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LONG TERM MONITORING OF COSMIC RAY FLUX AND ATMOSPHERIC PRESSURE: ESTIMATION OF THE BAROMETRIC COEFFICIENT BY A SIMPLE GEIGER COUNTER

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Abstract

In this document we want to discuss the possibility to observe the barometric effect and to extract an estimate of the barometric coefficient by the use of a simple and inexpensive experimental set-up. To this aim, atmospheric pressure and cosmic muon flux at sea level were continuously monitored for a period of about three months, using a small Geiger counter, together with an atmospheric pressure sensor. An accurate analysis of the data collected led to a value for the barometric coefficient of (0.051±0.015) %/mbar, in accordance with the expected value. This result showed that the study of the barometric effect does not necessarily require sophisticated apparata but can be easily carried out with equipments that even a high school could dispose of. For this reason such kind of measurements could offer to high school students a good opportunity to approach the field of experimental high-energy physics.

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1 INTRODUCTION

The problem of cosmic ray space and time variations is one of the most interesting and complicated aspect of cosmic ray physics. In the earlier decades after cosmic ray's discovery very little attention was paid to these variations. A real turning point in this field was reached when it was realized that the cosmic ray variations brought valuable information about the conditions in regions of space where they were created and accelerated. From then on, there has been a continuous research activity on these variations: the accumulation of experimental data on cosmic ray flux (measured by a world-wide net of observation stations) and the interpretation of these data allowed to recognize the different variations and to understand the geophysical and astrophysical causes that originate them (1).

Fluctuations of cosmic ray intensity at sea level may be caused by changes of the primary flux, resulting from alterations of the geomagnetic field or from solar activity. In this case the variations may have a periodic nature (with typical 11 years, 27 days, solar day, or semidiurnal cycles), or they may be the result of exceptional events, such as magnetic storms and large solar flares.

Other fluctuations of cosmic ray flux are due to changes in the distribution of atmospheric mass. These variations are usually called "meteorological effects" and they are very interesting from several point of view. First of all, a careful study of the atmospheric variations is necessary to correct the observational data for such effects in order to find variations originating outside the Earth's atmosphere. In the second place these variations form a valued tool for investigating variations of conditions in the terrestrial atmosphere and for understanding the interaction mechanisms of a high energy primary particle passing through a thick layer of air. It is obvious that the atmospheric variations have periods that reflect the periods of changes of meteorological factors (seasonal, diurnal, semi-diurnal). The two main atmospheric variations are the upper-air temperature effect and the barometric effect. The explanation of these effects is based on the processes of decay and nuclear interaction which take place in a nuclear-meson cascade. In fact the muonic component is the most penetrating part of secondary cosmic rays. So a variation of the cosmic ray flux at sea level is largely due to a variation of the muonic component. Therefore, when the temperature of the upper layers of atmosphere rises and hence the air density decreases, the fraction of π-mesons captured by nuclei decreases and a larger number of pions decay into muons. The temperature effect is often neglected because this kind of variation is evident only for muons with very high energy; muons observed at sea level suffer very little this effect and only high precision experiments can point out such kind of variation. Indeed the temperature effect is not simple to study because it is determined by the temperature profile along the Earth's atmosphere from the level of the origin to the detection level. On the contrary, the barometric effect is determined by only one factor, the pressure at the detection level, being more simple to interpret.

In this document we want to describe an educational study of the barometric effect of cosmic rays. Monitoring of the atmospheric pressure and of the muons counting rate at sea level was carried out by means of a Geiger counter, together with an atmospheric pressure sensor, both handled by an user-friendly acquisition system. The aim of this experiment is to establish if such a small effect can be studied with a simple and inexpensive experimental set-up. This kind of investigation has several educational aspects and can be intended as a pilot study in view of future involvements of high school groups in similar experiments. The idea is to establish a collaboration (partly already started) between the INFN, the Department of Physics and Astronomy of the University of Catania, and local area high schools, aimed at setting up cosmic ray experiments by the use of simple apparata. In this way high school students would have the possibility to learn about the basics of cosmic ray physics, to use statistical and data analysis methods, thus understanding the different aspects of a research activity.

2 THE BAROMETRIC EFFECT

2.1 Basic theory of the barometric effect

The barometric effect is a clear consequence of the mass absorption of muons in the Earth's atmosphere. In fact the atmosphere acts as an absorber for the muons and an increase of barometric pressure above the detector causes a greater absorption and thus a lower detection rate. The anti-correlation between pressure and intensity I of any secondary cosmic ray component may be computed with sufficient accuracy from the simple formula:

$$dI / I = - \_ \_ dh_0 \qquad (1)$$

where dI / I is the expected change in the intensity (in per cent of the mean value) due to a change dh_0 in atmospheric pressure at the level of observation h_0. The coefficient _ is called absorption coefficient and its value is characteristic of the particular secondary component considered. If _ is constant, the relation between intensity and pressure becomes

$$I = I_{h0} \ \_ \exp[-\_ \ \_ (h - h_0)] \qquad (2)$$

The quantity I_{h0} is the intensity for the pressure h_0 and it is influenced partly by the barometric effect, as well as by other kinds of effects. For this reason the relative change of cosmic ray intensity is usually expressed in terms of some constant quantity I_0. Indeed, when both _I = $(I – I_0) / I_0$ and $(h – h_0)$ are small, a first order approximation may be used:

$$\_I_{h0} = \_I - \_ \ \_ (h - h_0) \qquad (3)$$

where _ is the so-called barometric coefficient.

