THE COCORAD BALLOON-BORNE COSMIC RADIATION AND DOSIMETRY MEASUREMENTS IN THE FRAME OF THE BEXUS PROGRAMME

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Due to significant spatial and temporal changes in the cosmic radiation field, radiation measurements with advanced dosimetric instruments on board spacecrafts, aircrafts and balloons are very important. The Hungarian CoCoRAD Team was selected to take part in the BEXUS (Balloon Experiment for University Students) project. In the frame of the BEXUS programme Hungarian students from the Budapest University of Technology and Economics carried out scientific experiments on a research balloon, which was launched from Northern Sweden in September 2011. The main objective of the Combined TriTel/Pille Cosmic Radiation and Dosimetric Measurements (CoCoRAD) is to measure the effects of the cosmic radiation at lower altitudes where measurements with orbiting spacecrafts are not possible due to the strong atmospheric drag. By evaluating the deposited energy spectra recorded by TriTel and the glow curves obtained after the on-ground read-out of the retrieved Pille dosimeters, the Linear Energy Transfer (LET) spectra, the average quality factor of the cosmic radiation as well as the absorbed dose and the dose equivalent can be determined. The doses measured with the Pille thermoluminescent (TL) dosimeters and the TriTel 3D silicon detector telescope were intercompared for the first time. Based on the CoCoRAD results estimation can be also given for the doses that might be expected during launch of manned space flights or even commercial air flights. This paper presents the main objectives of the CoCoRAD experiment, the radiation environment in the altitude range of the BEXUS balloon, and the results of the CoCoRAD experiment.

I. THE BEXUS PROGRAMME AND THE COCORAD STUDENT EXPERIMENT

Among many other student projects ESA Education Office announced a call for proposals for the REXUS 11/12 and the BEXUS 12/13 flights for university students in 2010. The REXUS/BEXUS programme allows students from universities and higher education colleges across Europe to carry out scientific and technological experiments on research rockets and balloons. Each year two balloons capable of lifting their payloads to a maximum altitude of 35 km, depending on total experiment mass (40-100 kg) are launched 145 km North of the Arctic Circle from Sweden, carrying experiments designed and built by student teams[1].

A Hungarian student team were selected for the first time to take part in the BEXUS 12/13 project of the European Space Agency Educational Office. The name of the experiment was CoCoRAD, an abbreviation for Combined TriTel/Pille Cosmic RADiation and Dosimetric Measurements. The experiment flew on board the BEXUS-12 stratospheric balloon on the 27th of September 2011 from ESRANGE Space Center. The CoCoRAD experiment used the TriTel three dimensional silicon detector telescope for active monitoring and several Pille thermoluminescent dosimeters in order to study the usability of the Pille passive dosimeter system during stratospheric balloon flights. Both the Pille and the TriTel space dosimeter system have been developed in the former KFKI Atomic Energy Research Institute (MTA Centre for Energy Research from 1 of January 2012). The present paper addresses the main objectives of the CoCoRAD experiment, the radiation environment in the altitude range of the BEXUS balloon, and the results of the CoCoRAD experiment.

II. THE RADIATION ENVIRONMENT IN THE ALTITUDE RANGE OF THE BEXUS BALLOON

The primary cosmic radiation interacts with the magnetosphere and the atmosphere of the Earth. The particle intensities change with the magnetic and geographic latitude and with the solar activity.

The galactic cosmic rays determine the components of the radiation field in the atmosphere, which can be seen in Fig. 1. It consists of about 85% protons, 12% helium ions, 1% heavier ions and 2% electrons[2] .

