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Natural Radiation Dose and Geomagnetic Effect

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Abstract

Earth keeps getting bombarded by high-energy particles that originate in the outer space and in Sun. Cosmic radiation in Earth's atmosphere consists of a photon and directly ionizing component and a neutron component. Charged particles of cosmic radiation are deflected by the geomagnetic field that is more expressed at the equator than near the poles. Photon radiation was measured by Radiameter ESM FH 40G-L10 at 26 main meteorological stations in all parts of Croatia. The correlation between the photon dose rate and latitude was examined, as well as multiple correlations for the photon dose, latitude and altitude. The obtained positive correlation coefficients were statistically significant. The neutron component of the cosmic radiation was measured by series of nuclear track-etched detectors, at the same meteorological stations during one year period. The dependence of the neutron dose rate on the altitude was found and the associated equation of the linear regression was derived. Relation between the values of neutron dose N and altitude h, showed significant dependence of the neutron dose on altitude. However, the correlation of neutron dose and geographic (geomagnetic) latitude was not statistically significant, probably due to a small range of geographic latitudes for the measuring stations in Croatia.

Keywords

Cosmic Radiation, Track Etch Detector, Geomagnetic Effect, Dose Rate

1. Introduction

Cosmic radiation enters Earth's atmosphere with ionizing particles. The radiation has a galactic component, which is normally dominant and has solar origin. Cosmic rays consist of about 89% protons, 10% alpha particles and about 1% nuclei of heavier elements. By interaction of these particles with the atmosphere constituents, a complex set of secondary charged and uncharged particles (such as protons, neutrons and pions) is generated. Because of their long mean free paths, neutrons dominate the nucleic component at lower altitudes. Near Earth, galactic cosmic rays are affected by Earth's magnetic field [1]. Charged particles are deflected by the component of a magnetic field that is perpendicular to the direction of particle motion. This means that the cosmic radiation is more deflected at the equator than near the poles. The effect of Earth's magnetic field depends on geomagnetic latitude more than on geographic latitude. The effect of the magnetic field is greater for lower energy particles, *i.e.* those with lower magnetic rigidities. Particle magnetic rigidity is the product of the component of the magnetic field perpendicular to the particle momentum and radius of curvature of the particle trajectory. Likewise, rigidity can be calculated as a ratio of the particle momentum and the particle charge, usually expressed in units of GV. The cut-off rigidity is the minimum rigidity for a particle to penetrate towards the location on Earth. The value of the cut-off rigidity at the pole is 0 GV and about 15 GV at the equator. The geomagnetic latitude effect on the dose rate of photon and directly ionizing component of cosmic radiation at sea level is about 10% [2]. Cosmic radiation exposure will also vary with altitude, increasing by a factor of 2 for every 2 km above sea level [3] [4] [5].

The main purpose of our investigation is to give a better estimation of contribution of the cosmic component in the total radiation dose in Croatia. Point of special interest was to investigate well-known geomagnetic and altitude effects on cosmic dose rate and check whether these effects can be observed on ground measurements in Croatia with available equipment.

2. Materials and Methods

Photon and gamma radiations were measured by the Radiameter (Thermo Electron Corporation, ESM FH 40G-L10, dose rate measuring unit). All the measurements were taken 1 m above the ground in north-east (geological slate) and south (geological crush) parts of Croatia. Some measurements were also taken in the Manita peć cave which is located within the National Park Paklenica, in which the muon component of cosmic rays was measured (See **Figure 1**).

(a) (b)

Figure 1. Measurements of natural photon and gamma radiation dose were performed with the Radiameter in the open atmosphere 1 m above the ground. The neutron dosimeter consisted of CR-39 track detector (2×3 cm^2; Intercast Europe Company of Parma, Italy) and boron foil BN-1 or 10 B converter (Kodak-Pathe, France).

Neutron dosimeters consisted of CR-39 nuclear track-etched detector (with the surface 2×3 cm^2; Intercast Europe Company of Parma, Italy) and the boron foil consisted of ^{10}B sheet as converter (Kodak-Pathé, France) [6]. This detector set will further in the text be called D-4. In order to perform calibration, detectors were irradiated at CERN with neutrons, produced in the CERN-EU high energy Reference Field (CERF) facility, which is installed in one of the secondary beam lines (H6) from Super Proton Synchrotron (SPS), in the North Experimental Area on the Prevessin (French) site of CERN [7].

Track detectors were irradiated by CERF neutrons for 41.45 hours, during which period an ambient dose equivalent of 1 mSv was produced [8]. The CR-39 detectors were etched in 25% NaOH aqueous solution at 70˚C for 7 hours and afterwards visually counted under the 10×20 microscope magnification [9]. The neutron detectors were exposed to natural neutron flux in the atmosphere at 26 main meteorological stations all over Croatia during one year period.

