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On the trail of Prof. Albert Gockel

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Abstract

As part of our Bachelor studies, we measured the muons flux from cosmic radiation at different altitudes using a hot-air balloon and a scintillator detector. Our aim was to commemorate the discovery of cosmic rays by ALBERT GOCKEL, one of the first professors in Fribourg, by repeating the same measurements (with better quality instruments) while at the same time adding a novel aspect, namely the angular dependence of the particle flux. This paper recalls how cosmic rays were discovered and then explains how we carried out our measurements, including all the experimental constraints and the subsequent analysis.

Zusammenfassung

Als Teil unseres Bachelorstudiums hatten wir die Möglichkeit mit einem Heissluftballon und einem Myonen Detektor die kosmische Strahlung in verschiedenen Höhen zu messen. Ziel des Unterfangens war es einerseits, an die Ballonfahrten von ALBERT GOCKEL, einer der ersten Physikprofessoren in Freiburg, zu gedenken, sowie erstmals die Abhängigkeit des Myonenflusses in der Atmosphäre vom Winkel zum Zenit zu messen. Dieser Artikel erinnert an die Entdeckung der kosmischen Strahlung und erklärt wie wir selbst zu unseren Messungen gelangt sind, unter den gegebenen Herausforderungen, und wie wir unsere Messungen analysiert haben.

Résumé

Dans le cadre de nos études de bachelor, nous avons eu l'occasion de mesurer le rayonnement cosmique à différentes altitudes avec une montgolfière et un détecteur de muons. Le but de ce projet était d'une part de commémorer les vols d'ALBERT GOCKEL, l'un des premiers professeurs de physique à Fribourg, et d'autre part de mesurer pour la première fois la dépendance du flux de muons dans l'atmosphère en fonction de l'angle d'incidence. Cet article rappelle la découverte des rayons cosmiques et explique comment nous sommes arrivés nous-mêmes à nos mesures sous les contraintes données et comment nous avons analysé nos mesures.

1. Introduction

As part of the 42nd international balloon festival in Chateau-d'Oex, we were presented with the opportunity to carry out an experiment in honor of the scientists who pioneered measurements of atmospheric radiation early in the last century. One of these early scientists was ALBERT GOCKEL, a professor from the University of Fribourg who some 110 years ago also took off using a gas balloon. During his flight he discovered an unexpected dependency of radiation, in the sense that it did not decrease with altitude, as one would expect if radiation is coming only from the earth. This made him think of an extraterrestrial radiation source, and although his fly was too low in altitude to verify this hypothesis, he named this source "cosmic rays"[4]. The existence of these cosmic rays has been verified shortly after that by the Austrian VIKTOR FRANZ HESS during a gas balloon flight of his own. For this discovery he was honored with the Nobel Prize.

Today we know much more about Cosmic Rays and what they are. In fact, we know that uncountable amounts of energized particles (like electrons, protons, neutrons but also many others) are penetrating our atmosphere every second. The discovery of this extraterrestrial radiation lead to a better understanding of the building blocks of nature and has, in particular, advanced especially particle physics. Nowadays physicists still observe cosmic radiation to find particles, which cannot be produced even by the most powerful accelerators.

2. Flight and measurements

Due to bad weather conditions and later COVID-19, only one of two planned flights at Château d'Oex was carried out. The first flight was planned as a test flight. Because of the test nature of this flight, we only rose up to around 4000 m.

It is quite staggering to consider that such vast knowledge about nature and the universe started with a hot air balloon flight from the same place where we are determined to take off. From a distance hot air balloons, such as the one we used (see figure 1) look so calm and peaceful but standing on the snow covered field where the balloons are prepared for take-off, one notices the terrifying noise of the burners heating up the air in the balloons.

***Figure 1**: The balloon*

In contrast to an airplane or even a helicopter the take-off is very calm and suddenly we found ourselves 10 m above ground, without really having had the sensation of leaving earth. It was then that we first realized what it meant to fly with a hot air balloon: You are being carried by air! You cannot trust your sense of orientation in general as you have always the impression of not moving at all. A neighboring balloon which didn't rise as quick as ours did, seemed to be crashing into the ground.