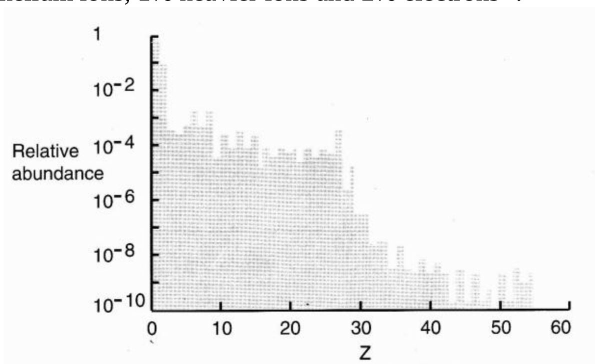

Fig. 1: Abundance of elements relative to hydrogen in the galactic cosmic radiation at a kinetic energy of 1 GeV/amu. Elements with charge >54 are not shown. The values are calculated for 1984[3].

The penetrating ability of particles into the geomagnetic field is determined by the magnetic rigidity (kinetic energy divided by the charge). For each point and each direction of incidence there exists a threshold value of magnetic rigidity, called the geomagnetic cut-off. Below this cut-off value no charged particle can reach the specified point from the given direction[4]. In the calculations, the magnetic cut-off rigidity is often approximated by the vertical cut-off rigidity:

$$R_{VC} = \frac{C_D \cdot \cos^4 \phi}{4 \cdot r_D^2}, \qquad [1]$$

where R is the magnetic cut-off rigidity in GV, r_D is the distance from the centre of the magnetic dipole in Earth radius, ϕ is the geomagnetic latitude, and C_D is a constant. Fig. 2 shows iso-contour lines of vertical cut-off rigidities at 20 km altitude in GV.

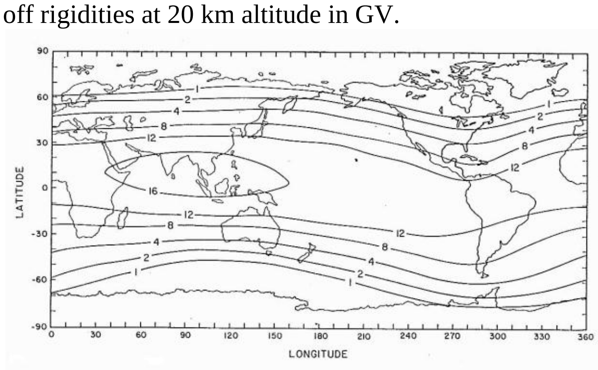

Fig. 2: Vertical cut-off rigidity R_c calculated for an altitude of 20 km[5 6].

The solar cosmic radiation is relevant during the maximum of the solar activity through the solar flares (sporadic eruptions of the chromosphere of the sun). They develop in minutes and the released energies range between 10^{22} to 10^{25} J. Proton fluences for solar flares in solar cycles 19, 20, 21 are shown in Fig 3. The solid line corresponding to the mean sunspot number clearly shows the 11-year solar cycle.

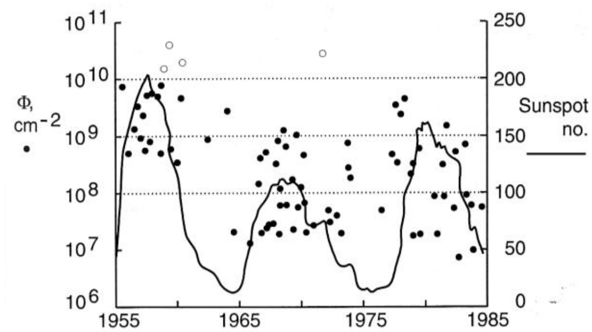

Fig. 3: Proton fluences for solar flares in solar cycles 19, 20, 21 •. The solid line shows the mean sunspot number. The anomalous flares are indicated by ∘ [7 8].

The interaction of a charged particles coming from space with the atmosphere is mainly the ionisation of atoms and molecules. Protons are most likely responsible for the production of secondary particles. Fig. 4 shows an example for secondary particles production.

