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CHARACTERIZATION OF THE GCR FLUX AND DOSE RATE DURING THE 2001-2010 TIME INTERVAL

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Abstract: *The fluxes and absorbed dose rates from Galactic Cosmic Rays (GCR) and their secondary were continuously measured in Low Earth Orbit (LEO) and at aircraft altitudes by Liulin type spectrometers between March 2001 and September 2009. This period covers the unique maximum of GCR flux observed in the end of the 23rd solar cycle. The aircraft detector was repeatedly placed in the cabin of Airbus A310-300 for approximately 50 days. 24 runs were performed, with more than 2000 flights and 13500 flight hours on routes over the Atlantic Ocean between Prague and New York and Toronto, and back mainly. Well seen increase of the dose rates from about 1.6 to 2.5 Gy h-1 connected with flux increase from 0.485 to 0.576 cm-2s-1 is found at aircraft altitudes during the declining of the solar cycle. In LEO, during the declining phase of the solar cycle, the dose rates at L>4.5 increase on average from about 6.14 to 12.2 Gy h-1. The flux increases on average from 1.64 to 3.23 cm-2 s-1. The short term (397 days) global average variations of the GCR dose rate on the ISS orbit is analyzed by about 3 million individual 10-second resolution measurements between February 2008 and June 2009. The finding is that for this period the global daily dose rate increases from about 85 to 90 Gy day-1, which is generated by average increase of the global GCR flux rate from 1.02 to 1.04 cm-2 s-1. GCR dose rates at 100 km lunar orbit also increase by the decrease of solar activity.*

ХАРАКТЕРИЗИРАНЕ НА ПОТОКА И МОЩНОСТТА НА ДОЗАТА ОТ ГКЛ В ПЕРИОДА 2001-2010 Г.

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Ключови думи: *Космическа радиация, Космическо време, Дозиметрия, Спектрометрия.*

Резюме*: Потоците и мощностите на абсорбираните дози от галактически космически лъчи (ГКЛ) и техните дъщерни излъчвания са измерени в околоземното пространство и на височината на полетите на граждански самолети между март 2001 и август 2010 г. Този период се характеризира с уникалния максимум на потока на ГКЛ, свързан с минимума в края на 23-тия цикъл на слънчевата активност. Детектор от типа „Люлин“ е използван многократно в кабината на самолети Airbus A310-300 в цикли от около 50 дни всеки. 24 цикъла на измервания, които включват повече от 2000 полета с около 13500 летателни часа са изследвани главно по трасета от Прага до Ню Йорк и Торонто и* *обратно, над Атлантическия океан. Наблюдава се добре изразено увеличение на мощността на дозата от около 1.6 до 2.5 Gy h-1. То е свързано с увеличение на потока от 0.485 до 0.576 cm-2s-1. Нарастването на дозата и потока на височината на полетите на граждански самолети е в резултат от намаляването на слънчевата активност в края на 23-тия и цикъл. В същия период в ниска околоземна орбита мощностите на дозите за L>4.5 нарастват средно от около 6.14 to 12.2 Gy h-1. Потокът нараства средно от 1.64 до 3.23 cm-2 s-1. Краткопериодичната (397 дневна) вариация на глобалната средна мощност на дозата от ГКЛ на Международната космическа станция (МКС) е анализирана с обработката на около 3 милиона отделни 10 секундни измервания между февруари 2008 и юни 2009 г. Намерено е нарастване на глобалната дневна доза от около 85 to 90 Gy day-1, което е генерирано от нарастване на глобалния поток от ГКЛ от 1.02 до 1.04 cm-2 s-1. Мощностите на дозите от ГКЛ в около лунна орбита също се увеличават, когато намалява слънчевата активност.*

Introduction

The dominant radiation component in near Earth and Moon space environment are the galactic cosmic rays (GCR) modulated by the solar activity. The GCR are charged particles that originate from sources beyond our solar system. They are thought be accelerated at the highly energetic sources like neutron star, black holes and supernovae within our Galaxy. GCR are the most penetrating of the major types of ionizing radiation. The distribution of GCR is believed to be isotropic throughout interstellar space. 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 high Z and energy (HZE) particles, play a particularly important role in space dosimetry (Benton and Benton, 2001). HZE particles, especially iron, possess high-LET and are highly penetrating, giving them a large potential for radiobiological damage (Kim et al., 2010). Up to 1 GeV, the flux and spectra of GCR particles are strongly influenced by the solar activity and hence shows modulation which is anti-correlated with solar activity.