Despite our initial fears, it seemed to work quite reliable and fear quickly gave way to excitement, especially after learning that our pilot NICOLAS TIÈCHE had just won the famous Gordon Bennett Cup. They all inflated their balloons next to each other, but they did not seem to care too much about bumping into other balloons. It is very exciting rising simultaneously with a lot of other balloons and gives a very unique atmosphere. We were also very lucky with the weather, as we could enjoy the marvelous view above the alps (see figure 2).

Figure 2: *View during the flight with our apparatus*

During our ascent to about 4000 m we were constantly measuring the flux of muons (a particle best described as a heavy electron that will described further below) going through our detector. When we reached our maximum height, we inclined our device in order to measure the dependence of the orientation of our detector. In order to do so we changed the orientation of the device in order to register muons at a 45 degree angle of incidence. Handling something outside the cabin is a very weird feeling because one can only think about it falling 4000 m to the ground.

The descent went pretty slowly and due to the unpredictable nature of the weather our expected landing site changed (see our itinerary with figure 3). As we slowly went down and arrived near our potential landing sites, we could see the world getting bigger again below our feet. Finally, we hovered over a farm and landed right next to a little street on a field where our colleague from the ground team were already waiting for us. And after we had put the vast parachute back in to its tiny bag we drove back to Chateau-d'Oex verifying that our detector had gathered good data and we called it a memorable, more than just an adventurous day.

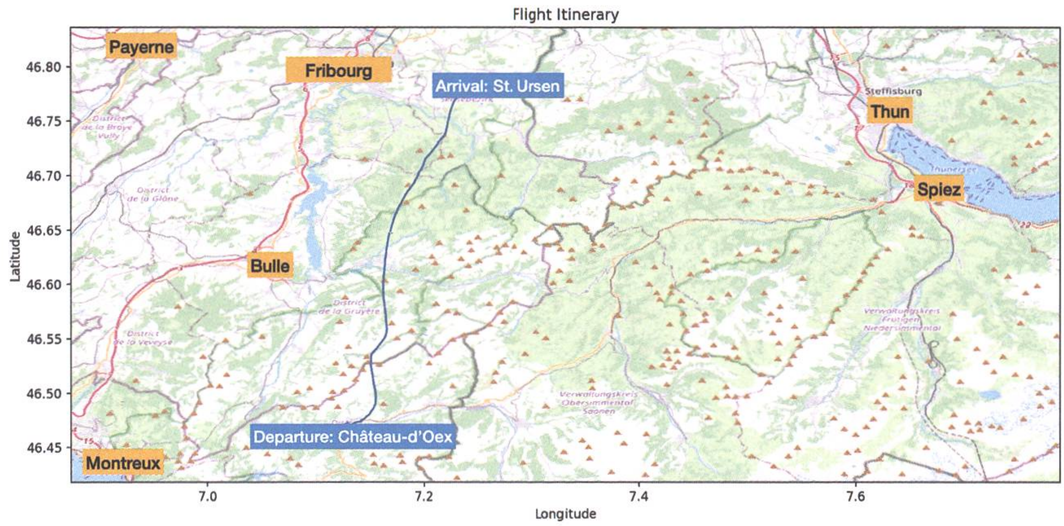

***Figure 3**: Flight itinerary*

3. Devices

Before the flight a large part of the work was to prepare the measuring device, which is summarized in this section.

The experiment included a hot air balloon flight up to 4000 meters for 4 to 5 hours. In addition to the difficulties associated with the measuring instrument itself, this fact also involves big changes in external conditions (such as temperature) that must be controlled. The purpose of this next section is to explain how we have set up our device to meet these challenges.

For our measurement we had the chance to use a prototype from the Italian enterprise CAEN. The device (called a *Cosmic hunter*) is composed of two scintillators connected to one detection – coincidence unit. The two scintillators are two 15 cm square plates that we have decided to space 15 cm apart as well. The detection unit counts only particles when they first hit one scintillator and, within a time interval a few ns, also the other one. The time of flight for muons between the two detectors is less than a ns, so the coincidence unit cannot distinguish between particles from above or from below. However, muons from sky are far more numerous than from below, so this small disadvantage doesn't play an important role. The distance between the two plates has been set to have a relatively small solid angle (to point to a fairly precise region of the sky) while respecting certain instrumental constraints (size of the box, ...). One suggestion to improve the experience would be to add a third scintillator to further reduce the solid angle.