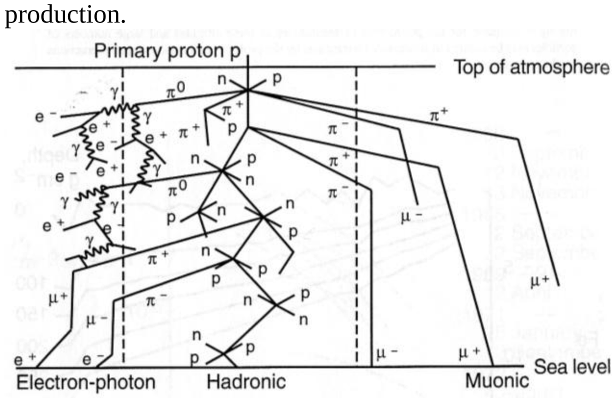

Fig. 4: Schematic representation of the particle production in the atmosphere [9 10].

The most important reactions are the production of secondary neutrons, protons and the pion triplet. The charged pions decay to muons and neutrinos. Most of the muons easily reach see level through the atmosphere and some of them decay to electrons and neutrinos. The neutral pions decay into gamma rays. The variation in the intensity of the charged particles in the atmosphere can be seen in Fig. 5. At an altitude of about 20 km a local maximum can be found, called Pfotzer-maximum. The reason for this maximum is that with increasing atmospheric depth the intensity increases due to the increased secondary particle production as far as the energy loss, absorption and decay processes become dominant[11]. Fig. 6 shows the intensity of the main components as a function of the altitude[12].

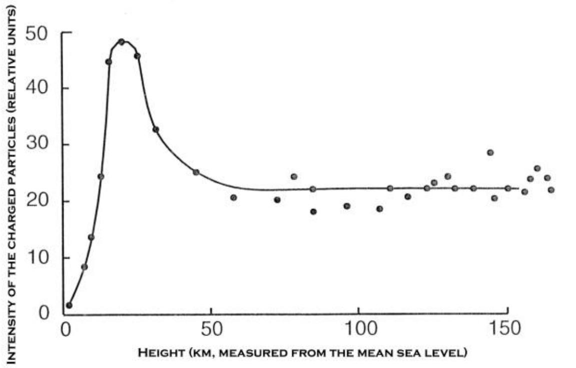

Fig. 5: Intensity of charged particles as a function of altitude [13 14].

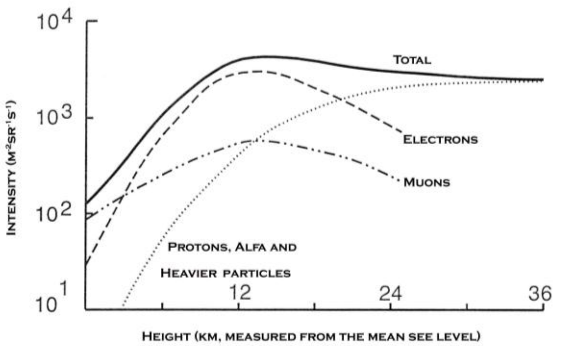

Fig. 6: Atmospheric depth profile of charged particles in the atmosphere [15 16].

Neutrons are produced in two different ways in the atmosphere. At energies below 10 MeV neutrons are evaporated from highly excited nuclei. Above 10 MeV neutrons are produced in collisions from high energy protons by means of charge exchange reactions.

III. INSTRUMENTATION USED IN THE COCORAD EXPERIMENT

The CoCoRAD experiment used two different types of measurement system during the flight of the BEXUS-12 balloon. One of them was an active space dosimetry system, the TriTel three-dimensional silicon detector telescope and the other one was the Pille passive thermoluminescent (TL) dosimetry system. In the following sections a short overview of these two instruments is given.

III.I The TriTel dosimetry system

TriTel is a three dimensional silicon detector telescope comprising six identical fully depleted, passivated implanted planar silicon (PIPS) detectors and designed to measure the energy deposit of charged particles. The detectors are connected as AND gate in coincidence in pairs forming the three orthogonal axes of the instrument (Fig. 7).