Instruments description

The main purpose of Liulin type Deposited Energy Spectrometer (DES) is to measure the spectrum (in 256 channels) of the deposited energy in the silicon detector from primary and secondary particles at the aircraft altitudes, at Low Earth Orbits (LEO), outside of the Earth magnetosphere on the route and on the surface of the planets of Solar system. The DES is a miniature spectrometer-dosimeter containing: one semiconductor detector, one charge-sensitive preamplifier, 2 or more microcontrollers and a flash memory. Pulse analysis technique is used for the obtaining of the deposited energy spectrum, which further is used for the calculation of the absorbed dose and flux in the silicon detector. The unit is managed by the microcontrollers through specially developed firmware. Plug-in links provide the transmission of the stored on the flash memory data toward the standard Personal Computer (PC) or toward the telemetry system of the carrier. DES sensitivity was proved against neutrons and gamma radiation (Spurny and Dachev, 2002, 2009), which allows monitoring of the natural background radiation also.

For the analysis of the GCR dose rate increase since 2001 following Liulin type spectrometers were used in near Earth radiation environment on different carriers:

Mobile Dosimetry Unit MDU-5 was used for more than 13500 hours between 2001 and 2009 on aircraft of Czech Airlines (CSA) at different routes. The experiments and data analysis were managed by Prof. F. Spurny (Spurny and Dachev, 2002, 2009);

Mobile Radiation Exposure Control System **-** Liulin-E094 containing 4 active batteries operated dosimeters worked successfully between May and August 2001 on the board of US Laboratory module of the International Space Station (ISS). The system was a part of the experiment Dosimetric Mapping E094. The Principal Investigator of the experiment was Dr. Guenther Reitz from DLR, Germany (Reitz et al., 2005; Dachev et al., 2008; Nealy et al., 2007; Wilson et al., 2007);

Radiation Risks Radiometer-Dosimeter (R3D) for Biopan (R3D-B) with 256 channels ionizing radiation monitoring spectrometer and 4 channels UV spectrometer known as R3D-B2 was successfully flown 31 May – 16 June 2005 inside of the ESA Biopan 5 facilities on Foton M2 satellite. The operation time of the instrument was about 20 days for fulfilling of the total 1.0 MB flash memory with 60 sec resolution (Häder et al., 2009);

R3D-B3 spectrometer is with almost same mechanical characteristics as R3D-B2. It was successfully used 14-29 September 2007 inside of the ESA Biopan 6 facilities on Foton M3 satellite. Together with R3D-B3, the Liulin-Photo instrument (Similar to MDU-5 instrument) was flown but inside of the capsule of the Foton M3 satellite (Damasso et al. 2009);

R3DE instrument worked on EuTEF platform outside of European Columbus module of ISS between 20th of February 2008 and 1st of September 2009 with 10 seconds resolution behind less than 0.4 g cm^{-2} shielding. (Dachev et al., 2002; Dachev, 2009);

RADOM instrument was launched successfully on Indian Chandrayaan-1 satellite on 22nd of October 2008. It starts working 2 hours after the launch with 10 seconds resolution behind about 0.45 $g.cm^{-2}$ shielding. The instrument sends data for number of crossings of the Earth radiation belts and continues to work on 100 and 200 km circular lunar orbit measuring mainly the GCR environment (Dachev et al., 2009).

Scientific results

Aircraft radiation environment

Figure 1 summarizes all data obtained by 2 Liulin type instruments on CSA aircraft between 2001 and 2009. All data in the period 2001-2007 was collected by the MDU#5 instrument. The data in 2009 was measured with a new build instrument, which have almost same characteristics as MDU#5. More than 64000 measurements with 10 minutes resolution are presented on the figure. Each patches of data were obtained in about 1-3 months of continues measurements campaign. Mostly aircraft flights on the destinations Prague - New York and Prague - Toronto at fixed altitude of 35000 feet (10.6km) are used. The cut-off rigidity varies between 0.16 and 2.0 GV when the latitude changes between 50 and 65°.