Furthermore, in order to be able to associate the measured muons with other relevant data, it is essential to be able to measure several external parameters. To do this, we were helped by a device loaned by the High School of Engineering of Fribourg, which, coupled with the GPS of a smartphone, allows us to efficiently measure temperature, pressure, position and altitude. With a measurement frequency of 1 Hz, it was then necessary to synchronize these data with those collected by the cosmic hunter (by taking the average value over 10 minutes to be consistent with the scintillator's measurements).

As explained in the operating instructions of CAEN, it is recommended to use the detector within a temperature range of +/– 5 degrees. Consequently, a protective box was constructed. This box (dimension 400 mm x 420 mm x 470 mm) is made of 1.5 cm thick wooden boards filled with PSE foam. Only the space for the measuring instruments is left free. Despite this passive protection, estimates have predicted that some heat loss would still occur. To counteract this, a heater (whose power can be determined between 0, 10 or 20 Watts) coupled with a thermostat was installed to stabilize the temperature. However, with this solution another problem emerged: that of the power supply. We then made calculations to predict that a car battery of at least 416 Wh should be more than enough. A connection was therefore created between the battery (protected in a carton filled with PSE foam) and the box. Furthermore, digital devices to measure the temperature and the battery's voltage were installed in order not to be blind when the box is closed during the flight. The last important option is the balloon box holder, which must be removable enough to be able to change the zenith angle by 45 degrees, as required by the aim of the experiment. Finally, the experimentalists in our group carried out long-term tests in cold rooms or at high altitudes to prove the effectiveness of the thermal insulation.

4. Description of muons

The next few lines describe the muons and more precisely what is expected to be measured with our instrument.

When particles of primary cosmic radiation (mainly protons with a proton to nuclei ratio of 0.74, according to [1]) penetrate the atmosphere, they interact with its constituents and, among other reactions, hadronic showers are then created. Among other particles also muons (μ^+, μ^-) and muon-antineutrinos are produced by the decay of Pion (π^+, π^-) following the decay equations $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$ [1]. Muons are fermions of charge e which mass is 207 times larger as the mass of the electron [1]. From its altitude of creation (approximately 15 km above the earth's surface), they deposit and lose some energy in the atmosphere and finally they decay in $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$ and in $\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu_e}$ [1]. In the case of muon, its energy deposited $-dE/dx$ by a particle of charge z evolving in medium with atomic number z can be computed with the so-called Bethe-Bloch equation [2]:

$$\frac{-dE}{dx} = \frac{4\pi}{m_e c^2}\frac{nz^2}{\beta^2}\frac{e^4}{16\pi^2\epsilon_0^2}\left(\ln\frac{2m_e c^2\beta^2}{I(1-\beta^2)} - \beta^2\right), \tag{1}$$

where m_e is the mass of electron, c the speed of light, n is the electron density of the medium, $\beta = v/c$ (where v is the speed of the particle), e is the elementary charge, ϵ_0 is the electric vacuum permittivity and $I \approx z \cdot 10$ eV is the mean excitation potential of the medium [1].

Muons have very short lifetime of 2.2 μs [1] but, thanks to relativity, they can reach sea level and penetrate the Earth's crust. Considering a muon created at an altitude with a typical energy of 6 GeV and considering an adiabatic atmosphere, the use of (1) reveals that the energy of the muon at sea level is about 4 GeV, i.e. the total energy deposit in the total atmosphere is about 2 GeV.

According to [1] some 2 GeV (of the 4-6 GeV at the creation altitude) of the muon energy is lost in the atmosphere and its flux I at sea level is approximately

$$I = 70\, m^{-2}s^{-1}sr^{-1} \tag{2}$$

The muons flux depends on the azimuthal angle. This direction is characterized by the so-called zenith angle (θ = 0 degree when the detector points at the zenith). The variation of the flux I in function of θ can be written, broadly speaking [1],

$$I(\theta) = I_0 \cos^2\theta. \tag{3}$$

Where I_0 is the muons flux at $\theta = 0°$.

