Analysis of the GCR Dose Rate Increase onboard Spacecraft and Aircraft in the Declining Phase of the 23rd Solar Cycle

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The absorbed dose rates from Galactic Cosmic Rays (GCR) and their secondary were continuously measured at aircraft altitudes with Liulin type spectrometer since 2001. These measurements were performed in cooperation with Czech Airlines (CSA). The data cover the declining phase of the 23rd solar cycle and show increase from about 1.7to 2.5 μGy/h. The dose rates from GCR were also independently measured with analogical instruments onboard following spacecraft: International Space Station in 2001 and 2008-2009; Foton-M2/M3 satellites in June 2005 and September 2007 respectively and on Indian Chandrayaan-1 satellite in 2008-2009. The dose rates in LEO and relatively high latitudes increase from about 6 to 12 μGy/h. Obtained experimental data are compared with computational models.

Introduction

The earth is continuously bombarded with high-energy ionising radiation from outer space. The intensity of the cosmic radiation is partly decreased by the magnetic field associated with the Sunôs solar wind and by the Earthôs magnetic field. Galactic Cosmic Rays (GCR) are mostly protons (~85 %) and helium ions (~12 %), the rest includes nuclei of all known elements and some electrons. Their energy extends up to about 10^{20} eV. The GCR interacts with the atmosphere producing secondary radiation, which together with the primary incident particles give rise to radiation exposure throughout the atmosphere decreasing in intensity with depth from the altitude of supersonic aircraft down to sea level. The dose from GCR varies not only with altitude but also with the geomagnetic coordinates (longitude and latitude) being larger towards the poles and smaller nears the equator. It also depends on the solar activity, which varies according to a cycle about 11 years long. The GCR contribution to the spacecraft crew exposure is about 70%, while at aircraft altitudes is even larger and reach 95 % [1].

Instruments descriptions

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. Different modifications of DES use displays and/or Global Positioning System (GPS) receivers. 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. Windows environment program in PC is used for the full management of the DES through standard serial/parallel or USB communication port. Same program store the full data sets on PC and visualize the data for preliminary analysis. DES sensitivity was proved against neutrons and gamma radiation (Spurny and Dachev, 2002), which allows monitoring of the natural background radiation also.

For the analysis of the GCR dose rate increase since 2001 following Liulin-4 type spectrometers were used in near Earth radiation environment on different carriers:

Mobile Dosimetry Unit MDU-5 was used for more than 6000 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 [1, 2];

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 [3-7];

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 ï 16 June 2005 inside of the ESA Biopan 5 facilities on Foton M2 satellite. The total mass was 0.128 kg and size was 82x57x25 mm. The operation time of the instrument was about 20 days for fulfilling of the total 1.0 MB flash memory with 30 sec resolution [8-11];

R3D-B3 spectrometer is with almost same mechanical characteristics as R3D-B2. Larger 2.0 MB flash memory was used for about 30 days measurements. 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 [12, 13];

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. The surface of its detector is orientated perpendicularly to the ñ+Zò axis of ISS [8, 14];

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 [15, 16].

Data analysis and discussions

RADOM instrument data

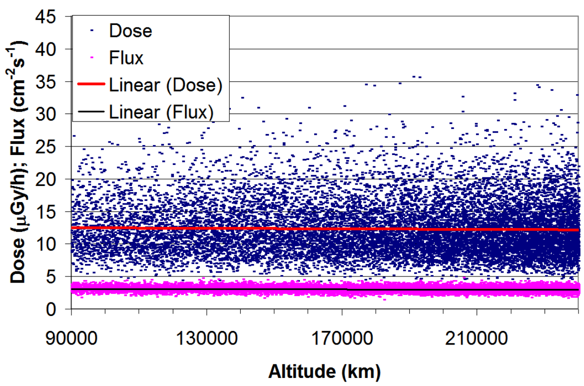

Fig.1. GCR doses measured at altitudes between 90000 and 230000 km from the Earth by RADOM instrument on Chandr ayaan-1 satellite

Figure 1 presents the measured from 29/10/2008 09:56:54 UT to 31/10/2008 10:20:25 UT by RADOM instrument dose rate and flux when Chandrayaan-1 satellite is going away from the Earth from 90000 to 230000 km. The linear approximations of the dose rate and flux shown with heavy lines are practically independent by the altitude and remain on fixed mean levels of 12.31 μGy/h and 2.99 cm^{-2}s^{-1}. These values can be taken as reference for the expected dose rates and fluxes in the interplanetary space at 1 astronomical unit.

