Liceo Scientifico Statale C. Cavour - Roma

PCTO EEE -Extreme Energy Events

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The Cosmic Box for the analysis of the variation of the number of cosmic rays with altitude

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Abstract

Cosmic rays are the product of the interaction of primary cosmic rays with Earth's atmosphere. The impact produces a swarm of particles of different types that can be detected by special instruments that exploit the properties of cosmic rays to interact with matter, for example by causing the ionization of a gas, as happens in detector chambers of the EEE (Extreme Energy Events) Project, or by stimulating the production of photons, as happens in the Cosmic Box scintillation chambers. One of the fundamental properties of cosmic rays is the variation of their flux with altitude, a feature that has historically characterized the identification of the same cosmic rays as radiation of an extraterrestrial nature.

The work presented in these pages is the result of an analysis carried out by some students of the State High School “Liceo Scientifico C. Cavour” in Rome. They used a Cosmic Box obtained in a competition sponsored by the Enrico Fermi Research Center (CREF-Centro Ricerche Enrico Fermi) as part of the EEE Project to study the variation of the cosmic ray flux with altitude. The results show, as expected, that the number of cosmic rays increases with altitude.

Introduction

The discovery of cosmic rays and the study of their properties began in the early twentieth century and developed along with the discoveries of modern physics. The discovery of cosmic rays is also a story of bold hypotheses and courageous experimental proofs such as that of V.F. Hess, who was not afraid to climb a balloon with his instruments to prove that the phenomenon he was studying was not due to terrestrial radiation but to an unknown radiation from the cosmos, which could discharge an electroscope faster the higher the balloon climbed.[1][2]

Hess' hypotheses weren't immediately accepted. C.T.R. Wilson, for example, suggested that radiation might be due to storms in the high atmosphere. R.A. Millikan was initially sceptical, but then developed further research to confirm Hess's hypotheses. In particular, he confirmed that cosmic rays come from the outer layer of the atmosphere. Weather balloons and the introduction of new experimental equipment (e.g., self-recording electroscopes) then enabled a more detailed analysis. Still, this wasn't enough to clarify the nature of such a mysterious radiation.

Until 1929, scientists attributed the same properties to cosmic rays as to photons of γ-rays, since cosmic rays proved to be very penetrating, and more so than γ-rays, which were the most penetrating known radiation. In 1929, W.W.G. Bothe and W.H.G. Kohlhörster, using a new instrument to "count" the particles, developed the "method of coincidences," using two closely spaced counters placed one above the other, and demonstrated that the radiation was from charged particles and not photons. In the following years, the studies on cosmic rays were carried out by different scientists, among them B. Rossi, who has a prominent place especially for his studies on the penetrating power of cosmic rays.

In Rossi's experiments, layers of lead of different thickness were placed between the counters to study how cosmic rays could be absorbed by matter. Actually, the experimental results showed how the interaction of cosmic rays with matter led to complicated processes that produced numerous secondary particles.

Rossi introduced the use of bulbs to build coincidence circuits and was able to measure coincidences with counters also arranged horizontally, revealing the presence of secondary particle swarms. These “swarms" of cosmic ray have been the subject of numerous studies; among the most accepted and new hypotheses for the time was the one that assumed that the interactions causing the waterfalls were due to the emission of radiation by electrons and the generation of pairs by photons.

The use of the cloud chamber [3] (C.T.R. Wilson, 1899) to study the charge and energy of cosmic rays led to the discovery of new particles such as the positron, which was discovered by C.D. Anderson in 1932 and whose existence was confirmed by the research of P.M.S. Blackett and G. Occhialini. Anderson and S.H. Neddermeyer were also responsible for the discovery of the μ-meson in 1937, which was confirmed by J.C. Street and E.C. Stevenson.

The analysis of the interaction of cosmic rays with the magnetic field of the Earth showed that the primary cosmic rays had to be positively charged particles. In 1940 M. Schein proved, with the help of balloons that could fly up to 21 km high, that these particles were protons; further studies showed that, together with the protons, the primary cosmics ray also consisted of nuclei of Hydrogen and Helium, a hypothesis confirmed using the method of nuclear emulsions with which probe balloons were also equipped for the study of cosmic rays in the upper atmosphere. In order to study cosmic rays, increasingly refined experimental methods were developed: these methods were well described by D.J.X. Montgomery in 1949 [4].