2.2 Influences of different types on the barometric coefficient

The value of the barometric coefficient is not unique and absolute, but depends on several factors. First of all every secondary component has a characteristic value of _. For example the barometric coefficient is about 0.7%/mbar for the neutron component, and only 0.1-0.2 %/mbar for the ionizing component. Another important factor which influences the coefficient _ is the geomagnetic latitude. Because of the Earth's magnetic field, the average energy of the secondary particles decreases with increasing latitude and therefore the atmosphere absorbs a larger number of particles. This means that the barometric coefficient increases going from the equator to higher latitudes. The coefficient _ also depends on the direction of incidence of the detected particles. Indeed the average energy of the secondary particles becomes larger as the zenithal angle is increased because the layer of atmosphere traversed is greater for particles coming from more oblique directions. The coefficient _ consequently decreases when higher and higher zenithal angles are considered. It is seen that the barometric coefficient depends considerably on the height of observation: an increase of altitude implies that particles have to pass a thicker layer of atmosphere and, according to what we have said before, the value of _ increases too. The barometric coefficient is finally influenced by the thickness of the shield surrounding the detector. The use of shields is a normal practice in such kind of experiment because it allows to decide the fraction of soft and hard components being detected. A careful study of this dependence shows that the value of _ rapidly decreases with increasing shield thickness.

It is now clear that the barometric coefficient is strongly dependent on the specific experimental set-up used for the detection of cosmic rays and a study of the barometric effect must hold in due consideration all the factors just described.

2.3 Experimental methods for the study of barometric effect

The study of variations of cosmic ray intensity and their connection with geophysical and astrophysical phenomena require usually an instrument with a large effective counting area in order to reduce statistical errors which could mask the small variations to be investigated. The monitoring of the cosmic ray flux should also be continuous and extended for a long time: this allows to discuss possible changes in the behaviour of variations with time and to discover fluctuations over long periods.

The early continuous recordings of cosmic ray intensity were carried out by the use of Geiger-Müller counters. These detectors were often arranged in cubical telescopes which have the advantage that their directional diagrams are independent of the dimensions of the counters used. This means that records performed by cubical telescopes situated all over the Earth can be easily compared because the dependence of cosmic ray intensity on the zenithal angle is the same for all these telescopes.

Nowadays Geiger-Müller counters are not much used in cosmic ray experiments since they don't allow to have a high statistical accuracy because of their small detecting area. Better results are obtained when measurements are carried out by scintillation counters: the large effective area of these detectors assures high count rates, which permit the study of very small cosmic ray variations and fluctuations with short periods.

In the light of what we have just said, a careful study of the barometric effect should requires sophisticated apparata because the value of the coefficient _ is usually very small. Moreover, an high accuracy in measurements makes easier to detect the barometric effect in presence of fluctuations in intensity due to a number of other causes. However the purpose of this work is not to carry out a precise measurement of the barometric coefficient but to ascertain whether it is possible to observe this effect by the use of a single Geiger counter.

3 THE EXPERIMENTAL APPARATUS

3.1 A description of the experimental set-up used

Measurements of atmospheric pressure and cosmic muon flux were performed by the use of the experimental arrangement sketched in Fig. 1.

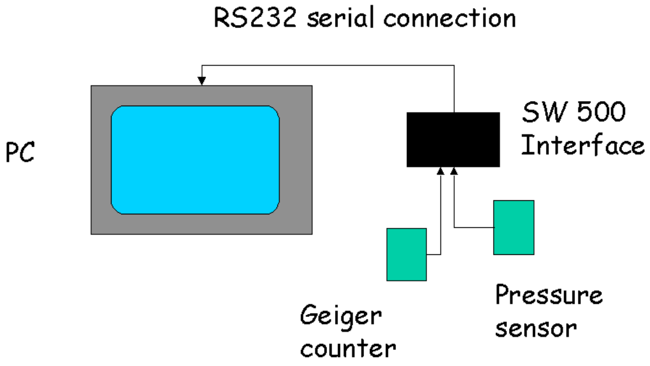


FIG. 1: A sketch of the experimental set-up used.

It is based on a small Geiger counter for the recording of the muonic count rate, together with a barometric pressure sensor.

We have also used a simple acquisition system (2) ,composed of a Science Workshop Model 500 Interface and a suitable software which allows to collect and store data as well as to perform other operations (such as graphics, simple data analyses and so on).

Measurements were carried out in a laboratory situated on the last floor of the Physics Department of the University of Catania. Since the geographical location of the detector influences the value of the barometric coefficient, a precise measurement of altitude, longitude and latitude of the observation point was taken by a GPS module. This device uses signals coming from 3 or more satellites and allows to make space measurements with an indeterminacy of about 0.003' on latitude and longitude and about 10 metres on altitude.

Fig. 2 shows the distribution of records of latitude, longitude and altitude performed by a GPS module during a period of a few days: the large number of events reduces considerably the statistical error that is about 10^{-4} arc second on latitude and longitude and only a few centimetres on altitude.