2.1. Photon Radiation Measurement

Measurements of natural photon and gamma radiation dose were performed with the Radiameter in the open atmosphere at 1 m above the ground. **Table 1** presents measurement results at various geological sites in Croatia as S1 (location of the Department of Physics, Osijek), S2 (Starigrad Paklenica, sea side), S3 (Manita peć cave, Paklenica) and S4 (at the sea surface, Dubrovnik). For five dose rate measurements at S1 site, mean value was 94.5 nSv/h, with the standard deviation of 3.1 nSv/h, and relative error 3.1/94.5 = 3.3%.

Generally, it was intended to determine a cosmic radiation dose (H_c) received in various Croatian regions or sites. The attempt to numerically determine the cosmic radiation dose is as follows: the sum of cosmic photon and direct ionizing radiation (K), neutron component (N) and muon component of the cosmic radiation (M):

$$H_C = K + N + M \tag{1}$$

where $K = I - G - M$, and G is gamma radiation from the Earth; thus we got:

$$H_C = I + N - G \tag{2}$$

To get the gamma radiation from soil G, we used the measured values from **Table 1**, more precisely, the difference between photon doses at the sea side (Starigrad Paklenica, dose above the ground) and the sea level (Dubrovnik, dose above the sea); as a principle relation, we got:

$$G = I_{S2} - I_{S4} = 16.6\ \text{nSv/h} \tag{3}$$

So, relative portion of the gamma radiation originated from the soil in the total photon dose rate was about 20% ($G/I_{S2} = 23.3\%$; $G/I_{S1} = 17.6\%$).

Otherwise, direct measurements of terrestrial gamma radiation from ^{226}Ra, ^{232}Th and ^{40}K gave the average annual effective dose equivalent from the outdoor terrestrial gamma radiation of 53.5 μSv (which correspond to average dose rate of 6.1 nSv/h) for Karabük, Turkey, for instance, which was a little lower than our obtained value for the terrestrial gamma radiation G [10]. However, the average radon concentration in Karabük dwellings was 131.6 Bq/m^3, but the average indoor radon concentration in Croatia was 68 Bq/m^3 [11].

Photon dose rates were measured with the Radiameter ESM FH 40G-L10 in all parts of Croatia 1 m above the soil, near the main meteorological stations (**Figure 2**). Measurements resulted with the values presented in **Table 2**.

If parameters in **Table 2** are closely studied one can find interesting relationships between measured dose rates (I), latitudes (L) and altitudes (h).

At first, the geomagnetic effect on the measured dose at the measuring sites with various latitudes was considered. Namely, cosmic radiation dose should increase with latitudes, and a possible correlation between the I and L values was examined. At the same time, there is a known dependence of the photon dose, I, on the altitude, h: for increasing altitude from sea level to 1000 m, the photon dose increases about 8% [2].

The first examination of the linear correlation between the measured photon dose rate I and geographic (geomagnetic) latitude L gave the Pearson's correlation coefficient r_1 = 0.430, which was statistically significant; namely, the calculated Kendall's variable, t, for the given sample with n = 26 pairs had the following value:

$$t = r_1\sqrt{\frac{n-2}{1-r_1^2}} = 2.333. \tag{4}$$

The critical value of the Student's t-distribution, for given number of degrees of freedom, $k = n - 2$, and significance level $\alpha = 0.05$, was $t_o = 1.711$. Because $t > t_o$, one can conclude that the variables I and L are correlated; *i.e.* the hypothesis, that there is no correlation in the population, can be rejected, and it can be claimed with confidence of $(1 - \alpha)$ 100% = 95%, that a linear correlation between the photon dose rate and latitude does exist.

Also, it was in our interest to examine how measured photon dose rates I correlate with the change in altitude h? It was an evident case of the multiple correlations: the variable $I = y$ depends on independent variables $L = x_1$ and $h = x_2$, that was described by the following multiple correlation coefficient [13]:

$$R = \frac{\sqrt{r_{yx_1}^2 + r_{yx_2}^2 - 2r_{yx_1}r_{yx_2}r_{x_1x_2}}}{\sqrt{1-r_{x_1x_2}^2}}, \tag{5}$$

Table 1. Photon dose rates I at typical geological sites.

