Radiation of Cosmic Rays Measured on the International Space Station

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Abstract: Radiation impact on astronauts and radiation risk are dominated by high LET (Linear Energy Transfer) particles. The preferred passive personal dosimeters used for astronauts are CR-39 plastic nuclear track detectors (PNTDs) sensitive to high LET. The Matroshka research facility is designed for investigating the depth distribution of the radiation dose in different organs of astronaut during a mission with or without an EVA (Extra Vehicular Activity). Matroshka experiments conducted successfully in Zvezda service module of ISS (International Space Station) from 2004 to 2006. Radiation LET spectra and quantities were measured for the different organs and skin locations of Matroshka phantom inside and outside ISS using CR-39 PNTDs. The experimental results can be used to determine the radiation quantities for astronauts in LEO (Low Earth Orbit). This paper introduces LET spectrum method using CR-39 detectors and the Matroshka experiments and presents radiation results measured with CR-39 PNTDs for the Matroshka experiments.

Keywords: GCR, ISS, Radiation, Nuclear Track Detectors.

1 Introduction

Radiation in low Earth orbit (LEO) is mainly composed of Galactic Cosmic Rays (GCR), solar energetic particles, electrons and protons in the SAA (South Atlantic Anomaly) and albedo neutrons and protons scattered from the Earth's atmosphere. Radiation risk is a key concern for human space flight. Research indicates that the radiation impact to astronauts and the radiation risk are strongly related to particle's LET and high LET particles dominate the impact and risk [1-4].

So far, the active personal dosimeters are not available and the best passive dosimeters which can measure LET spectrum are CR-39 detectors. Thermoluminescence Dosimeters (TLDs) sensitive to low LET and CR-39 detectors sensitive to high LET were used for Matroshka experiments by JSC-SRAG (Space Radiation Analysis Group) and DIAS (Dublin Institute for Advanced Studies). Radiation for all LET can be obtained by combining the results measured with CR-39 PNTDs and TLDs.

Matroshka phantom with a human torso composed of different passive dosimeters allows measurement for organ dose and depth dose. Matroshka experiments were conducted successfully from 2004 to 2006.

2 LET Spectrum Method

2.1 Radiation Measurement Using CR-39

After exposure and recovery, CR-39 detectors were chemically etched (NaOH, 6.25N, 60^{o}C). Chemical etch will produce etched cones in CR-39 detector. Following etch, bulk etch for each CR-39 detector was calculated by Henke formula [5], and events were identified, the major and minor axes of the cone surface on CR-39 detector were measured and collected with optical microscope by manual scan or semi-automatic scan (events viewed and adjusted by human eyes). The scanned data were then analyzed, for each event, the etch rate ratio was calculated by Somogyi formula [6] and the LET value was calculated using LET calibration [7], then LET was binned, LET spectrum was generated and the radiation quantities were obtained.

An important advantage of manual scan is to recognize and collect data for high charge and high energy particles (HZEs) - mainly long range GCR heavy nuclei, in the same procedure of data scan for all kinds of primary and secondary particles. The approach to find out HZEs is as below. When scan data for the top surface of CR-39 detector, every selected etched cones is focused downwards to the bottom surface along the direction of major axis for the top cone to determine the events is coincident or not, if a symmetric bottom cone is found, the event is coincident and the particle is selected as a long range HZE particle [9-11].

2.2 LET Spectrum Generating

Research in cosmic ray physics indicates that GCR particles in LEO are near isotropically distributed. For an isotropically distributed radiation field, the particle differential fluence can be expressed as:

$$F = (2\pi A \cos^2 \delta_{cut})^{-1} \frac{dN}{dLET}$$

where F is in particles/(cm^2.sr.keV/µm water); A, the scanned detector area; dN, the number of events; dLET, the LET bin; δ_{cut}, the cutoff dip angle (particle's incident angle to the detector), above which the detector efficiency of CR-39 detector is 100% [9-11]. The dip angle correction for the LET spectrum is realized through δ_{cut} which can be determined accurately from data of etch rate ratio and dip angle.

The net differential fluence is obtained by subtracting the background radiation from the total differential fluence, which is contributed by both space and background radiation. The differential absorbed dose D (Gy) is then

$$D = 4\pi \times 1.6 \times 10^{-9} \times LET_{\infty} \times F$$

The differential dose equivalent is obtained as D×Q, where Q is the quality factor recommended by ICRP 60.

The integral LET spectra of the radiation field (fluence, absorbed dose and dose equivalent) are generated by summing the differential spectrum from high LET to low LET (~5 keV/µm water for JSC and DIAS CR-39).