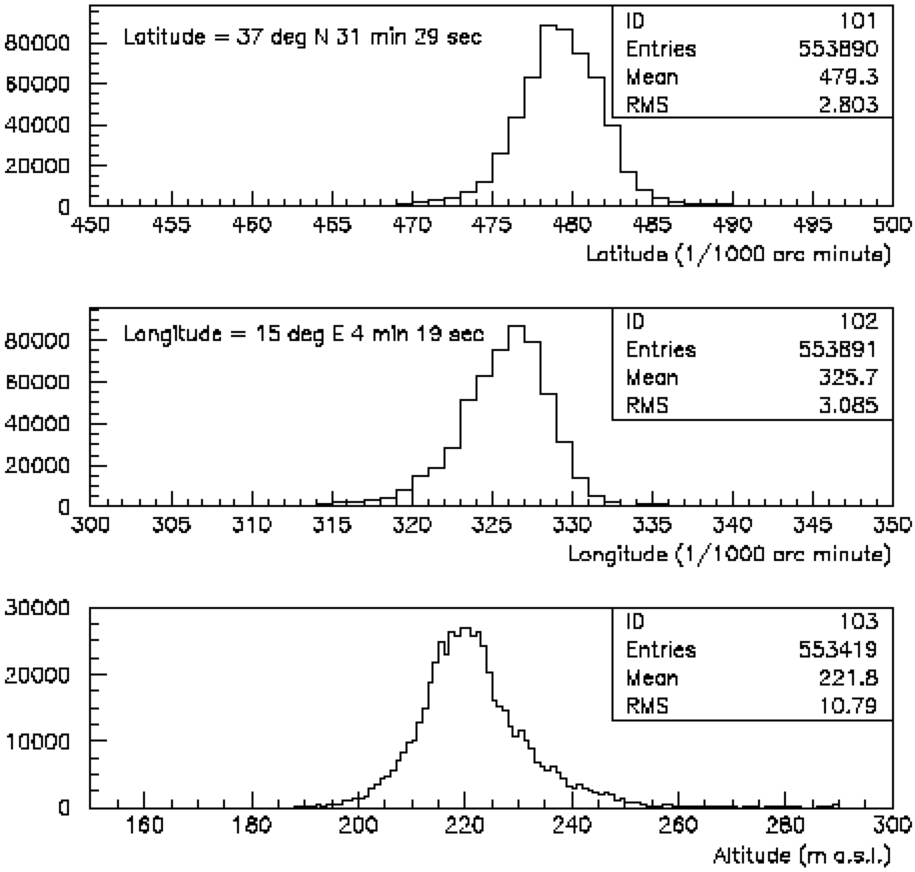


FIG. 2: Distribution of measurements of latitude, longitude and altitude carried out over a period of a few days by a GPS module.

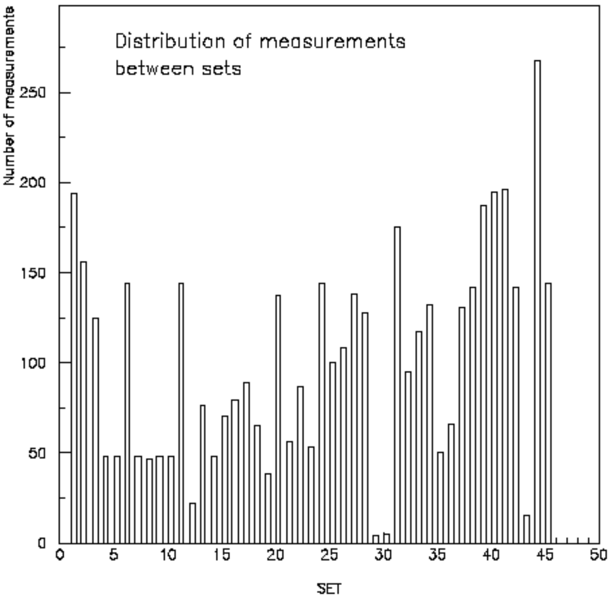
A GPS module can also be used to assign to each event an absolute time with a precision between 10 and 100 ns, depending on the number of satellites intercepted by the antenna. However the use of such module is not so common in this kind of experiments and it can be avoided when there is not the necessity to correlate the data collected with other data coming from different stations.

A particular attention was paid to the shielding of the detector caused by the surroundings. In fact the Geiger counter was located inside a building, approximately 2 m below the concrete roof so that cosmic rays had inevitably to traverse some “natural” shield thicknesses (like the roof, the surrounding walls and so on) before reaching the detector. In the determination of an average shield thickness we considered two important aspects: in the first place the Geiger counter was able to detect particles coming from all directions because only a telescope can define a particular orientation; in the second place we took into consideration only the roof influence, neglecting all the other obstacles. This last simplification is anyway a good approximation because most of the cosmic rays detected come from directions not far from the vertical, due to the zenithal angular distribution cos^2_ of cosmics. With a simple simulation we found that the cosmic rays traverse on average a concrete thickness of 42 cm, which is equal to a surface density of 100 g/cm^2. That is the same as saying that the Geiger counter is shielded by a lead thickness of 14 cm. This result allowed us to affirm that most of the soft component was stopped by the concrete shield and the Geiger counter detected prevalently muons, which are the most penetrating particles.

3.2 Experimental measurements

Measurements of the counting rate and of the atmospheric pressure were carried out continuously for a period of approximately 100 days, from April 9 to July 19, 2004. The system was stopped regularly every one or two days (in order to save the collected data) and this caused short interruptions (about some minutes) in the measurements. However the greatest loss of data is due to four lengthy stops (three of 24 hours and one of 43 hours) caused by power failures.

FIG. 3: A summary of the sets of measurements.



The Geiger counting rate was about 0.3 Hz because the detecting area was very small. We preferred to collect data in time steps of 30 minutes (approximately 550 counts): in this way we obtained an acceptable statistical error (about 4.3%) on each individual measurement.

Fig. 3 shows a schematic summary of the measurements carried out in these 3.5 months. Altogether there are 45 data sets and each of them includes a number of measurements depending on the length of the set itself: most of the sets lasted only one or two days, but technical reasons caused the presence of sets of only a few hours and sets of several days. On the whole, we carried out 4552 measurements and about 2.5_10^{6} events were collected.

4 RESULTS AND ANALYSIS

4.1 Analysis of the pressure variations

The upper graph of Fig. 4 shows the plot of the atmospheric pressure versus time during the overall run period.