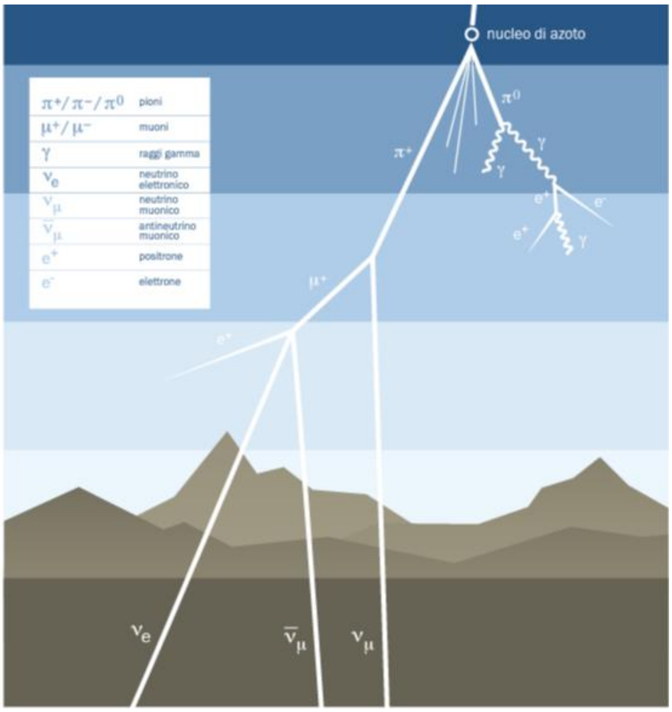

Fig. 1 Representation of secondary cosmic ray swarm and its composition (source: [5])

Although the composition of cosmic rays and their behaviour seem to have found an adequate scientific explanation, this is not true for the very energetic cosmic rays contained in the primary radiation. In fact, the energy spectrum of cosmic rays extends over several orders of magnitude.

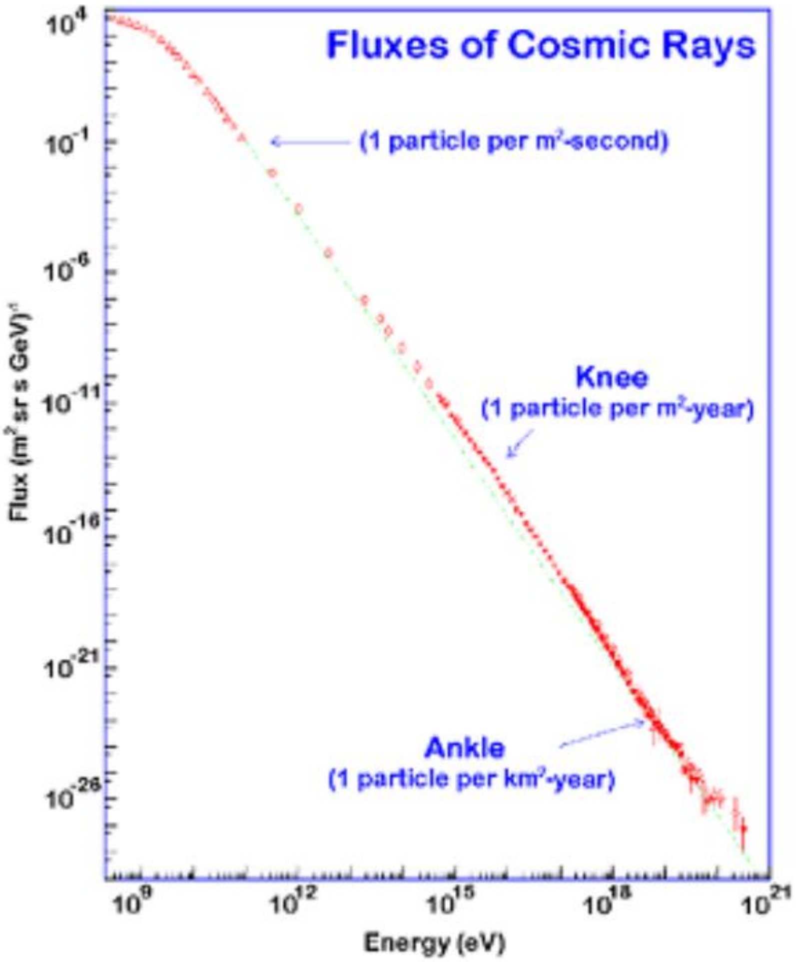

Fig. 2. Flux of cosmic rays as a function of their energy (source: [6])

The relatively copious flux of cosmic rays with energy up to 109 eV is due to radiation produced by the Sun, while the nature of high-energy radiation, which is extremely rare, is still unknown. [4] It is precisely for the study of this very energetic radiation that the EEE (Extreme Energy Events) project was launched: its purpose is to increase the probability of detecting high-energy cosmic rays by extending the observation area.

EEE (Extreme Energy Events) Project

The EEE project is a real research project carried out by CERN (Conseil Européen pour la Recherche Nucléaire - European Nuclear Research Council), INFN (Istituto di Fisica Nucleare- National Institute of Nuclear Physics) and MIUR (Ministero dell’Istruzione, Universita’ e Ricerca - Ministry of Education, University and Research) together with the schools in which a detector for the identification and study of cosmic rays is hosted [6].