The average radiation quality factor is calculated by

$$Q(\geq LET) = \text{integral dose equivalent} (\geq LET) / \text{integral absorbed dose} (\geq LET)$$

The relationship of LET_{∞} in water and LET_{200} in CR-39 can be expressed as

$$\log(LET_{\infty}\ \text{water}) = 0.1689 + 0.984\log(LET_{200}\ \text{CR-39})$$

The LET spectrum method using CR-39 detectors and the procedures in detail can be found in [9-11].

2.3 LET Calibration for CR-39 Detectors

The relationship between LET_{200} in CR-39 and etch rate ratio was determined by calibrating CR-39 detectors with heavy ions and protons generated by accelerators. Accelerator centers HIMAC, NSRL, BNL and Cyclotron Institute at Texas A and M University (TAMU) can provide a variety of heavy ions and protons with different energies and LET values. The values of LET_{200} in CR-39 for the charged particles can be calculated by computer codes and the etch rate ratio can be calculated by Somogyi formula. Thus the relationship between LET_{200} in CR-39 and etch rate ratio is obtained [7]. When CR-39 material was manufactured, a thin plastic film was covered on the CR-39 surface to protect CR-39. The LET calibration indicates that the sensitivity of CR-39 in good oxygen condition (film was removed when CR-39 stack was prepared) is higher than those in poor oxygen condition (film was kept on CR-39 surface until etch).

3 Matroshka Experiments

Matroshka - a European Space Agency (ESA) research facility under the coordination of DLR (German Aerospace Center) - is an experiment unit for investigating the depth distribution of the radiation dose in different organs of astronaut in LEO. Matroshka phantom consists of a contained human torso, allowing dedicated radiation measurement. Passive detectors of Matroshka phantom comprised TL/OSL detectors in polyethylene tubes for the depth dose measurement as well as a combination of TL, OSL and CR-39 dosimeters positioned in 5 so called "organ dose boxes" - at the sites of radiation sensitive organs (eye, lung, stomach, kidney and intestine). In addition the phantom was dressed by a "Hood" and a "Poncho", made of Nomex with sewed in TLDs to measure the skin dose. Skin doses were also measured on the phantom surface with so called "Poncho boxes" (mid thorax, upper abdomen, lateral left, lateral right, mid dorsal and lumbar and marked as Poncho 1 to 6 respectively). Active devices of Matroshka include five silicon scintillation detectors and a silicon DOSTEL (DOSimetry TELescope) located on the top of the phantom head.

The Matroshka-1 spent 616 days in orbit (29 Jan.04 - 10 Oct.05, 77d inside the ISS and 539d outside the Russian Zvezda module). Two reference detectors were also placed inside ISS during the whole experiment to account for the dose received inside ISS. The Matroshka-2 was conducted inside the Zvezda module (21 Dec.05 - 22 Dec.06). The total exposure time for Matroshka-2 was 367 days (30d at reference, 337d at phantom organs).

Figure 1 shows Matroshka torso and Figure 2 shows the location of Matroshka experiments, the facility (encircled) was mounted outside the Zvezda Module.

Figure 1. Matroshka torso.

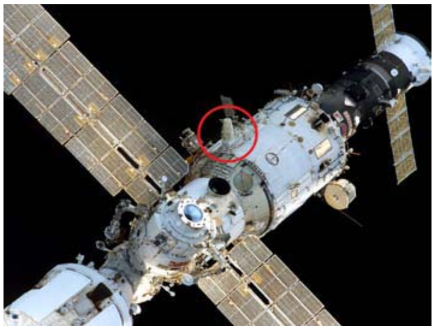

Figure 2. Matroshka Facility outside the ISS.

Following the Matroshka-1 post-flight processing of the CR-39 detectors and subsequent analysis of the nuclear tracks it was discovered that the doses observed at all seven locations were much lower than those expected for the orbital inclination, altitude and stage of solar cycle involved. The main suspect was a sensitivity fading over the very long period of exposure to space radiation. Same fading problem was discovered again for Matroshka-2 experiment. Consequently a formula for correcting the sensitivity fading was found using data measured from Matroshka-1 (616d), Matroshka-2 (367d) and ISS Expedition12 (30 Sept.05 - 8 Apr.06, 190d) with the method of internal LET calibration based on the GCR iron peak at ~1 GeV/n and LET of ~137 keV/μm water.