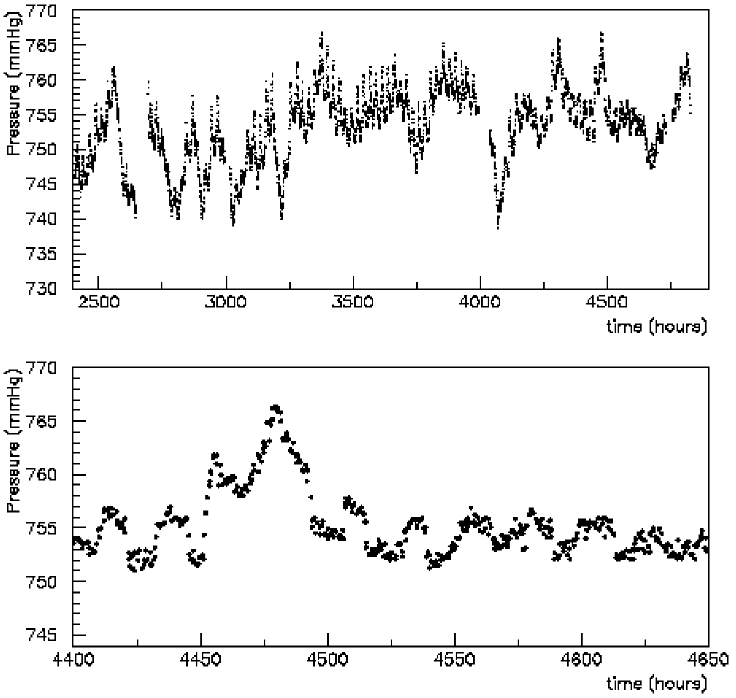


FIG. 4: Plot of pressure variations during the overall run period (upper) and an expanded portion of it (lower).

One can immediately note the presence of very large variations (some dozens of mmHg) of the pressure during long periods. These fluctuations are connected to complicated meteorological phenomena: as a matter of fact it is well known that low pressure causes periods of bad weather and high pressure periods of fine weather. Apart from these variations, the atmospheric pressure shows a periodic behaviour with 24 hours cycles. These smaller fluctuations are more visible in the lower graph of Fig. 4, which shows an expanded portion (about 10 days) of the preceding plot. This graph shows the presence of a further small variation with a period of 12 hours.

The periodic behaviour of the pressure is an obvious consequence of the diurnal variation of the atmospheric temperature, which presents a maximum in the early afternoon and a minimum during the night.

There are several methods for a quantitative analysis of such time series. A generally accepted method consists in extracting a correlogram from the data. A correlogram is obtained plotting the points (k, r_k), where r_k is the correlation coefficient, defined for each k by the following equation

$$r_k = \left[\sum_{i=1}^{N-k}\left(p_i - \langle p\rangle\right)\left(p_{i+k} - \langle p\rangle\right)\right] / \sum_{i=1}^{N}\left(p_i - \langle p\rangle\right)^2 \tag{4}$$

where the p_i's are the N values of the pressure and <p> is the average value of the series of N values.

This procedure can be applied only to a stationary series, i.e. when a series does not present strong variations of the average value during long periods. In our analysis the large variations of the pressure don't allow us to use equation (4). Nevertheless we can make our time series more stationary considering the first differences _p = $p_i - p_{i-1}$ and applying equation (4) to the new time series. The result is shown in Fig. 5.

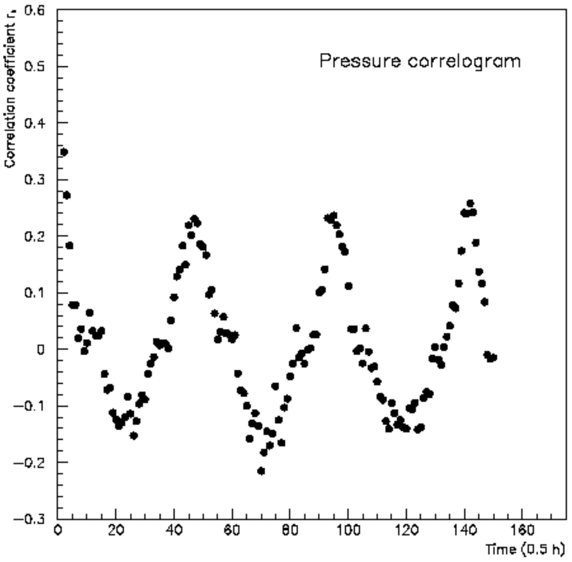


FIG. 5: Correlogram for a selected part of the pressure time series.

Those values of k for which the corresponding r_k is large show the periodicities of the time series. In our case the correlation is high when $k = 24$ and $k = 48$. These results confirm, in a quantitative manner, the periodicities of 12 and 24 hours emerging from Fig. 4.

4.2 Analysis of the muon counting rate variations

Owing to the announced anti-correlation between atmospheric pressure and muon counting rate, we expect to observe evident changes in the muon flux as a result of the pressure variations just described. Fig. 6 shows the plot of the Geiger counting rate for all the examined period.