The detector is built by the students themselves at CERN, under the supervision of researchers from CERN and INFN, and then transported and installed in the school. The management and maintenance of the detector is completely entrusted to the students and teachers who verify its proper functioning. The data collected by the detectors are transmitted in real time to the CNAF (Centro Nazionale Analisi Fotogrammi - National Frame Analysis Center) in Bologna, the computing center of the INFN, which keeps the data. However, these data remains fully available to the students, who can use them for practice purposes. These simulations and studies are always carried out under the careful guidance of the Enrico Fermi Research Center, which organizes and coordinates the activities of the schools through regular run meetings, where the objectives of the research are set and space to present their work are given to the students.

The schools participating in the project but not yet having the detector still conduct data analysis activities. Periodically, the students meet with their coordinators and researchers at the Foundation and Center for Scientific Culture "Ettore Majorana" in Erice to take stock of the research activities and set the goals for the next phases of work.

The EEE detector is a Multigap Resistive Plate Chamber (MRPC) that measures the time-of-flight of subnuclear particles to an accuracy of one picosecond. It consists of three superimposed chambers containing a gas that is ionized when a charged particle passes through. Only the signals that pass through the three chambers of the device simultaneously are considered, i.e., only the signals commonly called “coincidences”. [7]

The energy and direction of the primary cosmic rays are determined by counting and reconstructing the direction of the muon component. Two or more muons detected by distant stations originate from the same swarm if they occur simultaneously (within 1 ms) and have a small angular divergence. Correlation of events measured by different telescopes is done a posteriori using GPS technology, which can identify simultaneous events with 100ns accuracy.

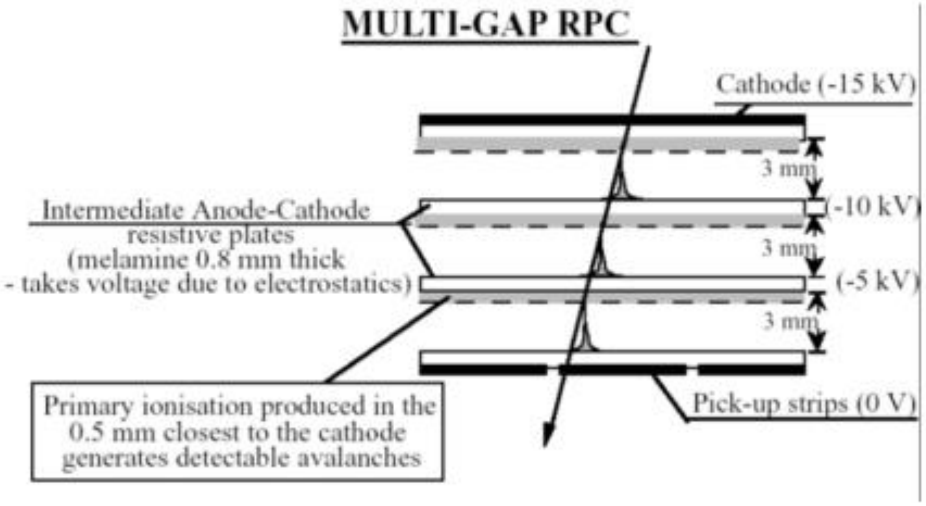

Fig. 3 The EEE detector (source: [2])

To enable schools that do not have a telescope to carry out measurements, smaller and manageable instruments for detecting cosmic rays have been developed in recent years. These instruments are named Cosmic Boxes and schools can borrow them participating in a contest launched by the Enrico Fermi Research Center.

Materials and methods: the Cosmic Box

The Cosmic Box is a device consisting of two parallel plates (15cmx15cmx1cm) of scintillator material, overlapping and spaced about 30 cm. [8]

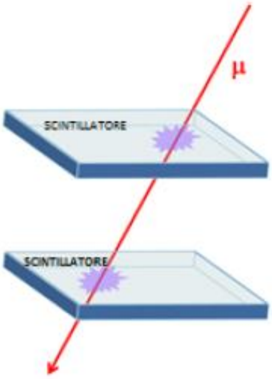

Fig.4 Scheme of the functioning of the Cosmic Box (source: [8])

When a charged particle passes through the scintillator material, part of its energy is converted into a light signal. Thanks to appropriate design measures, the photons thus generated are transmitted to a photosensor SiPM (Silicon Photo Multiplyer) and converted into an electrical signal. Cosmic Box's scintillators produce meaningful signals, without too many spurious events, when used together, i.e. when only the signals passing through both plates are recorded. In addition, the distance between the plates determines the solid angle (angle of acceptance) at which the particles are detected.

