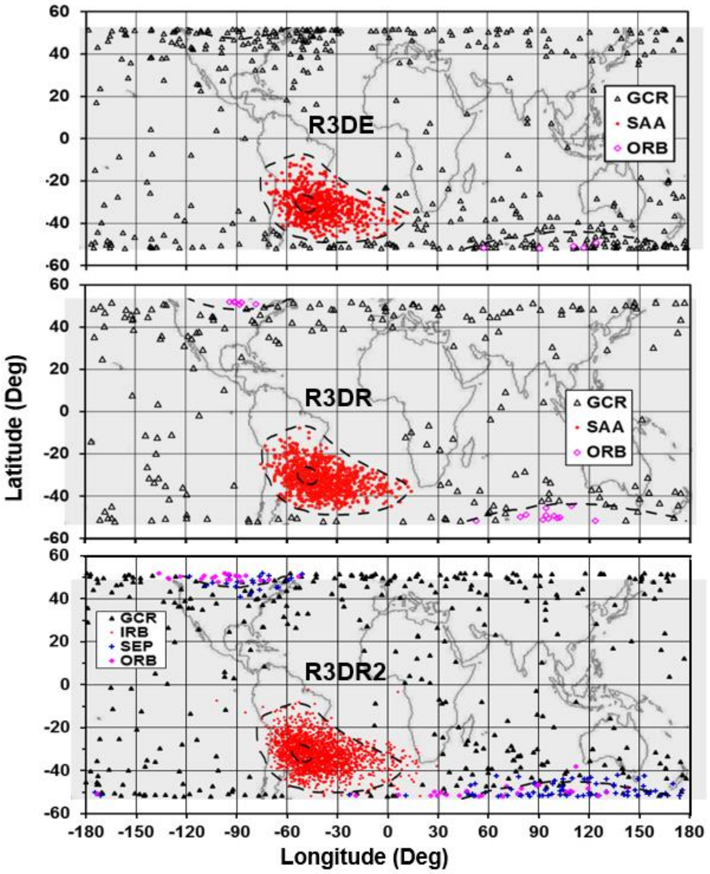

Fig. 3. Global distribution of the locations of the high energy deposition events as observed R3DE/R/R2 instruments

Fig. 2 illustrates how the high energy deposition events in the IRB source are seen in the energy deposition spectra. The presented GCR, ORB and SEP spectra are obtained by the R3DR2 instrument from 21 to 30 June 2015. The deposited dose rate is the area between the abscissa and the curve of the deposited energy spectrum that is why the GCR spectrum (black line) is in the bottom of Fig. 2. The ORB spectrum (green line) shows large maximum in the range up to 2 MeV because the high energy electrons, which built it, are relatively low energy deposition particles. The magenta line presents the SEP spectrum from the solar proton event on 22 June 2015. The event was built by relatively low energy protons, which produces the maximum in the range between 1 and 10 MeV.

The red line IRB spectrum presents the result from averaging of all (254,320) R3DR2 IRB spectra. The existence of high energy deposition events in the 256 channel (the last point in the spectra) is not seen because of relatively low number of spectra, which contains 1 there. The blue line IRB spectrum presents the result of averaging only the spectra, which have 1 in the last channel (1822 spectra). In the 256th channel of this spectrum is seen large vertical blue line, which presets this large value. The blue spectrum is higher than the red one because the probability for observation of high energy depositing events are higher in higher flux, respectively higher dose rate.

Fig. 4 presents the global distribution of the locations where the high energy depositing events in the 256th channel were observed in the spectrometers of the R3DE/R/R2 instruments. This means that in the 10 sec interval of each measurements in the 256 channel of the spectrometer is observed value greater than zero. Usually this value is 1 and in very rare occasions, only in the SAA source 2. The dashed lines in Fig. 4 represent the isolines of flux observed with R3RE instrument equal to 2.5 and 120 cm^{-2} s^{-1}, giving to the reader an idea where the SAA in flux is situated and where the high latitude regions in the both hemispheres are extended.

We consider to investigate more precisely only the fluxes of particles observed in the GCR and ORB sources because the fluxes in SAA and SEP sources have known origin from long path proton crossings of the detector in the region of the SAA and during SEP events.