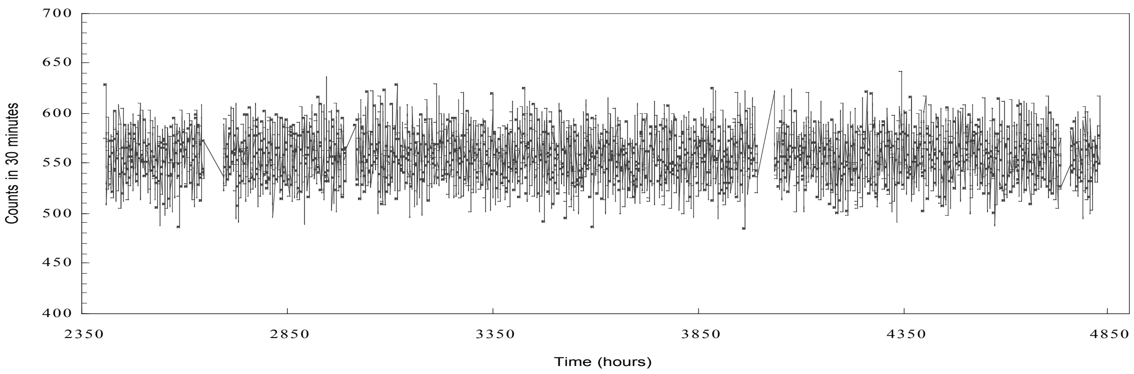
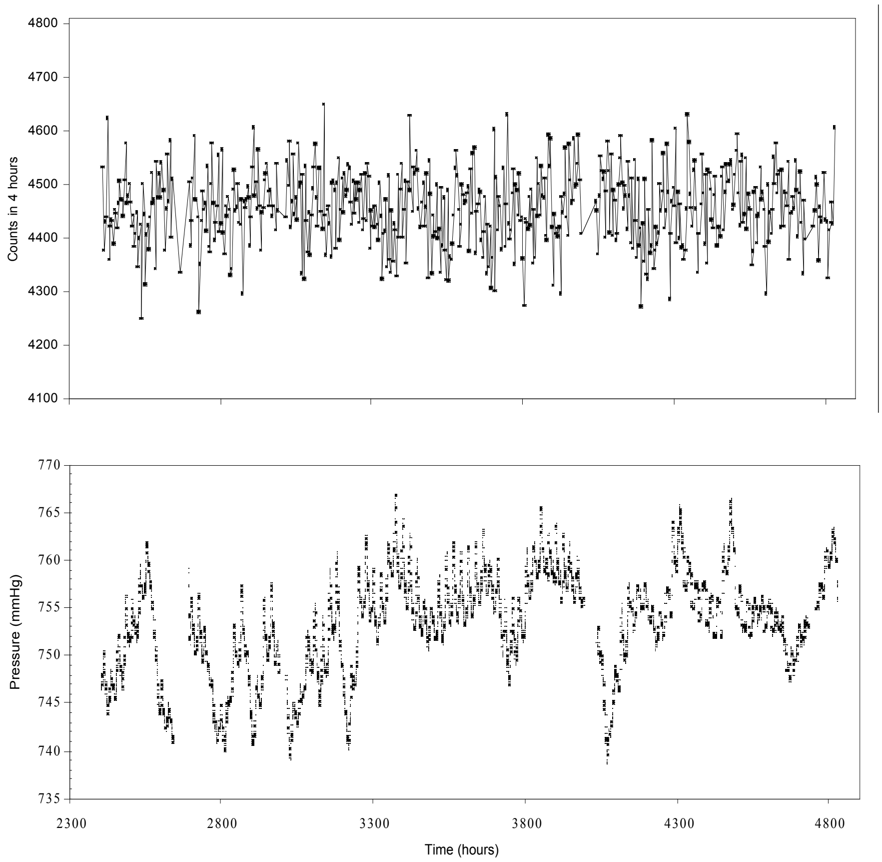


FIG. 6: Plot of the muon counting rate during the overall run period.

It would seem that the muon counting rate has not any kind of trend, but it is necessary to consider two important aspects: first of all, the barometric coefficient is very little for the muonic component (about 0.1 %/mbar), so only substantial pressure variations can produce changes in the muonic flux; in the second place the large statistical fluctuations (due to the small detecting area of the Geiger counter) could mask variations of the muon counting rate.

The situation does not seem to change even if we integrate the counts over a period of 4 hours (Fig. 7): in this case the anti-correlation is visible, scarcely, only in some periods of time. Better results are obtained considering the daily averages of the atmospheric pressure and Geiger counting rate. Even if measurements were carried out in a period of 101 days , the daily averages are only 93 because sometimes the interruptions present in measurements don’t allow to have uninterrupted periods of 24 hours. Fig. 8 shows these 93 daily averages of counting rate and pressure: there is an evident anti-correlation only in those periods in which the pressure changes considerably, such as on the 40th and 70th day. This kind of analysis has the advantage that the effect of daily variations in muon flux is minimized by considering the daily averages of counting rate and pressure.



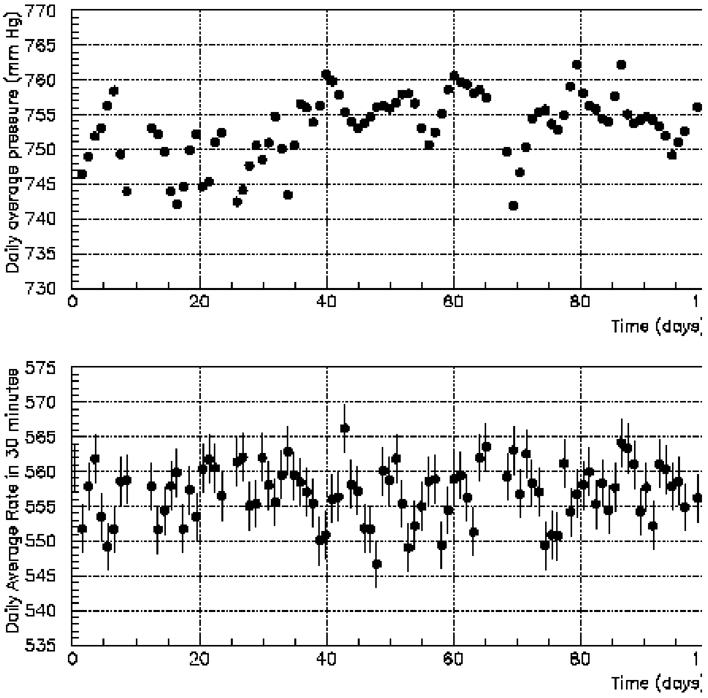


FIG. 7: Variation of the counting rate integrated over 4 hours (upper) and atmospheric pressure (lower).

FIG. 8: Daily averages of pressure (upper) and Geiger count rate (lower).