5. Analysis of the data

Figure 4 represents the number of counts per 10 minutes as function of the mean altitude during the flight. Large horizontal errors can be explained by the fact that measurements are taken continuously and that, at the beginning or end of the flight, the altitude at which the balloon is located increases or decreases rapidly (see figure 5). The vertical error bars indicate only the statistical uncertainty for the Poisson distribution for a 68% confidence interval, i.e. $\sqrt{N}$. Measurements made at take-off (at 958 m altitude), landing (at 800 m altitude) and cruising altitude (about 3000 m) are however more accurate. The flux at 45 degrees is only half the size of the flux at 90 degrees (see table 1) and this is consistent with the angular dependency given by $\cos^2(\theta)$.

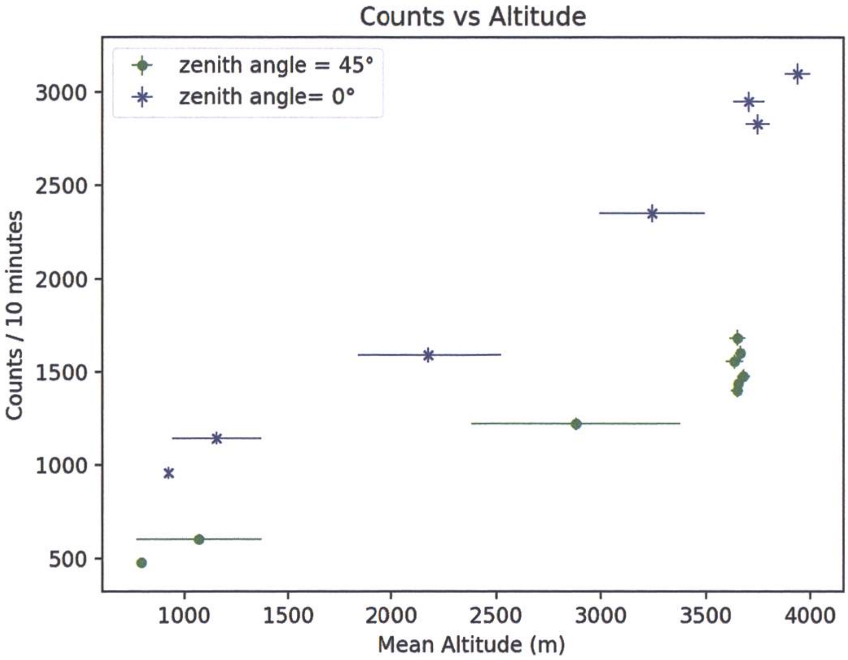

Figure 4: *Counts per 10 minutes as function of the mean altitude. Blue is for zenith angle of 0° and green for zenith angle of 45°.*