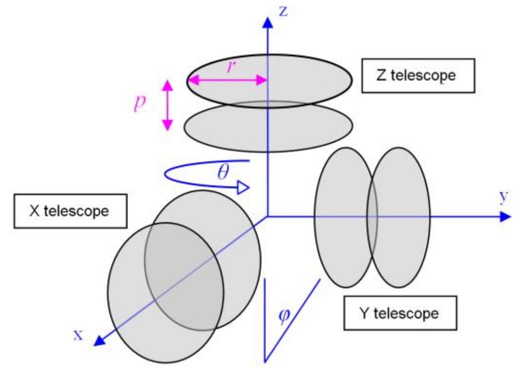

Fig. 7: The 3D telescope geometry (*r* is the radius of the detectors, *p* is the distance between two detectors in the telescope)[17].

By evaluating the deposited energy spectra recorded by TriTel the absorbed dose, the LET spectra in three directions, the quality factor and the dose equivalent can be determined. Since we are interested in the equivalent dose in tissue, the LET spectra in silicon is converted to LET spectra in human tissue.

Although the instrument can't determine the arrival direction of the individual particles, due to the three-axis arrangement an assessment of the angular asymmetry of the radiation might be possible. Another, even more important advantage of the geometry is that TriTel has an almost uniform sensitivity in 4π (Fig. 7).

The effective surface of each detector is 220 mm^2 with a nominal thickness of 300 μm. The most important geometrical parameters of the TriTel telescope are summarized in Table 1.

parameter	value
radius of the detectors (r)	8.4 mm
effective surface of the detectors (A)	220 mm^2
separation between the detectors in one telescope axis (p)	8.9 mm
ratio of the separation between the detectors and the radius (q = p/r)	1.06
geometric factor, G (for one telescope axis in 4π)	5.1 cm^2sr
maximum angle of incidence (for one detector pair)	62.1°
minimum path length in the detector (depletion layer thickness, w)	300 μm
average path length in the detector (for an isotropic field)	361 μm
maximum path length in the detector (for maximum angle of incidence)	641 μm
ratio of the maximum and minimum path lengths	2.14

Table 1: Geometrical parameters of the TriTel telescope.

In the CoCoRAD experiment setup the Y-axis of the TriTel instrument pointed towards the zenith direction. The x- and y-axis were orthogonal to the y-axis and parallel with the side walls of the gondola. The effective thinckness of the shielding in front of the detectors was ~0.5-0.6 g/cm^2 aluminium.

The noise level for the x-axis telescope was an order of magnitude higher due to manifacturing defects. However, since the gondola is rotating during the flight about its vertical axis, the possible anisotropies average out in the horizonal directions, i.e for the x- and the z-axis.

III.II The Pille Space Dosimetry System

The development of the Pille thermoluminescent dosimeter system started in the KFKI AEKI in the 1970s. The aim of the development was to invent a small, compact, space qualified TL reader device suitable for on-board evaluation of TL dosimeters. The Pille TL dosimeter contains $CaSO_4$:Dy TL material produced by the Budapest University of Technology and Economics. The TL material is laminated to the surface of a resistive, electrically heated metal plate inside a vacuum bulb made of glass. The dosimeter also contains a memory chip that holds identification data and individual calibration parameters of the device such as TL sensitivity, TL glow curve integration parameters or the time of the last read-out.

The Pille TL Reader (Fig. 8) is designed for spacecraft: it is a small, light-weight device with a low energy consumption. The reader is capable of heating the dosimeters, measuring the emitted light during the read-out, performing preliminary data evaluation, storing and displaying the results. The measurement results are stored on a removable flash memory card which can store up to 8000 data blocks consisting of the TL glow curve, the time of the last read-out, the results of the background and sensitivity measurement (performed in the beginning of each read-out) and all derived data such as the absorbed dose[18].

One of the main advantages of the Pille TL system is the possibility of the onsite data acquisition and evaluation, which means no transport dose in the calculations.

Fig. 8: The Pille TL dosimeter system in its transporting case (reader and ten dosimeters).

IV. THE OBJECTIVES OF THE COCORAD EXPERIMENT

Table 2 contains the primary (1), the secondary (2) and the tertiary (3) experiment objectives of the CoCoRAD experiment.