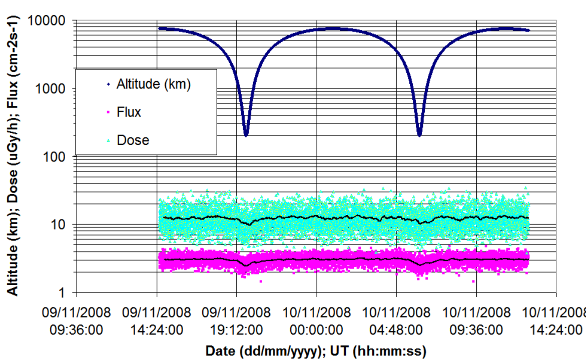

Fig.2. Variations of GCR doses and fluxes measured at altitudes between 201 and 7508 km from the Moon by RADOM instrument on Chandrayaan-1 satellite

When Chandrayaan-1 satellite entrée in lunar orbit 9-10 November 20008 with perigee 201 and apogee 7503 km the observed dose rates and fluxes start to depend strongly by the altitude because as closer to the Moon the satellite is as higher the Moon body shielding is. On the Figure 2 is seen that the averaged doses fall down from about 12.94 μGy/h in the apogee to 9.72 μGy/h in the perigee region and the fluxes changed from 3.11 to 2.57 cm^{-2}s^{-1} respectively. The values in the apogee region are higher than the seen on the Figure 1 but we believe this rise up of the doses and fluxes is connected with the total increase of the GCR flux. For example the Oulu Neutron Monitor count rate increase from an average value of 6677.1 counts/min on 29-31 October 2009 to 6694.9 counts/min on 9-10 November 2009.

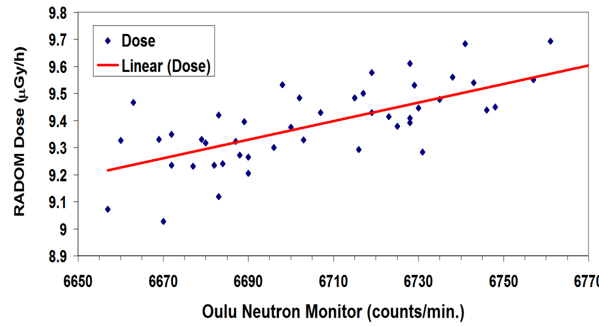

Fig.3. Dependence of GCR doses measured at altitudes between 90 and 120 km from the Moon by RADOM instrument on Chandrayaan-1 satellite from Oulu Neutron Monitor count rate

The dependence of the RADOM dose rates from the Oulu Neutron Monitor count rate for the period between 12th of November 2008 and 30th of December 2008 is shown in Figure 3. A well defined linear approximation of the data is presented, which prove the idea that both data sets are connected.

On 19th of May 2009 the satellite orbit was rise up to 200 km I average. This brings an increase of the average RADOM instrument dose rate to 10.85 mGy/h.

The results from the comparison of the obtained by RADOM instrument fluxes, absorbed dose rates and apparent dose equivalent [2] at 100 and 10000 um altitude and the Moon radiation model are presented in Table 1.

Table 1. Comparison of the measured and model data

Altitude	Flux (cm^{-2}s^{-1})	Absorbed dose rate (μGy/h)	Apparent dose equivalent (μSv/h)
10000 km data	2.79	10.78	25.80
10000 km model	3.05	11.16	26.76
100 km data	2.45	9.39	23.21
100 km model	2.55	9.76	23.90

It is well seen from the table that the preliminary model [2a] and measured data well coincide. Further work on the model is required.