Site	I (nSv/h)	Standard deviation (nSv/h)	Relative error (%)
S1	94.5	3.1	3.3
S2	71.2	3.9	5.5
S3	39.4	3.2	8.1
S4	54.6	3.2	5.9

where the r were belonged correlation coefficients. The calculation with data from Table 2 gave the following values:

$$r_{yx_1} = 0.430,\ r_{yx_2} = 0.680,\ r_{x_1x_2} = 0.378 \text{ and } R = 0.71$$

A similar test for correlation coefficient values, like the one above in the text, with Kendall's variable, was performed. The results showed that the coefficients were statistically significant, meaning that the magnitudes of the measured photon dose rates I and latitudes L were correlated, as well as measured photon dose rates I and altitudes h.

Table 2. Photon dose rate (I), north latitudes (L), altitudes above sea level (h) and neutron dose rates (N) on the main meteorological stations (MS) corresponding to the map shown in Figure 2.

MS	I (nSv/h)	L (˚)	h (m)	N (nSv/h)
1	99	45.516	89	109.7
2	95	45.148	85	112.9
3	95	45.174	95	129.2
4	99.8	45.704	130	119.9
5	87.4	45.837	115	115.2
6	103	45.595	161	113.5
7	95	45.483	98	122.1
8	64.5	45.954	130	136.7
9	75.7	45.904	125	109.0
10	110.6	46.024	145	121.6
11	86	46.245	155	106.4
12	81.7	46.376	166	132.2
13	88	46.312	167	135.2
14	85	45.815	157	122.2
15	64.6	45.492	110	113.3
16	115	45.264	328	109.5
17	102	45.597	510	148.2
18	123	44.549	560	145.8
19	76.2	43.727	77	128.8
20	79.3	43.508	122	131.3
21	64.7	43.291	2	127.2
22	64.7	43.167	20	138.5
23	65	43.047	20	118.9
24	68	42.771	26	137.1
25	84.5	43.055	2	92.8
26	75	42.642	52	141.7

2.2. Neutron Dose Measurement

Besides the above mentioned, Table 2 also contains values of the measured neutron component of cosmic radiation N, distributed according to the measuring sites (some of the main meteorological stations in Croatia) marked on Figure 2. The procedure for measurement of the neutron dose rate was as follows [8]. After being exposed for one year in the atmosphere, the CR-39 detectors were etched and then their track densities d (tr·cm^{-2}) were determined. The response (r_4) of detector D-4 was determined after detector exposition to the known neutron dose during the calibration at CERN (EU high energy reference field):

$$r_4 = \frac{1\,\text{mSv}}{d_4} = \frac{1}{3285}\ \text{mSv}\cdot\text{cm}^2\cdot\text{tr}^{-1} = 304\ \text{nSv}\cdot\text{cm}^2\cdot\text{tr}^{-1} \quad (6)$$

The neutron dose (H) in the atmosphere for measured track densities (d) was calculated by following equation:

$$H = r_4 \cdot d \quad (7)$$

The dose rate was calculated as the ratio of the dose and time, *i.e.* $N = H/t$, where the exposure time was one year ($t = 8.76 \times 10^3$ h).

The examined linear correlation between the measured neutron dose rate N and altitude h showed that the belonging correlation coefficient was statistically significant and positive ($r = 0.36$). So, variables N and h are correlated, and the linear regression equation is derived:

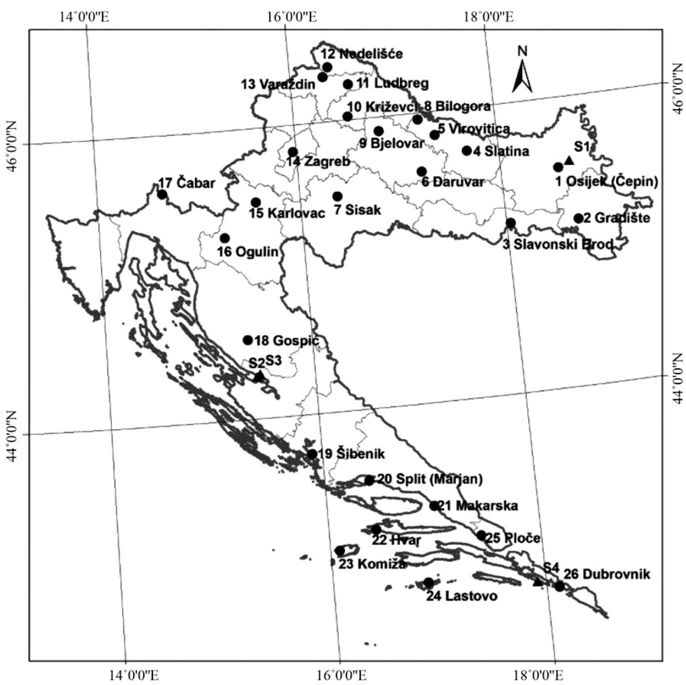

Figure 2. The main meteorological stations (MS) in Croatia with marked sites, where the cosmic photon dose and neutron dose were measured (results in Table 2). The figure shows particular sites S1, …, S4, where the photon doses were measured (results in Table 1). The map shown in this figure was created using the ArcGIS software by Esri [12].

$$N = a \cdot h + b \tag{8}$$

with values $a = (0.036 \pm 0.019)$ (m^{-1}nSv/h) and $b = (119 \pm 4)$ (nSv/h), or with the graphical presentation in Figure 3.