Exp. obj. #	Description of the objective	Priority
Obj.1	To perform dosimetry measurements with the TriTel 3D silicon detector telescope at altitudes up to maximum 35 km	1
Obj. 2	To measure the excess absorbed dose of the BEXUS balloon mission with the Pille thermoluminescent dosimeters	1
Obj. 3	To intercompare the results of the measurements	1
Obj. 4	To use TriTel data for improving the Pille results (correction)	1
Obj. 5	To measure the altitude dependence of the dose rates and LET spectra with TriTel	2
Obj. 6	To monitor first time the working of the TriTel detector in real mission conditions	2
Obj. 7	To estimate the possible altitude of the Pfotzer maximum based on the measured data	3

Table 2: CoCoRAD experiment scientific objectives.

V. RESULTS OF THE DOSIMETRY MEASUREMENTS IN THE FRAME OF THE COCORAD EXPERIMENT

The CoCoRAD experiment flew on board BEXUS-12 on the 27th of September 2011 from ESRANGE Space Center located in Northern Sweden close to the city of Kiruna (latitude of N68°). The floating altitude was about 27.6 km for two hours. The geographical latitude indicates a very low cut-off rigidity which results more particles in the altitude range of the balloon[19]. In the experiment ten Pille bulbs were used for flight while two were used as reference dosimeters and remained on ground at the ESRANGE base during the entire mission of the BEXUS-12.

V.I Results of the measurements performed with the Pille space dosimetry system

Table 3 shows the results of the Pille read-outs after the recovery. The results of the second read-outs during calibration of the dosimeters can be found in the fourth column. These values indicate the background level of the chosen Pille bulbs. In the last column the measured doses corrected with the background level of each bulb are shown.

ID	Type	Absorbed dose (μGy)	Absorbed dose corrected with the background level (μGy)
B01	flight	20.7	19.2
B02	flight	22.7	20.4
B03	flight	23.0	21.0
B04	flight	24.0	22.9
B05	flight	21.6	19.9
B06	flight	21.1	20.0
B07	flight	20.1	20.1
B08	flight	21.4	20.7
B09	flight	22.7	21.9
B10	flight	23.4	21.7
B18	ref.	6.7	5.4
B21	ref.	6.3	5.3

Table 3: Pille read-out results after the recovery (ref. means reference dosimeters).

The results of the Pille measurements of the BEXUS-12 flight are summarized in Table 4.

	Value
The average background level of the chosen bulbs	1.4 ± 0.5 μGy
The mission time	4.3 ± 0.2 h
The time between the read-outs	70 ± 0.5 h
The measured average absorbed dose (flight bulbs)	20.8 ± 1.1 μGy
The measured average absorbed dose (reference bulbs)	5.4 ± 0.1 μGy
The measured average dose rate at the surface (in ESRANGE)	77.7 ± 1.5 nGy/h
The excess absorbed dose of the BEXUS-12 flight	15.6 ± 1.1 μGy
The estimated error of the measurements	~ 7-10 %

Table 4: The results of the measurements with the Pille dosimeters in the BEXUS-12 flight.

The reference dosimeters were stored on ground in ESRANGE during the mission while the flight dosimeters landed close to the city of Kolari in Finland. Based on the radiation monitoring data at the station close to Kolari the background radiation where the flight dosimeters landed was about 100±10 nGy/h[20]. It is with a 25% more than what was measured in ESRANGE with the reference dosimeters. The difference is about +30-40 nGy/h. For the 70-hour-long measurement the total difference is about 2.1-2.8 μGy. The corrected measured result from the flight dosimeters is 13.1±1.5 μGy. This result is in the expected dose range of 10-35 μSv[21]. Since the Pille TL system provides onsite data acquisition and evaluation no transport dose measurements were needed.

V.II The results of the TriTel Dosimetry System

The float altitude of the BEXUS-12 balloon was approximately 27.0±0.5 km. The balloon was floating for 2 hours during which 12 primary and 12 coincidence 10-minute-long spectra were received for each telescope. The spectra were integrated for the 2 hours.