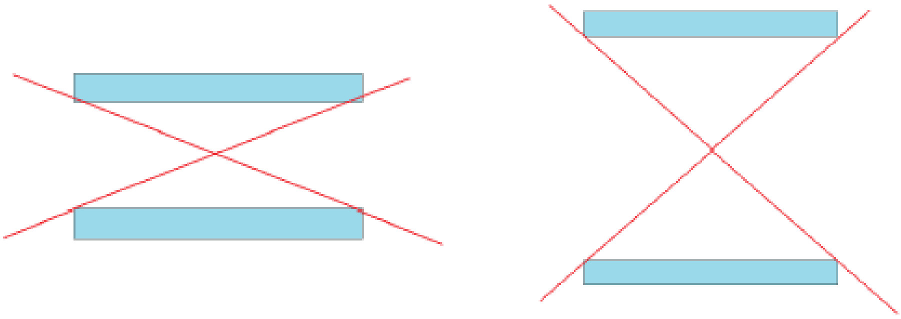

Fig.5 Acceptance of the Cosmic Box as a function of the distance between the plates (source: [9])

The scintillator used for the Cosmic Box emits at 425 nm, i.e. at the wavelength with the highest efficiency for the photosensor used.
The Cosmic Box operates on a 5V voltage that can be supplied from the mains or from a power bank, allowing the device to be used outdoors. The configuration of the Cosmic Box allows the measurement of frequencies of about 0.5 Hz. The counts appear on the display located on the front of the device, where the start, stop and reset buttons are also located.

Two measurement campaigns were carried out with the Cosmic Box, the first at the different floor of Building B of the State High School “Liceo Scientifico C. Cavour” in Rome and the second in the Basilica of San Clemente in Rome , which has the peculiarity of having three different levels to a depth of about 30 meters
The expected result is the increase in the number of counts with altitude.

Measurements at Cavour High School

The measuring device was positioned at the different floors of the building, always at a distance of about (1.0 ± 0.1) m from the back wall of the corridor in front of the elevator shaft.
Times were measured using the stopwatch of a commercially available smartphone with an error of about 2s.
Pressure (763 mmHg) and temperature (19°C) were measured using a dedicated cell phone app.

The acquisition time of the counts was set to 60s for each of the 10 measurements in all the series of measurements.
The number of counts for each measurement is shown in Table 1; the mean was calculated for each of the series; the error on the mean was calculated using the standard deviation.

Table 1: Counts of the number of cosmic rays detected at different altitudes

		Height with respect to the ground floor (m) ±0,10(m)			
		0,0	**7,0**	**12,0**	**17,0**
	(s)±2(s)	**±2 count error for each measurement**			
n	**Time**	**1- Ground Floor**	**2_First Floor**	**3_Second Floor**	**4_Roof**
1	**60**	20	38	37	41
2	**60**	19	36	40	36
3	**60**	23	31	21	40
4	**60**	25	31	30	35
5	**60**	27	32	26	29
6	**60**	16	36	26	45
7	**60**	25	32	30	30
8	**60**	20	40	32	33
9	**60**	16	17	38	42
10	**60**	24	23	32	34
Average		22	32	31	37
Standard Deviation		4	7	6	5

Results

Diagrams A, B, C, and D in Figure 6 show the distribution of the number of counts for the different altitudes.