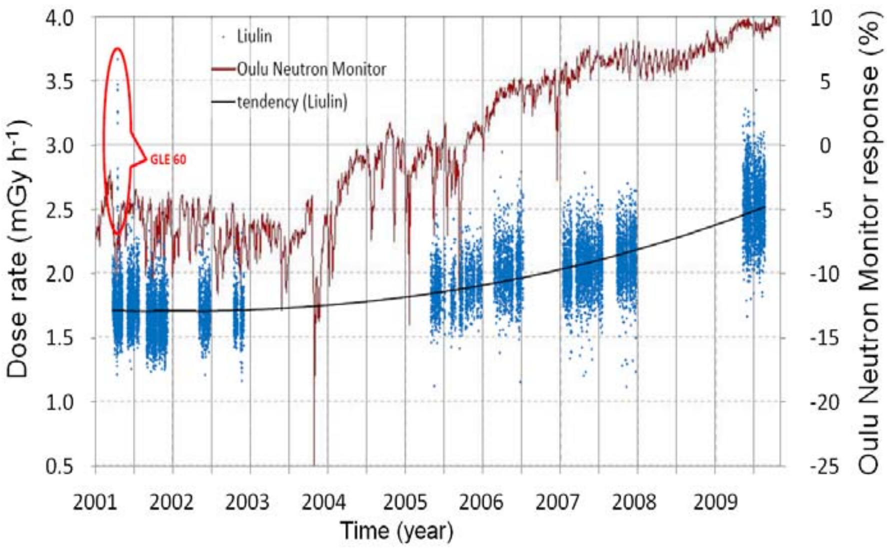

Fig. 1. Variations of the average deposited dose rate for transatlantic flights at altitude 10.6 km.

On the X axis is plotted the date between January 2001 and October 2009. On the left hand Y axis the measured absorbed dose rate in the silicon of the detector is plotted. The right hand Y axis is for the Oulu Neutron Monitor response in percent. The Oulu data http://cosmicrays.oulu.fi/ are seen on the figure as continues heavy black line, which varies in average between -7% in the maximum of the solar activity (2001-2004) and +9% in the minimum of solar activity in 2009.

The Liulin data rises in average from about 1.75 to 2.5 μGy h^{-1}. This tendency is presented on the plot by polynomial fit of data shown as black line through them. The dose rates obtained during the solar proton event and Ground Level Enhancement on 15th of April 2001 (GLE 60) (Spurny and Dachev, 2001) form the absolute maximum in the data and are specially mentioned in the left hand side of the picture. The increase of the GCR data in 2009 shows single points, which are comparable with those obtained during GLE 60. The calculated apparent dose equivalent dose rates shows very similar to the presented at Figure 1 variations but in an average range from 4-6 μSv h^{-1}. Some extreme high measurements in 2009 reach values of 11 μSv h^{-1}.

Figure 2 was specially designed to present how closer the measured GCR dose rates and fluxes on aircraft and spacecraft are. There are 2 panels on the figure. The X axes is for the geographic latitude in the range from 0 to 70° in the Northern hemisphere. The data in the figure are selected from relatively narrow longitudinal range – ±40° from the Greenwich meridian. Two facts allow us to conclude that only GCR data are separated: 1) This latitudinal and longitudinal range is away from the region of the South Atlantic Anomaly (SAA); 2) There are no Solar Proton Events in the mentioned above time intervals.

In the panels are presented the measured absorbed dose rates (bottom panel) and fluxes (top panel) at 4 vehicles, which data are taken for the periods and altitudes as follows: Aircraft -05.05-

26.06 2005 at 10.6 km; Foton M2 1-12 June 2005 at 260 km; Foton M3 15-24 September 2007 at 267 km; ISS (MDU#2) 6-13 July 2001 at 393 km.

The main results from the analysis of Figure 2 are: 1) All latitudinal profiles shows similar shape with minimum at low latitudes and rising values toward high latitudes; 2) In the range 10-30° the values are practically independent from the latitude. The averaged dose rates in this range are 0.66 μGy h^{-1} at aircraft, 1.34 μGy h^{-1} at Foton M3/M3 satellite and 1.93 μGy h^{-1} at ISS. Simple calculations reveal that the ratios of the dose rates in this range at altitudes 10.6, 260 and 393 km are as 1:2:3 i.e. the GCR component of the Earth radiation environment is attenuated only 3 times from the Earth magnetic field and atmosphere on it path from space to the ground; 3) The aircraft dose rates and fluxes shows almost fixed values in the range 50-60°.