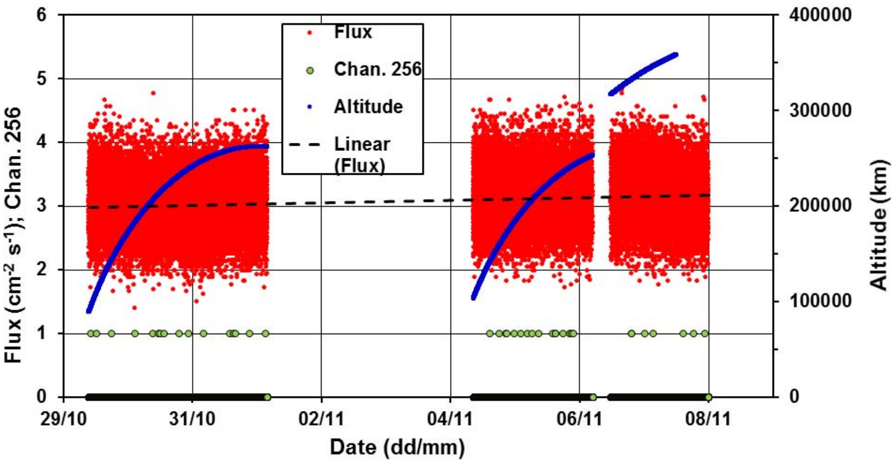

Fig. 4. Interplanetary GCR flux variations as observed with RADOM instrument

Figure 5 presents the RADOM GCR data obtained in the interplanetary space between Earth and Moon in the time interval 29/10/2008 09:46:12-08/11/2008 00:00:00 UT. On the left hand axis are plotted the measured flux (red points) in cm^{-2} s^{-1} and the values of the 256th channel (green points) being in the most of the time equal to 0 and in 39 cases equal to 1. On the right hand axis is plotted the altitude (blue points) of the Chandrayaan-1 satellite above the Earth surface.

It is seen that the flux values are stable in the range 1.4–4.8 cm^{-2} s^{-1}. The linear average of the flux, presented with heavy black line, have very small trend of increase between 3.0 and 3.15 cm^{-2} s^{-1}, which is connected with a real increase of the GCR flux in the Earth vicinity, as observed by the Oulu neutron monitor [4].

As GCR pass through a target, a multitude of electromagnetic and nuclear interactions cause the incident particles to deposit some of their kinetic energy into the target material. The energy is deposited primarily in the form of ionization of atoms in the target. The rate at which the incident particle deposits its energy in the target is termed linear energy transfer (LET=-dE/dx), energy deposited per unit path length) [8]. The LET spectrum and its evolution through the human body are essential ingredients in understanding and mitigating the potential radiation risk posed by energetic particles [9].

Fig. 5 compare [10]:

- 2012–2013 silicon LET spectrum (large black points) from RAD instrument on Curiosity rower at the surface of Mars behind ~21 g cm^{-2} CO_2 shielding;
- 2009–2011 silicon LET spectra from CRaTER instrument [11] on board the Lunar Reconnaissance Orbiter (LRO), which orbited the Moon in a 50 km (average) polar orbit with a period of about 100 min [9]. The data was obtained behind 0.2 g cm^{-2} (CRaTER D1/D2, small black points), 6 g cm^{-2} (CRaTER D3/D4, small red points), and 9 g cm^{-2} (CRaTER D5/D6, small blue points);
- 2008 silicon LET GCR spectrum (magenta points) from RADOM instrument, obtained behind 0.3 g cm^{-2} shielding in the interplanetary space between Earth and Moon between 29/10/2008 09:46:12 and 08/11/2008 00:00:00 UT. 52,687 10 sec spectra were averaged;
- 2014–2016 silicon LET GCR spectrum (dark green points) from R3DR2 instrument, obtained behind 0.3 g cm^{-2} shielding. The spectrum was obtained by averaging of 3,393,592 10 s GCR spectra in the period 23/10/2014 10:31:43-10/01/2016 23:59:56 UT.

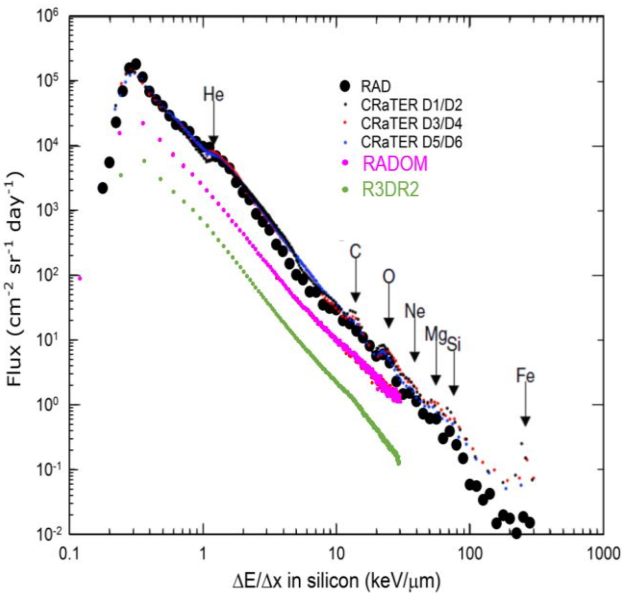

Fig. 5. Comparison of LET spectra, obtained by different instruments at different carriers