4.3 Study of the anti-correlation between pressure and muon counting rate

Up to now the correlation between pressure and counting rate has only been analyzed from a qualitative point of view. Now we are trying to estimate the value of the barometric coefficient, taking into account the limits of the detection apparatus used and the possible presence of variations in the cosmic ray flux, which may originate from causes different from the atmospheric pressure. According to what we have said before, we can suppose that the relation between counting rate and pressure is linear, that is

$$\text{Count Rate} = a + bP \qquad (5)$$

Considering this approximation, we performed a standard weighted fit of all data through the equation (5) and obtained for the angular coefficient a value b=(-0.17±0.07) (counts in 30 minute)/mmHg, which is equivalent to a barometric coefficient _=(0.023±0.009)%/mbar. Fig. 9 shows the correlation plot of the overall set of data and the corresponding best-fit line.

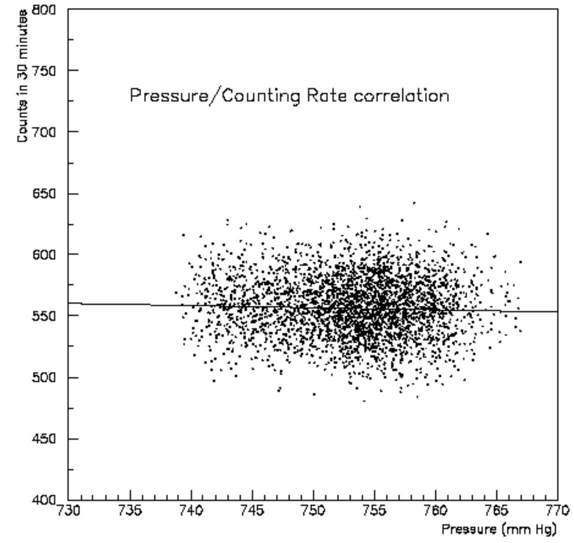


FIG. 9: Scatter plot of the pressure and counting rate.

Even if the correlation coefficient r is very low (r = 0.04), it indicates anyway an high correlation because of the great number of points considered (4552). This first analysis led, without doubt, to a positive result: we succeeded in finding a negative correlation between pressure and counting rate and this is not at all an obvious result because the angular coefficient b could even assume positive values if we consider measurements carried out only for short intervals of time.

In order to estimate the reliability of the extracted value of _, we studied the behavior of the coefficient b when the number of measurements becomes higher and higher. This kind of analysis is very common in the study of time series because it allows to discover possible “anomalous periods” which could influence the final result. Fig. 10 shows how the angular coefficient changes increasing the number of days of measurement (the values of b are obtained considering not the original data but the pressure and counting rate daily averages).

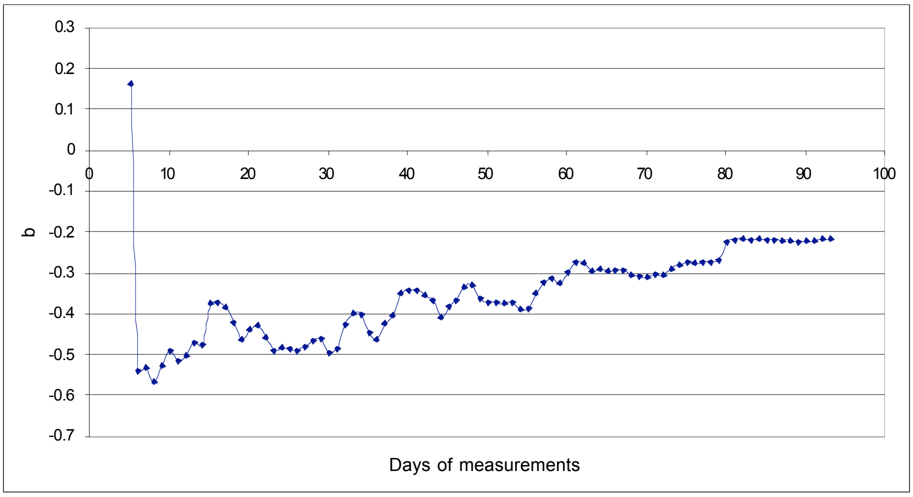


FIG. 10: Plot of b versus number of days of measurements.

One can see that, except some fluctuations, b has a different behavior between the first and the second part of the measurement period: indeed the angular coefficient, that is about -0.4 for the first 40 days of measurement, decreases considerably after the 40th day. This fact can be explained if we assume that a long term variation of the muon flux (not due to the atmospheric pressure) has affected the second period of measurement. This hypothesis is confirmed by other experimental results, such as the anomalous behavior of the correlation coefficient. According to statistics, this coefficient should decreases with the increasing number of measurements and this comes true when we calculate r for increasing numbers of measurement days. However when we put in reverse order the daily averages of pressure and counting rate, we notice that the coefficient r increases with the number of measurement days. This means that in the second period of measurement the correlation is really lower because of the effect of a variation in the muon flux.

Fig. 11 shows the correlation plot between daily averages of pressure and counting rate for the overall set of data (upper) and for the first and second half of the measurement period (middle and lower respectively). This subdivision allows to better observe the differences between the first and the second part of measurements: while the first half of points seems to arrange along a line (i.e. they have a high correlation), the second half of measurements is all concentrated in the zone of high pressure and the corresponding values of counting rate seem to be greater in comparison with the previous period. This is a further confirmation of the presence of a long term variation, more exactly an increase, that doesn’t depend on the atmospheric pressure. The effect of this variation is to destroy the correlation because the average value of pressure is very different from that in the first half of the measurement