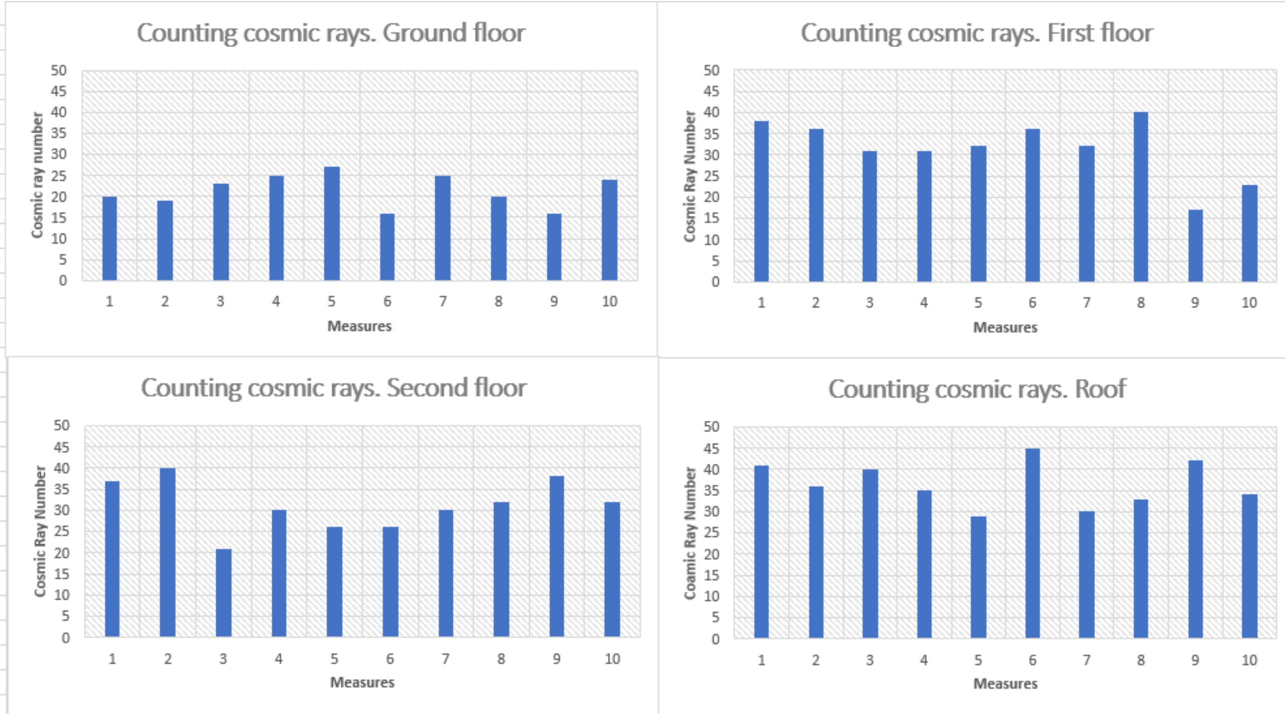

Fig. 6. Trend of cosmic ray counts at different altitudes

The diagram in figure 7 represents the trend of the average of the counts with the altitude.

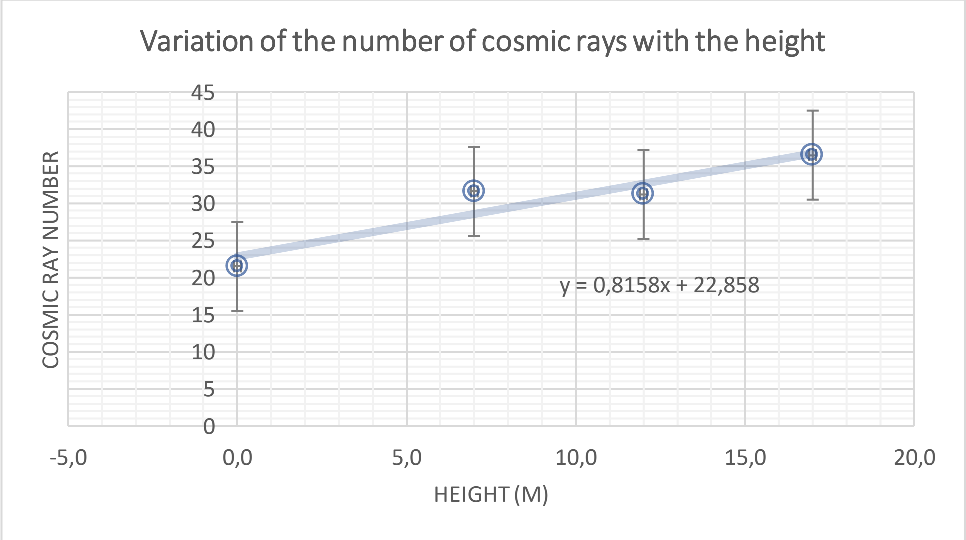

Fig.7 Trend of the average of the counts with the altitude

The diagram shown in figure 8 shows the trend of the accumulated counts over time.