Figure 5 shows relatively good agreement between the shapes of the different spectra. The RADOM and R3DR2 spectra are shorter than the RAD and CRaTER spectra because they were obtained with single silicon detector, which covers only the LET range between 0.233 and 29.8 keV μm^{-1}. The RADOM and R3DR2 spectra include the energy depositions of Neon (Ne) ions as obtained by Dr. Y. Uchihori [11] (see Fig. 11 there) but in Fig. 4 this is not seen, probably because not very clear position of Neon maximum in the CRaTER spectra. The RADOM spectrum is below the RAD and CRaTER spectra because smaller shielding. The R3DR2 spectrum is obtained inside of the Earth magnetosphere and atmosphere that is why the amount of CGR particles building the spectrum is smallest and this spectrum is in the bottom of Fig. 4.

3. Data analysis

The analysis of the data in the figures and Table 1 reveal the following:

Table 1. Statistics of the observations with the R3DE/R/R2 and RADOM instruments.

Experiment	Time interval of the measurements **Number of days of GCR measurements**	Flux of GCR particles in 256 ch. [cm^{-2} sr^{-1}]	Flux of ORB particles in 256 ch. [cm^{-2} sr^{-1}]	Flux of GCR+ORB particles in 256 ch. [cm^{-2} sr^{-1}]	Flux GCR+ORB [part./day cm^2 sr]	Flux of SAA particles in 256 ch. [cm^{-2} sr^{-1}]	Flux of SEP particles [cm^{-2} sr^{-1}]
R3DE	31/05/2008-23/06/2009 **287.1**	68.47	0.80	69.27	0.24	107.8	Not observed
R3DR	11/03/2009-19/08/2010 **261.2**	30.73	3.03	33.76	0.13	159.1	Not observed
R3DR2	23/10/2014-10/01/2016 **418.7**	54.94	7.80	62.74	0.15	286.9	16.2
RADOM	29/10/2008 09:46:12-08/11/2008 00:00:00 **6.1**	6.21			1.02		

1) The events in 256 channel of the spectrometer are distributed in the 3 different sources. The IRB fluxes, as expected, are concentrated in the region inside the dashed line, which gives the boundary of the120 cm^{-2} s^{-1}. The frequency of observation of IRB events raise toward the center of the SAA, which confirm the hypothesis that this events are generated by long path proton crossings of the detector. The maximal IRB flux is seen during the EXPOSE-R2 mission because of the maximal altitude of ISS and that is why maximal IRB fluxes. The ORB events, as expected, are seen in the region outside the dashed line, which gives the boundary of the 5 cm^{-2} s^{-1}. The SEP particles (Seen in Fig. 2 with blue crests) was observed only on EXPOSE-R2 facility during the solar proton events in 2015. The largest fluxes was observed on 22 June 2015 [14];

2) The GCR flux in 256 channel from R3DE instrument is the largest because the flux of secondaries, generated in the heavier surrounding shielding of this instrument [13];

3) The ORB flux in 256 channel from R3DE instrument is the smallest because of the very low solar and geomagnetic activity during the measurements in 2008–2009. The largest ORB flux is observed during the EXPOSE-R2 mission in 2014–2016 [7];

4) The IRB flux in 256 channel from R3DE instrument is the smallest because of the relatively smaller altitude of ISS and smaller IRB fluxes during this measurements in 2008–2009 [7].

Conclusions

The observed maximal frequency of the IRB events in the 256 channel close to the center of the SAA confirm the hypothesis that this events are generated by long path proton crossings of the detector. Relatively small energy of the IRB protons and the lack of heavy ions define the smaller health risk from this particles.

The high energy deposition fluxes in the 256 channel of the spectrometer in GCR source, observed by RADOM instrument, outside the Earth magnetosphere and atmosphere outside Chandrayaan-1 satellite, are 6.8 times higher than the average by R3DR2 instrument outside ISS. Also the presence of high charge and energy (HZE) ions poses higher health risks for the humans being on missions on the Moon or Mars surfaces or in the Solar system interplanetary space.

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