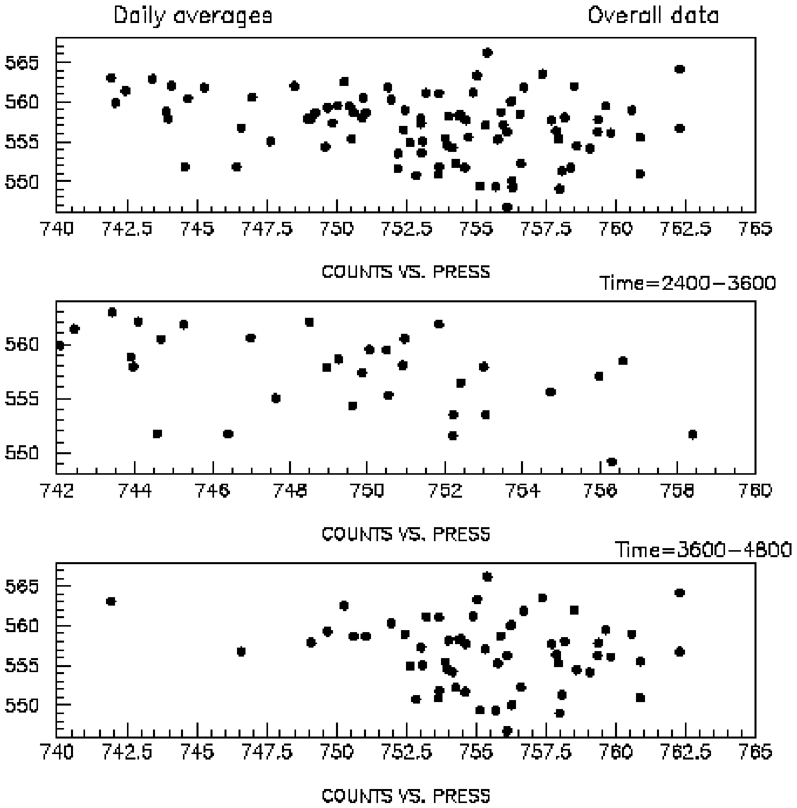


FIG. 11: Correlation plot between daily averages of pressure and counting rate for the overall set of data (upper) and for the first and second half of the measurement period (middle and lower respectively).

period.

This increase of the cosmic flux is also visible when we analyze the changes of the counting rate average calculated for selected bins of pressure, as a function of the time. If our measurements had been affected only by variations due to the barometric effect, the average value of the counting rate in a definite pressure bin would not change during the time. On the contrary, what we generally observed is an increase of this average value in the second part of measurements, an increase that is not caused by a change of the atmospheric pressure.

Since many professional stations for the detection of cosmic ray allow access to measured data, we could verify if an increase of the cosmic flux has been observed by other detection apparata. Fig. 12 shows cosmic data obtained by the Moscow Neutron Monitor for the period under consideration (3). These data confirm the presence of a variation (about 1%) which just starts around middle May 2004.

In the light of these results, the value of b = -0.17 ± 0.07, extracted from the overall set of data, must be considered unreliable because of the long term variation in the muon flux. For such reason we tried to minimize the effect of this variation, for example selecting from the original data only those intervals of measurements in which the pressure changes

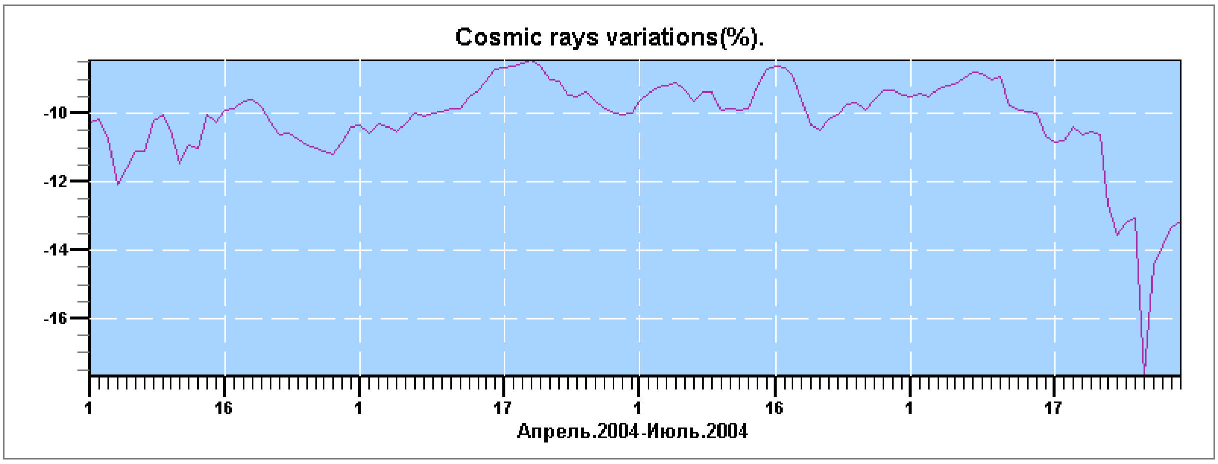


FIG. 12: Cosmic data obtained by the Moscow Neutron Monitor for the period under consideration.

considerably in short periods of time. In this way we could dispose of a data set which includes all values of pressure (from the lowest to the highest) but without being affected too much by possible long term variations. Taking the weighted mean of the coefficients b extracted from each interval, we obtained b = -0.32 ± 0.25 with _ = (0.043 ± 0.034) %/mbar. Since the choice of the intervals of measurements is completely arbitrary and the indeterminacy on _ is very high, we preferred to solve the problem of long term variation in another way. We subdivided the averages of pressure and counting rate in small time intervals of 10 days (as some authors suggest) and we calculated the weighted mean of the angular coefficients obtained for each interval. The result was b = -0.38 ± 0.11, corresponding to a value of the barometric coefficient _ = (0.051 ± 0.015) %/mbar.

In our opinion the value of _ obtained with this procedure is the most reliable, because it is calculated taking into account the overall set of data (and not only selected intervals) and minimizing the effect of daily and long variations.