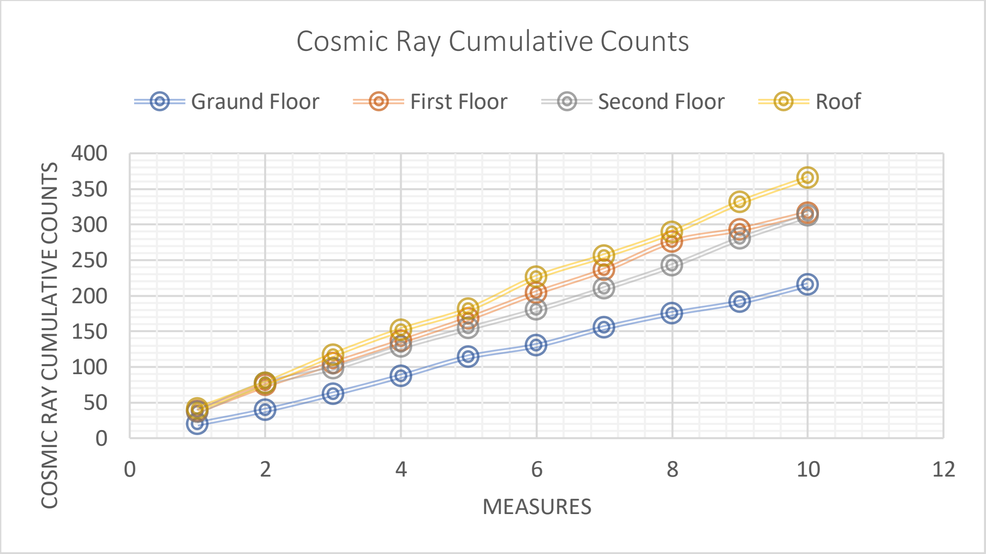

Fig. 8 Trend of the number of accumulated counts with respect to time

Conclusion

The obtained experimental results confirm the increase of the number of cosmic rays with altitude.
The fit of the experimental data shown in Fig. 7 shows an increasing trend with a gradient of about 0.8 counts per meter and confirms the increasing trend in the total number of muons recorded at different altitudes over time.
More meaningful measurements could be made with larger altitude differences.
A more detailed analysis of the phenomenon should take into account the behaviour of the secondary radiation due to the massive thicknesses of the floors on the different floors of the building.

Measurements at the Basilica of San Clemente *

The history of the church is reported on the site of the Basilica of San Clemente [10], which is briefly summarized below:
The Basilica of San Clemente is situated some three hundred yards above the Colosseum, on a road that rises gradually to St John Lateran from the valley between the Coelian Hill on the south and the Oppian Hill on the north.
It is named after Pope St Clement, the third successor of St Peter in the See of Rome, who died about 100 A.D. Until a hundred years ago, indeed, it was commonly thought that the present church was that to which St Jerome referred when he wrote about 390 that « a church in Rome preserves the memory of St Clement to this day ».
But in 1857, Fr Joseph Mullooly, the then Prior of San Clemente, began excavations under the present basilica, uncovering in the process not only the original, fourth- century basilica directly underneath, but also at a still lower level, the remains of an earlier, first-century building.

**Thanks to the Irish Dominican Fathers for allowing the scientific activity in the Basilica and to Dr. Di Gregorio for promoting the contact between the Rectors of the Basilica and the Liceo Cavour. **

Later excavations, notably those conducted in 1912-1914 by Fr Louis Nolan when a drain was being built between San Clemente and the Colosseum, showed that underneath this third layer of buildings there was still a fourth stratum, that containing buildings destroyed in the fire of Nero in 64 A.D.

The level, therefore, of the valley in which San Clemente lies was about sixty feet lower in the first century than the present level.
After the fire of 64 the gutted buildings were filled in and used as foundations for further houses, at a level that is roughly that of the floor of the Colosseum today.
At this third level at San Clemente there are two buildings that are separated from each other by a narrow passageway. The less pretentious of these is a brick building, possibly an « insula » or apartment house, in the courtyard of which there is a small Mithraic temple of the end of the second century.

The measurements were carried out in the Basilica of San Clemente in the building floors of the church. The ground floor of the basilica has an ornate coffered ceiling, the first underground floor was renovated and has a tiled roof, the lower floor from the Roman period shows the typical Roman wall and there are large tuff blocks.
A meteorological station and a thermometer were used to measure air pressure and temperature.
Data were collected at the basilica level, at the first and second levels in the subfloor.
The pressure in the floors was recorded as 767, 767 and 766 mmHg with an error of ±1 mmHg. The temperature was 19, 17, 16 Centrigrade degrees with an error of ±1 °C. Relative humidity was 70%, 84%, 98%.
At the lower level, the measurements were made in a room where there was a spring.

The acquisition time of the counts was set to (120±2) s for each of the 10 measurements in each series. The number of counts for each measurement is shown in Table 2; for each measurement the error is ±2 counts; the mean was calculated for each of the series; the error on the mean was calculated using the standard deviation

Table 2: Counts of the number of cosmic rays detected at different depth. Error is ±2 counts

	Church level	**First Underground Level**	**Second Underground Level**
n	3	2	1
1	54	37	4
2	67	22	34
3	47	34	18
4	64	33	17
5	60	18	32
6	58	51	30
7	55	15	32
8	59	3	40
9	51	9	36
10	43	5	38

Average	**56**	**23**	**28**
St. Dev	**7**	**16**	**11**

Results

Diagrams in Figure 9 show the distribution of the number of counts for the different depths.