Correction formula for the fading of CR-39 sensitivity was found to be $Sc=So/[1-(9.5394+2.4424\times T)\times 10^{-3}]$ [8], where So is the etch rate ratio without sensitivity correction, Sc is the etch rate ratio after sensitivity correction and T is the exposure time of CR-39 detector in months. The correction was applied to all JSC-SRAG and DIAS CR-39 detectors.

Radiation results reported in the paper are obtained by subtracting the reference radiation from the total. The Matroshka experiments in detail can be found in [9,12].

4 Matroshka Radiation Measured

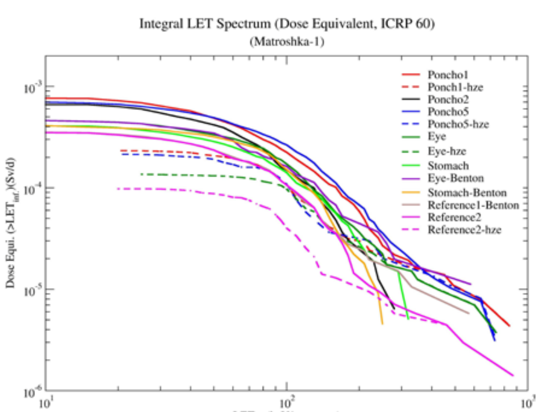

Figure 3. LET spectra of dose equivalent (Matroshka-1).

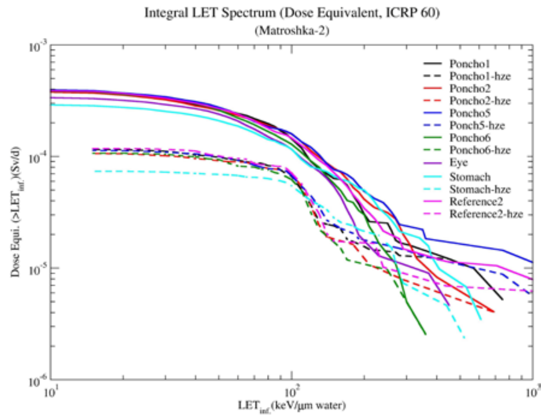

Figure 4. LET spectra of dose equivalent (Matroshka-2).

Figure 3 and 4 show the integral LET spectra of dose equivalent (ICRP 60) measured with CR-39 detectors for the Matroshka-1 and -2 experiments respectively. The figures indicate that: radiation at poncho 1, 2, 5 and 6 are close and the lowest radiation is at location of stomach; HZE particles make an important contribution to radiation in LEO; the shielding material of ISS can screen the radiation effectively.

*Scanned for CR-39 detectors from Benton.

Detector Location	Dose Rate	Dose Equi. Rate (ICRP 60)	Q Factor
	(μGy/d)	(μSv/d)	
Matroshka-1			
P1 (Total)	64.47±2.73	762.56±32.34	11.83±0.50
P1 (HZE)	11.95±1.21	232.51±23.62	19.46±1.98
P2 (Total)	55.87±2.88	661.19±34.06	11.83±0.61
P5 (Total)	58.48±3.04	699.11±36.33	11.95±0.62
P5 (HZE)	11.25±1.35	214.40±25.86	19.07±2.30
Eye (Total)	36.00±2.12	461.00±26.99	12.80±0.75
Eye (HZE)	6.29±0.96	136.03±20.80	21.63±3.31
Eye*(Total)	35.73±2.68	458.94±34.18	12.84±0.96
Sto. (Total)	30.98±2.02	407.24±26.31	13.14±0.85
Sto.* (Total)	31.08±1.89	409.01±24.59	13.16±0.79
Ref.* (Total)	29.11±1.56	352.78±18.91	12.12±0.65
Ref.2 (Total)	28.49±1.46	349.09±17.89	12.25±0.63
Ref.2 (HZE)	4.91±0.60	97.86±11.95	19.92±2.43
Matroshka-2			
P1 (Total)	32.87±1.93	383.94±22.40	11.68±0.68
P1 (HZE)	6.55±0.62	115.16±10.86	17.58±1.66
P2 (Total)	32.31±2.11	376.53±24.45	11.65±0.76
P2 (HZE)	5.78±0.77	106.17±14.48	18.37±2.51
P5 (Total)	33.88±2.08	395.10±24.36	11.66±0.72
P5 (HZE)	6.65±0.83	113.38±14.21	17.08±2.14
P6 (Total)	32.66±2.02	384.66±23.59	11.77±0.72
P6 (HZE)	5.57± 0.71	107.03±13.77	19.22±2.47
Eye (Total)	27.18±2.20	335.93±27.03	12.35±0.99
Sto. (Total)	23.23±1.60	289.46±19.64	12.46±0.85
Sto. (HZE)	3.65±0.59	73.68±11.78	20.08±3.23
Ref.2 (Total)	33.08±1.74	388.39±20.68	11.74±0.63
Ref.2 (HZE)	6.40±0.71	117.63±12.83	18.36±2.00