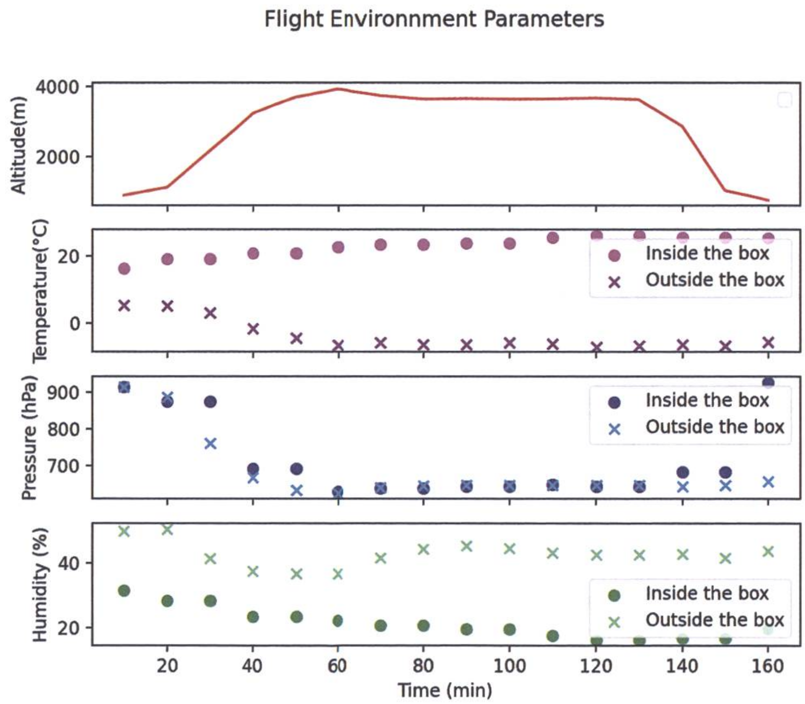

Figure 5: *Evolution of the environmental parameters, i.e. altitude, temperature, pressure and humidity during the flight. The last three parameters have been measured inside and outside the isolating box. The unexpected difference for the last pressure measurement between in and out of the box is probably due to the fact that the device outside the box was switched off directly after landing while it would have been necessary to wait till the end of the measurement cycle of 10 minutes to get the correct pressure reading. Fortunately, this does not affect the validity of our data.*

***Table 1**: Ratio r between the mean count rate N_0 at $\theta = 0°$ and N_{45} at $\theta = 45°$ (given in counts per 10 minutes) for two different altitude ranges h_{approx}. Only the points with reasonable uncertainty on the altitude are considered.*

h_{approx}	$\overline{N_0}$	$\overline{N_{45}}$	$r = N_0/N_{45}$
850 m	961	478	2.01
3700 m	2889	1519	1.90

After this, the muon flux values (number of muons per unit area per unit time and unit solid angle) as a function of altitude were calculated from the number of counts by the detector oriented at 0°, i.e. in the vertical direction. To perform these calculations, we assume the detector efficiency for muon to be close to 1 and that the detector only counts muons (μ^+ or μ^-). According to [3], the muon flux I is given by:

$$I = \frac{N}{(\tau G)}, \tag{4}$$

where N is the number of counts for a given measurement of duration τ (for this experiment t = 600 s) and G is the geometric factor. For the detector which consists of the superposition of two square scintillators with half sides X = 7.5 cm separated by a distance Z = 15 cm, the geometric factor taking into account the $cos^2(\theta)$ distribution of the muon flux according to the zenith angle can be written as [3]

$$G = \frac{16X^4}{Z^2} = 0.0225\, m^2. \tag{5}$$

Using data from figure 4 and equation (4) we calculated the muon flux I for the different altitudes of our measurements. Figure 6 compares our results with calculations and experimental results reviewed in [1]. The order of magnitude of the measurements made during the flight corresponds to the data in the literature, but the slope is higher. Different facts may contribute to differences: Firstly, the muon flux varies depending on solar activity and on the latitude at which the measurement takes place. Secondly, as a lack of detector calibration data with assumed an efficiency of 1 and finally as a random phenomenon it is subjected to statistical fluctuations.

6. Conclusion

Despite the fact that our flight left us with very few data points to work with due to the limited maximal reached altitude, it was a success in the sense that all the setup worked perfectly and allowed us to compare our data. After analysis, our measurements show a dependence of the muon flux with altitude and zenith angle consistent roughly with what we expected from comparison with literature and theory. Given the numerous factors involved, this is a pleasing result, as it was the main goal of the experiment to show this dependence. This also means that the muon detector from CAEN (Cosmic hunter) works properly and also the protective heated box surrounding the detector worked as intended. All of this, and of course the adventure at the Balloon Festival of Château-d'Oex made this experiment a very successful and memorable moment of our bachelor studies.