The axes of the TriTel telescope were aligned as follows: X-axis was perpendicular to the zenith direction (balloon was rotating); Y-axis was looking to the zenith direction; Z-axis was perpendicular to the zenith direction (balloon was rotating).

The X-telescope had high noise level which was detected. The noise level had a significant temperature dependence, for which the results can be corrected.

The differential LET spectra averaged for the floating time are shown in Fig. 9.

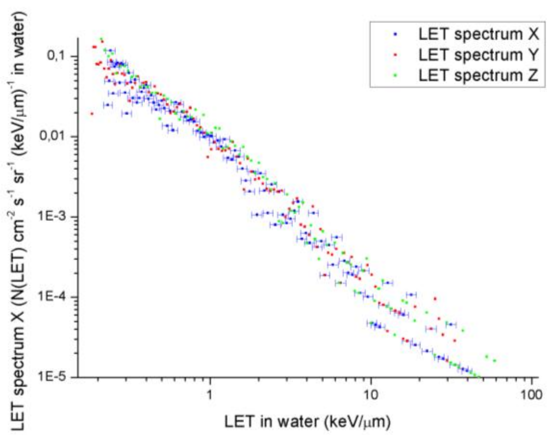

Fig. 9: The differential LET spectrum measured for the float altitude.

The total absorbed doses measured from the primary spectra for the floating time are as follows (Table 5).

Measured total absorbed doses (μGy)	
D_X (X-axis, high noise)	16.3 ± 2.0
D_Y (Y-axis)	11.5 ± 1.0
D_Z (Z-axis)	11.9 ± 0.3

Table 5: The results of the dose measurements with the TriTel in the BEXUS-12 flight.

The dose values obtained for the Y- and Z-axes do not differ significantly. In case of the Z-axis, the standard deviation was lower due to the shift in the offset (we had better energy resolution in the low-energy range).

V.III Intercomparison between the TriTel and Pille results

It is the absorbed dose that can be intercompared, since Pille is able to measure only the absorbed dose.

The doses measured during the ascent (Asc.), the floating (Float) and the descent (Desc.) phases give contribution to the total flight dose. In case of Pille, the dose is measured integrated, while in case of TriTel the doses are measured separately for each phases.

	Absorbed doses measured (μGy)			
	X	Y	Z	Pille
Asc.	14.8 ±0.8	5.4 ±0.3	5.5 ±0.2	-
Float	16.3 ±2.0	11.5 ±1.0	11.9 ±0.3	-
Desc.	7.4 ±0.4	2.7 ±0.1	2.8 ±0.1	-
Sum	38.5 ±1.8	19.6 ±1.2	20.1 ±0.8	13.1 ±1.5

Table 6: Absorbed doses measured with TriTel (X: TriTel X-axis, Y: TriTel Y- axis, Z: TriTel Z-axis) and Pille for the total balloon flight

The absorbed doses measured with TriTel for the balloon flight are higher than the one measured with Pille, as it was expected due to the low sensitivity of TL detectors to particles with LET higher than 10 keV/μm.

We used only the doses measured with TriTel's Y- and Z-axis to determine correction factors for improving the Pille results. The correction factor calculated from the values for the BEXUS-12 stratospheric balloon flight (from Table 6 above) is: 1.5 ± 0.2.

V. CONCLUSIONS

The Hungarian CoCoRAD student team were selected for the first time to take part in the BEXUS project and designed, built and carried out a scientific experiment on board a stratospheric research balloon. The CoCoRAD experiment used first time in real mission conditions the TriTel 3D silicon detector telescope to measure the cosmic radiation and its dose contribution during the BEXUS balloon flight. First time were provided an intercomparison between the Pille TL dosimeter system and the TriTel. We found an expected difference between the passive and active dose measurements due to the low sensitivity of TL detectors to particles with LET higher than 10 keV/μm. Based on the measurement results we have shown that a correction factor can be determined using Pille and TriTel simultaneous measurements. Since the Pille nowadays a part of the service system of the International Space Station it will be important in the future to determine this correction factor.

VI. ACKNOWLEDGEMENTS

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