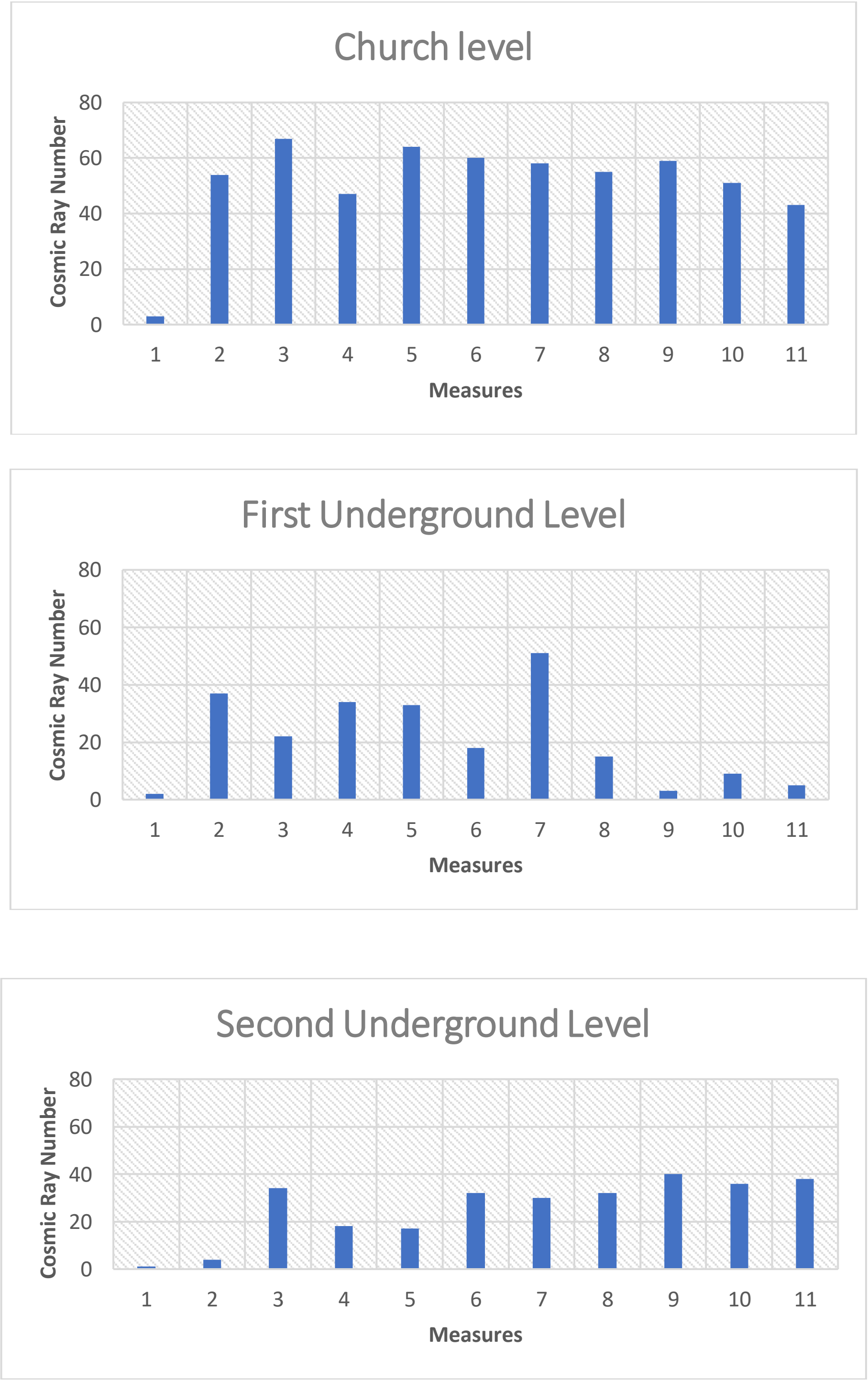

Fig. 9. Trend of cosmic ray counts at different depths

The diagram in figure 10 represents the trend of the average of the counts with the depth.