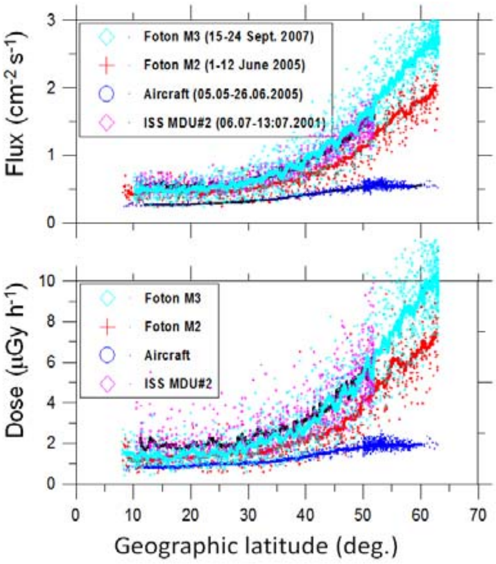

Fig. 2. Latitudinal profiles of the dose rate and fluxes at aircraft, Foton M2/M3 spacecraft and ISS.

Spacecraft radiation environment

In Figure 3 is presented the distribution of the obtained dose rates on 4 spacecraft are plotted as a function of the McIlwain's L-parameter, that corresponds to the equatorial radius of a magnetic drift shell in the case of a dipole field. The plots show the different radiation components and how they are distributed in the space around the Earth. The dose rate data from the Foton M2/M3 satellite shows 2 well seen maximums – one at L values about 1.4 and another at about 3.8. The lower L value maximum correspond to the inner (proton) radiation belt, which is populated mainly by protons with energies from few tens to few hundred MeV. These maximums are also in anticorrelation with the solar activity (Dachev et al., 1999) but here because the stronger dependence by the altitude and shielding these variations isn't seen clear.

The higher L value maximum corresponds to the outer (electron) radiation belt, which is populated mainly by electrons with energies from hundreds of keV to few MeV. These maximums are not seen in the bottom and top panels where ISS data are presented. On the top panel there are no outer belt electrons because they are not generated in the low solar activity of the measurements in June 2009 (Wrenn, 2009). The bottom panel also don't shows relativistic electrons (Dachev et al., 2009) because the data are taken inside the ISS Destiny module behind more than 20 g cm^{-2} shielding, which absorb them.

The large amount of points with low doses and fluxes are obtained at low and mid magnetic latitudes outside of the radiation belts and is generated mainly by GCR particles, which shows a "knee" at L value about 2.5–3. After the knee toward high latitudes the dose rates are practically fixed and show a straight line, because these measurements are in the region where practically open space GCR data are recorded. The averaged values there are: 2001 - 6.14 μGy h^{-1}, 2005 – 7.38 μGy h^{-1}, 2007 - 10.3 μGy h^{-1} and 2009 - 12.2 μGy h^{-1}. The 2009 values are about twice higher than the observed in 2001 by the Liulin-E094 instrument inside the ISS. In same time the flux increases in average from 1.64 to 3.23 cm^{-2} s^{-1}.

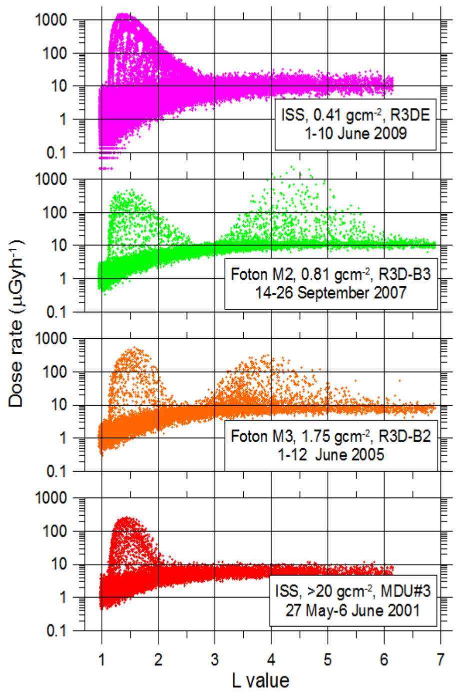

Fig. 3. Profiles of the dose rates at 4 different spacecraft. From bottom to top panel a well seen increase of the GCR value is observed. (Look the values in the right parts of the panels.)

Figure 4 presents the temporal variations of the daily (for 400 days) GCR dose rate measured by R3DE instrument on ISS in the period between 21st of February 2008 and 22nd of June 2009. The daily GCR dose rate was obtained by averaging of 5000-8200 measurements per day (7024 in average) with 10 s resolution at all latitudes in the altitudinal range 350-375 km above the earth. Totally more than 2.8 million points were used. The averaged flux is obtained to be 0.997 cm^{-2} s^{-1}, while the averaged dose rate is 3.67 µGy/h with averaged maximum of 27.44 and minimum of 0.041 µGy h^{-1}.