Since both correlation coefficients for dependence of neutron and photon doses on altitude had positive values (r, r_{yx2}), one can conclude that increment in altitude is associated with the higher radiation dose for both components of cosmic radiation. This fact is also shown with the appropriate experimental curves $N(h)$ and $I(h)$ [14].

So, using Equation (2) and collected data in Table 2, it is possible to calculate the cosmic radiation dose in a location of interest. For example, at the measuring location MS1 (altitude of 89 m, latitude of 45.516˚N) the total cosmic radiation dose is:

$$H_C = 99 + 109.7 - 16.6 = 192.1\ \text{nSv/h} \tag{9}$$

Considering the natural cosmic radiation dose, one can say, that it is better to live farther from the pole and closer to sea level.

Mean values for the measured photon dose rates I and neutron dose rates N shown in Table 2 are I_m = 86.45 nSv/h and N_m = 123.80 nSv/h, with the respective standard deviations s_I = 16.67 nSv/h and s_N = 13.6 nSv/h. Coefficients of relative deviation were calculated with the values: $K_I = s_I/I_m$ = 19% and $K_N = s_N/N_m$ =11%. This calculation showed greater variation of the photon dose rate than the neutron one (photon dose included more influence from the local ground characteristics).

Correlation between the values of neutron dose rates N and geographic latitudes L from Table 2 was also investigated and a low correlation coefficient was obtained. This fact is not in concordance with the known geomagnetic effect on neutrons in the north hemisphere [2]. It was of course recognized as measurement errors due to a small span of geographic (geomagnetic) latitudes L between the northernmost and southernmost parts of Croatia (from 46.245˚N to

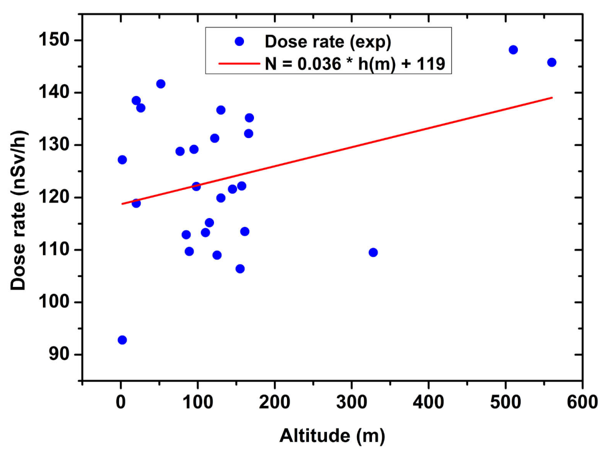

Figure 3. Neutron dose rate N versus altitude h of the MS (experimental data + linear regression with Microsoft Excel).

42.642˚N). The other reason for a low correlation coefficient, which was obtained, is multiple correlations between the measured values (N, h and L).

3. Conclusion

Using a series of specific measurements of the photon and gamma radiation on the typical geological sites enabled determination of the cosmic photon dose rate I, as well as the gamma radiation dose from soil G at 1 m height. The known geomagnetic effect on the photon component of cosmic radiation was examined at the sites of various latitudes and a significant positive correlation coefficient was obtained. Examination of multiple correlations for photon dose I, latitude L and altitude h showed yet stronger correlation, *i.e.* higher correlation coefficients were obtained. It would be interesting to examine actual soil samples (*in situ* measurements of gamma radiation from soil with the gamma spectrometer, for example) at several measuring locations and correct the Equation (2) for each type of soil characteristic for different parts of Croatia. Future work is planned in this sense in cooperation with other laboratories in Croatia. The relation between the values of neutron dose N and altitude h showed significant dependence of the neutron dose rate on altitude, and the equation of the linear regression was derived. However, the correlation between the values of neutron dose rates N and geographic latitudes L from **Table 2** was also investigated and a low correlation coefficient was obtained. This fact is not in concordance with the known geomagnetic effect on neutrons in the north hemisphere. Of course, it was recognized as measurement errors due to a small span of geographic (geomagnetic) latitudes L between the northernmost and southernmost parts of Croatia. Considering the natural cosmic radiation dose, one can say, it is healthier to live farther from the poles and closer to sea level.

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