R3DE instrument data

Figure 4 presents the global view on the R3DE data for the time period between 21/10/2008 and 24/02/2009. The ISS altitude for this period vary between 364 and 375 km. The total amount of data to be produced each panel is mentioned in the right upper corner of the panel. The first 2 panels contain 393927 measurements of the flux in the upper panel and of the absorbed dose rate in the panel below. On the

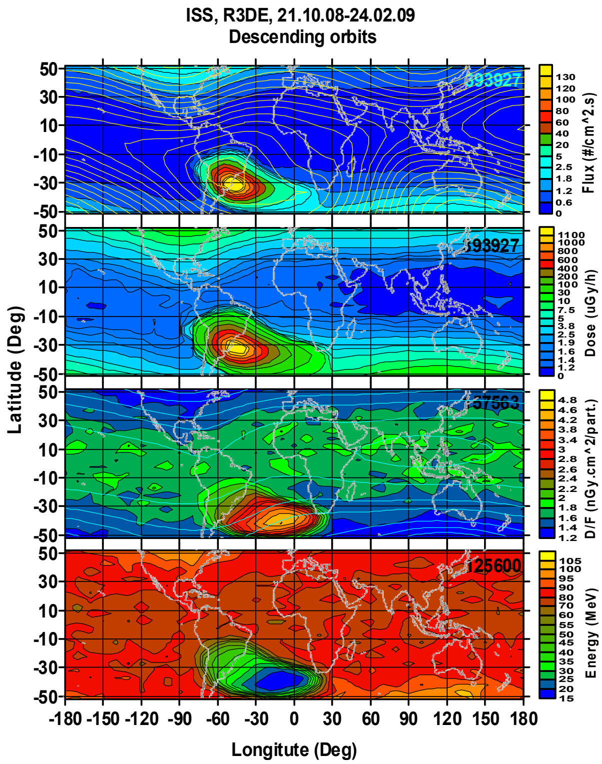

Fig.4. Global distribution of the R3DE dose rate, flux, D/F and incident energy data for the descending orbits of ISS in the period 21 October 2008-24 February 2009

upper panel except the flux the isolines of the total Earth magnetic field strength at the altitude of the ISS are also presented with yellow lines. The place and area of the South Atlantic Magnetic Anomaly (SAA) is well seen by the last close isoline of 0.26 Gauss. Because of relative low magnetic field strength in the SAA the protons in the inner radiation belt penetrate deeper in the upper atmosphere and reach the altitude of the station forming large maximums of the flux and dose respectively. The flux maximum is displaced from the magnetic field minimum in South-East direction, while the dose rate maximum goes even further to the same direction.

In the third from above panel the global distribution of the dose to flux ratio [14,18] is presented. It is seen that the ratio form a maximum in the South-East edge of the anomaly. The global distribution of the calculated from the Heffnerôs formulae [14] incident energy of the arriving to the detector protons is presented at the bottom panel of Figure 4 and as expected form a minimum at the places of the dose to flux ratio maximum in the above panel. The centre of the 15-20 MeV protons maximum is with coordinates 15°W, 38°S. This result is controversial than the AP-8 MIN [19,20] predictions, which show the place of the maximum almost at same latitude but at about 38° west longitude.

The GCR dose and flux global distribution is presented in the upper 2 panels of Figure 4 with all areas outside the SAA region. It forms wide minimum close to the geomagnetic equator and rise toward the magnetic poles in both hemispheres. For the regions outside the SAA the calculated values for the dose to flux ratio and for the incident energies presented in the lower two panels of Figure 4 are not valid because of the small statistics in the spectra.

Figure 5 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 millions 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.

Except the daily GCR dose rate (diamond points) the Oulu NM [21] count rate (square points) are presented. It is seen that the daily GCR dose rate slowly rise up from about 84 to 90 μGy/d, which in general follow the Oulu NM count rate. The linear regression between the both values shows the following formulae:

((Daily CGR [μGy/d]) = 0.0202*(Oulu NM counts [c/min.]) - 48.887))