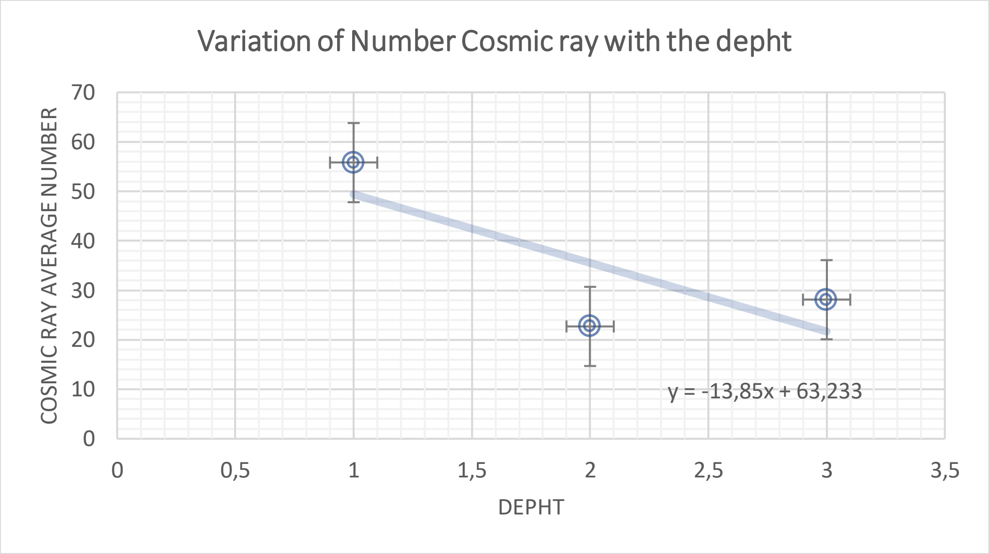

Fig.10 Trend of the average of the counts with the depth

The diagram shown in figure 11 shows the trend of the accumulated counts over time

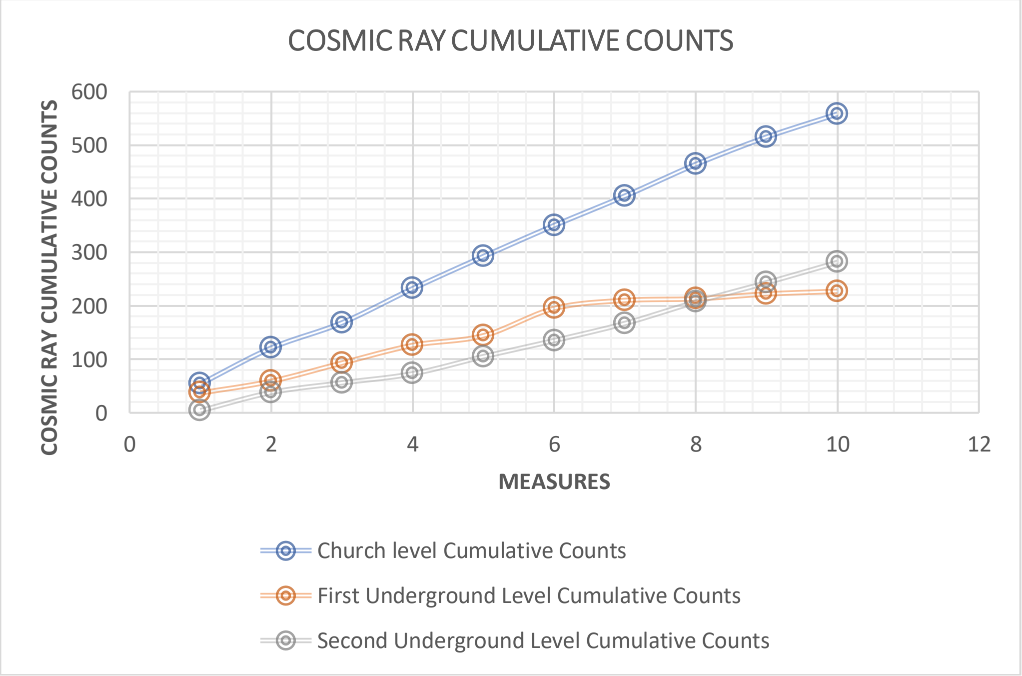

Fig. 11 Trend of the number of accumulated counts with respect to time

The analysis of the data and diagrams obtained during the measurements inside the basilica show some peculiarities, because it was expected that the number of cosmic rays would decrease towards the lower levels of the basilica. On the first subterranean level, there is a clear decrease and variability in the counts, but this is not observed on the lowest level, where the number of cosmic rays seems to be higher than expected.

To verify that no signals unrelated to cosmic rays were recorded at the lowest level, measurements were made at a later time than that of the initial measurements using only the bottom chamber of the Cosmic Box, which, however, recorded only an insignificant number of signals. Measurements were also made outside the basilica, which, as expected, recorded a higher number of counts.

The variability in the number of counts could be due to the different materials that make up the floors of the basilica, which has undergone several restorations over time. On the first floor of the basilica the ceiling is coffered, on the first basement a restoration was carried out with the classical bricks, while on the lower floor the Roman tuff wall is still preserved.

The measurements carried out inside the basilica showed quite a variability in the number of cosmic rays, even if the increasing tendency of the number of cosmic rays with the height is still confirmed.

Conclusions

The two campaigns of measurements carried out with the Cosmic Box confirmed, despite some anomalies, the behaviour of cosmic rays whose number tends to increase with height.

Further investigations should also consider the behaviour of cosmic rays when they pass through materials of different types.

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