Table1. Radiation measured with CR-39 PNTDs (ICRP 60, ≥10 keV/μm water)

Table 1 collects radiation quantities measured with CR-39 detectors, in the table poncho1-6 are denoted as P1-P6. The ratio of radiation dose equivalent for Matroshka-2 and -1 is 50.0%, 57.0%, 56.5% and 71.1% for pocho1, 2, 5 and stomach respectively. Radiation quantities for HZE particles were also collected in the table. For the Matroshka-2, the contribution of HZE particles to the total dose equivalent is 30.3%, 30.0%, 28.2%, 28.7%, 27.8% and 25.5% for reference2, poncho1, 2, 5, 6 and stomach respectively.

5 Radiation Combined (Total LET)

Table 2 collects dose equivalent rate for Matroshka-1 and -2 (marked as M1 and M2), including those measured with TLDs for low LET radiation and with CR-39 detectors for high LET radiation as well as the combined results for all LET [7,9]. The table shows that inside ISS the contribution of radiation dose equivalent from low LET (≤ 10 keV/μm water) and high LET (≥ 10 keV/μm water) radiation is ~1/3 and ~2/3 of total dose equivalent respectively. The effect of ISS shielding for radiation is to decrease dose equivalent by ~56%.

Dosimeter Location	Dose Equi. Rate (≤ 10 keV/ μm water)	Dose Equi. Rate (≥ 10 keV/ μm water)	Dose Equi. Rate (All LET)
	(μSv/d)	(μSv/d)	(μSv/d)
P1-M1	536.59±9.28	762.56±32.34	1299.14±33.65
P1-M2	194.04±3.26	383.94±22.40	577.98±22.64
P2-M1	460.82±9.28	661.19±34.06	1121.99±35.29
P2-M2	190.03±2.97	376.53±24.45	566.56±24.63
P5-M1	417.35±9.28	699.11±36.33	1116.46±37.50
P5-M2	193.53±2.67	395.10±24.36	588.62±24.50
P6-M2	185.07±5.64	384.66±23.59	569.72±24.95
Eye-M1	219.11±1.86	461.00±26.99	680.10±27.07
Eye-M2	170.83±2.37	335.93±27.03	506.77±27.12
Sto.-M1	167.77±1.86	407.24±26.31	575.01±26.36
Sto.-M2	148.10±2.08	289.46±19.64	437.57±19.76
Ref.2-M1	140.76±1.86	349.09±17.89	589.85±17.96
Ref.2-M2	201.85±3.86	388.39±20.68	590.24±21.01

Table 2. Comparison of radiation contributed from different LET regions (ICRP 60)

For the Matroshka-1 experiment, dose equivalent rate at poncho1 for all LET measured with passive dosimeters is ~1299 μSv/day, consistent very well with the value 1265 μSv/day measured with the active dosimeter DOSTEL located on the top of the phantom head. The result can be achieved only after correction for the sensitivity fading of CR-39. By this research we know, all results obtained from CR-39 detectors used for LDEF (Long Duration Exposure Facility, Apr.84 - Jan.90, 5.7y) without correction for the fading of CR-39 sensitivity are too low.

In addition to radiation calculation for astronauts on ISS, the LET spectra measured for Matroshka experiments are also useful for the calculation of radiation risk.

6 Conclusions

Several conclusions can be obtained from this work:

(1) The LET spectrum method using CR-39 PNTDs and the JSC LET calibration for CR-39 detectors are successful and reliable. The radiation LET spectra and quantities measured with CR-39 PNTDs for Matroshka phantom can be used to calculate the radiation quantities for astronauts in a mission with or without CEV on the ISS.

(2) The fading effect of sensitivity for CR-39 detectors with long time exposures was observed and a correction formula was found. The simplest formula is a function of exposure time. After fading correction, radiation quantities can be comparable with those measured using active dosimeters. A better correction formula can be expressed as a function of both the exposure time and LET, the formula should be determined by the future experiments.

(3) The radiation impact and risk are dominated by high LET and CR-39 detectors are sensitive to high LET, so radiation LET spectra measured with CR-39 for different organs of Matroshka phantom are unique, they can be used to calculate the radiation risk suffered by astronauts.

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