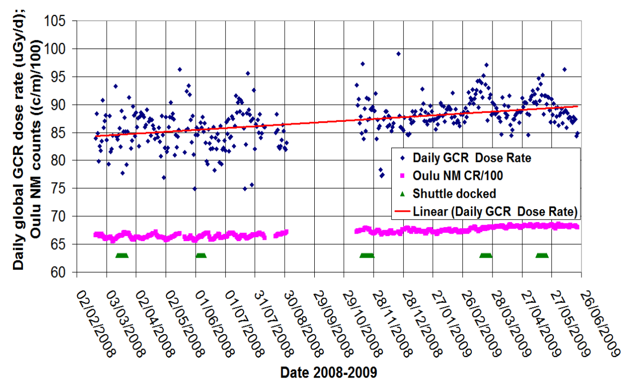

Fig.5. Long term variations of the R3DE daily dose rate on ISS in the period 21 February 2008-22 June 2009

The short term variations with about a month length donôt 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 [22].

The calculated daily GCR apparent dose equivalent dose rate [2] shows the following averaged values: 9.77 μSv/h, 0.041 μSv/h minimum and 99.89 μSv/h maximum value, 223.9 μSv/d. The value of 223.9 μSv/d is about twice less than the measured by the NASA Tissue Equivalent Proportional Counter (TEPC) values inside the Columbus module of ISS in march 2008 [23]. This difference may be explained by 2 factors: 1) the GCR dose equivalent rates inside the Columbus module are higher than these in R3DE instrument because thicker shielding and respectively secondaries build up; 2) the TEPC did have smaller sensitivity in the geomagnetic equator regions and overestimate the doses.

The averaged values of the hourly dose rates at high latitudes (5.0<L<5.05) for the same period as on Figure 5 have a considerably higher values but shows similar increase from about 10-11 μGy/h in the first half of 2008 up to 11-12 μGy/h in the middle of 2009. These values are about twice higher than the observed in 2001 by the Liulin-E094 instrument inside the ISS.

Comparison of GCR satellite data

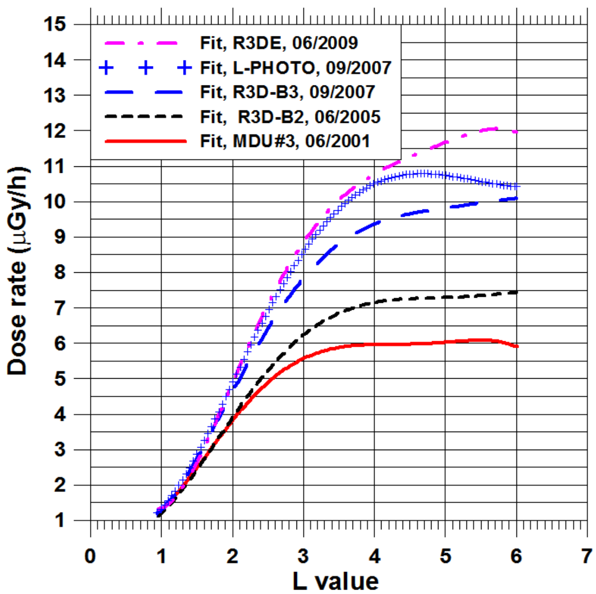

Fig. 6. Latitudinal profiles of the dose rate observed on different satellites during the declining phase of solar cycle

Figure 6 presents the variations of the GCR dose rate latitudinal profile as observed by 5 different instruments at 3 different vehicles between June 2001 and June 2009 when the decline of the 23rd solar cycle take place and respectively increase of GCR flux and dose. From bottom to up the 5 curves are obtained by polynomial fitting of fifth degree of data from the following experiments:

-MDU#3 of Liulin-E094 instrument [3,5] inside of American laboratory module Destiny of ISS in June 2001 at altitudes in the range 377-400 km. 19840 measurements with 30 s resolution are used;

-R3D-B2 instrument [10,11] on Foton M2 satellite in June 2005 at altitudes in the range 262ï 304 km. 9760 measurements with 60 s resolution are used;

-R3D-B3 instrument [12] on Foton M3 satellite in September 2007 at altitudes in the range 263ï 302 km. 10565 measurements with 60 s resolution are used;

-Liulin-PHOTO instrument [13] on Foton M3 satellite in September 2007 at altitudes in the range 263ï 302 km. 9783 measurements with 60 s resolution are used. The selection requirements of the data are same as for R3D-B3 instrument;

-R3DE instrument [14] outside of ESA Columbus module of ISS in June 2009 at altitudes in the range 350-370 km. 28949 measurements with 10 s resolution are used.