Except the daily GCR dose rate (diamond points) the Oulu NM count rate (square points) are presented. It is seen that the daily GCR dose rate slowly rise up from about 88 to 94 µGy d^{-1}, which in general follow the Oulu NM count rate. The linear regression between the both values shows the following formulae:

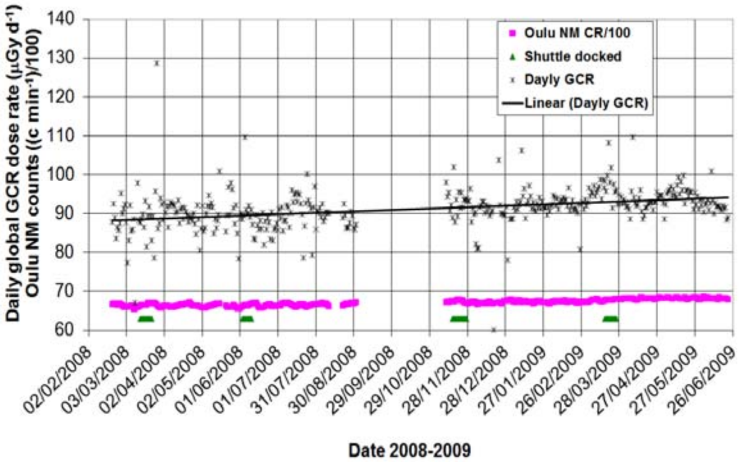

Fig. 4. Long term variations of the R3DE daily dose rate on ISS in the period 21 February 2008-22 June 2009.

(1) Daily CGR [µGy d^{-1}] = 0.0237*Oulu NM counts [c $min.^{-1}$] – 67.818)

The short term variations with about a month length don't have any explanation till now and seem there are not connections with the presented in the bottom with triangles periods when the Space Shuttle were docked to the station (Dachev et al., 2010).

Figure 5 shows the RADOM dose rate (upper curve) and flux in the lunar orbit between 20 November 2008 and 18 May 2009 in dependence by Oulu NM count rate. The RADOM 10 and 30 sec resolution data were added and averaged to obtain hourly flux and dose rates (Vadawale et al., 2010). The averaged particle flux for this period in the 100 km orbit was found to be 2.45 particles cm^{-2} s^{-1}, and the corresponding absorbed dose rate was 9.46 µGy h^{-1} over 3545 hours of measurements. The averaged Oulu NM count rate was 6762 counts min^{-1}. During the last three months of the mission (20/05/2009-28/08/2009), Chandrayaan-1 was in 200 km orbit, where the flux and dose rate increased slightly to 2.73 cm^{-2} s^{-1} and 10.7 µGy h^{-1} respectively. Oulu NM count rate also increase to 6809 counts min^{-1}. The observed increase of particle flux and dose rate at 200 km can thus be explained as due to reduced self-shielding of GCR by the Moon.

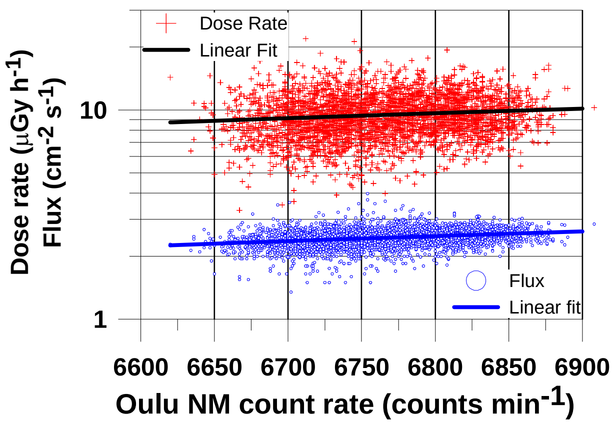

Fig. 5. Dependence of the RADOM hourly dose rates by the Oulu NM count rate for the period 20 November 2008 – 18 May 2009.

From Figure 5 it can be seen that both RADOM parameters over show linear dependence from the Oulu Neutron monitor data. This could be attributed to the increase in GCR intensity due to decreasing solar activity and consequential decrease of interplanetary solar magnetic field.

Summary

The paper collects large amount of Liulin instruments measurements in the declining phase of the 23rd solar cycle in the range of altitudes from 10.6 km above the Earth, in low Earth orbit up to 100 km around the Moon. In all altitudes the measured absorbed dose rates and fluxes show well defined increase when solar activity decrease in all time intervals starting with few days and finishing with the almost whole solar cycle.

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