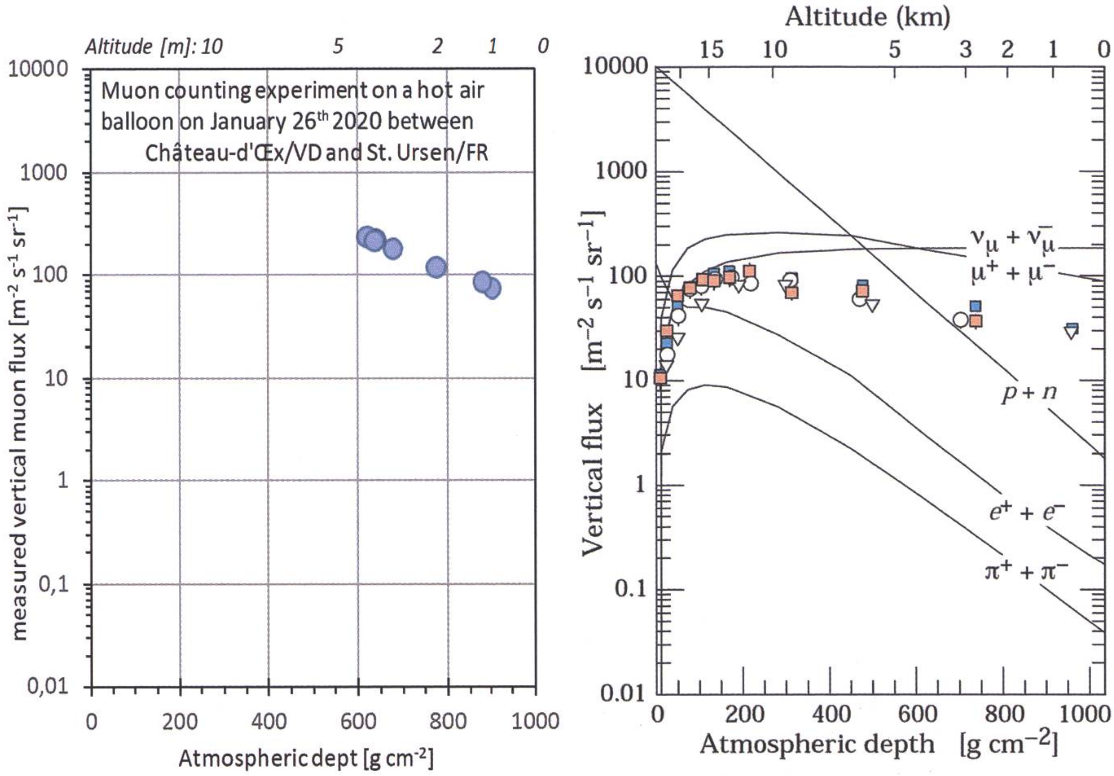

***Figure 6**: Left: Our measured vertical muon flux, assuming a detection efficiency of 1. Our data points agree somewhat with the $\mu^{+}+\mu^{-}$ solid line of the graph on the right, but the slope is slightly higher. **Right:** Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux. The colored points show measurements of negative muons with $E_{\mu} > 1$ GeV. Adding the μ^{+} and considering a μ^{+}/μ^{-} ratio of 1.2-1.3, the point should approach the solid line. The graph is taken from the Review of Particle Physics [1], Fig. 30.4. on page 512.*

7. Acknowledgment

This experience took place thanks to the funding of the flight by the Châteaux-d'Oex Balloon Festival, thanks to the loan of the measuring device by the CAEN company and thanks to the weathermeter designed by the High school of engineering of Fribourg. We thank them very much for their generosity. The physics department of the University of Fribourg offered technical assistance via the workshop and EMMANUEL GENDRE who took care of the electronics part. Special thanks go to Prof. HANS PETER BECK for initiating this project and encouraging us to participate, to Dr. CHRISTOPHER NICHOLSON for the correction of the report and to Dr. BAPTISTE HILDEBRAND and Prof. HANSRUEDI VÖLKLE for their guidance and answers to our numerous questions.

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***Figure** 7: Group photo before ascending. The muon telescope inside its insulating box is mounted to the balloon basket. From left to right: Pierre Adatte, Augustin Muster, Nicolas Bruder, Frédéric Chassot, Hans Peter Beck, Michael Hoch, Baptiste Hildebrand. (Picture taken by Michael Hoch and Fred-Paulin Gétaz)*

Figure 8: *Landing on January 25th 2020 near St. Ursen/FR (Picture taken by H. Völkle)*