The analysis of the Figure 6 gives the following: 1) The latitudinal profile at each vehicle shows similar feature with a minimum close to the geomagnetic equator, rising up part up to L=3.5 and knee followed by fixed values or smaller slope of the curve; 2) The doses in the equatorial region (L the range 0.9 -1.5) are similar and donôt show a dependence by the change of the solar activity; 3) The doses in the L range 1.5-6 shows strong dependence by the solar cycle and rise up when the solar activity decline. In average the dose rates rise twice between 2001 and 2009 from 6 to 12 μGy/h; 4) The doses measured on Foton M3 satellite by Liulin-PHOTO instrument are higher than the R3D-B3 doses because the secondaries developed in the larger shielding of about 20 gcm^{-2} at which the Liulin-PHOTO instrument is situated.

Analysis of the GCR aircraft data

Figure 7 summarize all data obtained by 2 Liulin type instruments on CSA aircrafts between 2001 and 2009 [1,2]. 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 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°.

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 percents. The Oulu data are seen on the figure as continues heavy 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.

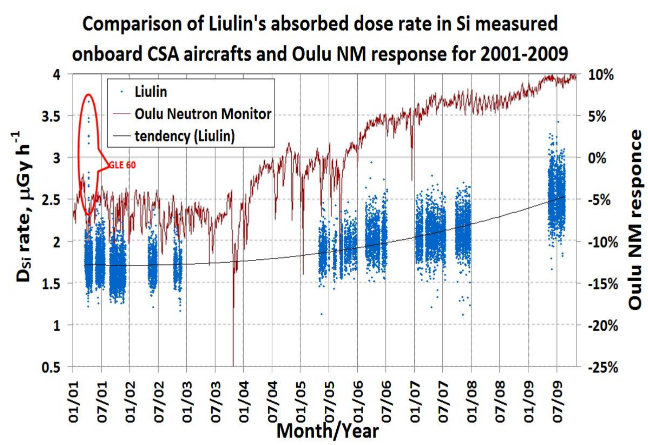

Fig. 7. Absorbed dose rates variations as observed on CSA aircraft flights over the Atlantic oucean at altitude of 10.6 km

The Liulin data rises in average from about 1.75 to 2.5 μGy/h. This tendency is presented on the plot by polynomial fit of data shown as black line trough them. The dose rates obtained during the solar proton event and Ground Level Enhancement on 15th of April 2001 (GLE 60) [24] 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 7 variations but in an average range from 4-6 μSv/h. Some extreme high measurements in 2009 reach values of 11 μSv/h.

Conclusions

The presented paper collect large amount of Liulin instruments measurements in the declining phase of the 23rd solar cycle. Data collected in the range of altitudes from 10.6 km above the Earth up to 100 km Moon orbit shows well defined dependence from the solar activity in all time intervals starting with few days and finishing with the almost whole solar cycle.

Acknowledgements

The authors would like to thank to: P. Dimitrov and Y. Matviichuk from Solar-Terrestrial Influences Institute at the Bulgarian Academy of Sciences for the cooperation in the development of the Liulin type spectrometers and for the assistance with data analysis; Gianni De Angelis for the calculation of model dose rate data around the Moon; Donat Haeder, University of Erlangen Germany, Gerda Horneck and Guenther Reitz, DLR, Institute of Aerospace Medicine, Germany for the cooperation in the realization of the instruments for Foton M2/M3 satellite and for R3DE instrument on Columbus module of ISS; ISRO staff and more specially to: Mr. M. Annadurai, Project Director and J. N. Goswami, Project scientist of Chandrayaan-1 satellite, P. Sreekumar and V. Sharan, Space Astronomy & Instrument Div., and Dr. J D Rao, ISTRAC/ISRO Bangalore for the RADOM instrument support.

This work is partially supported by the grant HZ-1505/1511/2005 from the Bulgarian Science Fund.

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