Finally we want to point out that the determination of the amplitude and duration of the long term variation is beyond the scope of the present investigation. Anyway the statistical fluctuations present in our data wouldn't allow us to analyze more carefully this variation. We can only ascertain whether the seasonal change of temperature in the upper part of the atmosphere could explain the presence of this variation. Unfortunately, even if we strongly overestimate the value of the temperature coefficient, the change of the effective temperature between April and July 2004, that is about 1.2% (4), produces a small variation of the angular coefficient b, from -0.17 to -0.24. It is clear that the origins of such variation are various and complicated, and they could be discovered only by performing measurements for very long periods and using apparata with high statistical accuracy.

4.4 Discussion of the results obtained

A careful analysis of the data collected gave a barometric coefficient _ = (0.051 ± 0.015) %/mbar. Now we have to ascertain whether this value of _ is in accordance with that expected. Taking into account all the factors that influence the barometric coefficient (as the muon energy threshold, the particular geometry of the experimental set-up, the effect of shielding due to the surroundings and so on) we estimated a value of _ between -0.06%/mbar and -0.08%/mbar. The experimental value of _ is in agreement with the expected one, although it is slightly smaller. Nevertheless we must consider that, in our evaluation of _, we had to refer to results –published by other authors (1)- that were obtained at geomagnetic latitudes different from that of Catania (about 37°). For example we estimated that the coefficient _ can decrease of 0.015%/mbar going from latitude 56° to latitude 37°. Besides, when we neglect the variations not due to the pressure, we can introduce an effective barometric coefficient (5); for muons with low energy threshold, this coefficient is smaller than the real barometric coefficient of about (0.01-0.02)%/mbar.

4.5 Correction of the original data for the barometric effect

Once the experimental value of the barometric coefficient has been determined, we could correct the original data for the atmospheric pressure in order to discover possible fluctuations of the primary flux. Fig. 13 shows the corrected average values of the counting rate as a function of time.

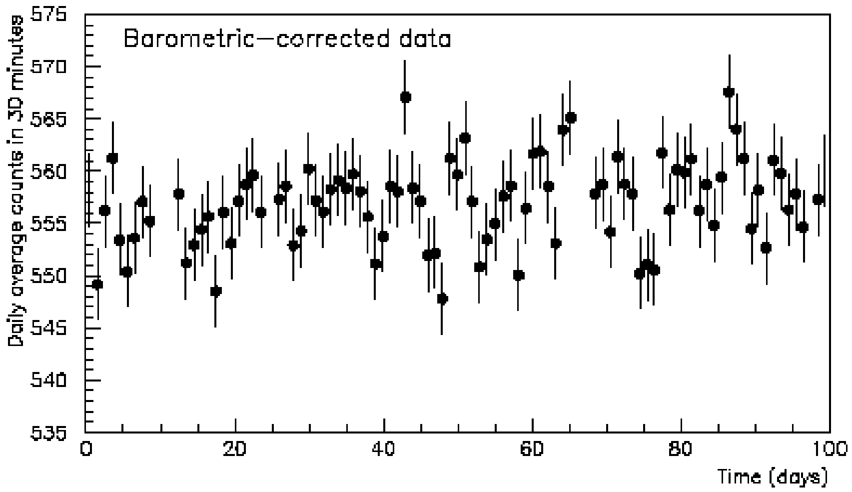


FIG. 13: Average values of the counting rate corrected for the barometric effect.

We analyzed this new time series with the statistical method of the correlogram and found a scarcely visible periodicity of a week, as shown in Fig. 14.

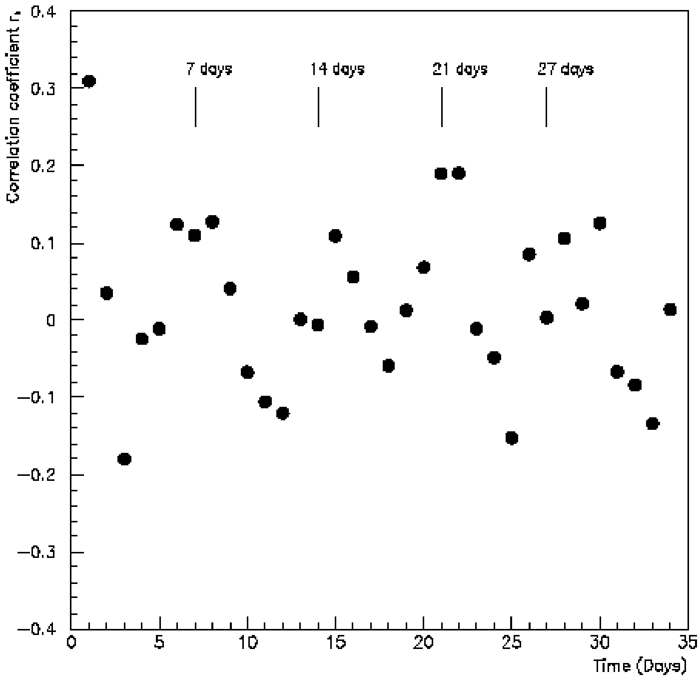


FIG. 14: Correlogram for the corrected cosmic data.

It’s not clear which is the origin of such variation, perhaps connected to the well-known periodicities of 13.5 and 27 days due to the solar activity. We also found a significant correlation between our data and those obtained by the Moscow Neutron Monitor. Of course this is only a preliminary analysis; we could obtain more precise results if we could extend measurements for a long period (about some years), preferably using detectors with a large effective area, in order to have small statistical errors.

5 CONCLUSIONS

The results of this experience show how the use of a simple experimental set-up, based on a small Geiger counter, allow to observe the well-known anti-correlation effect between the muon flux at sea level and the atmospheric pressure. Indeed, the value of the extracted barometric coefficient can be considered reliable and in accordance with the expectations. This result is not trivial at all, especially because of the large statistical fluctuations and of the presence of a long term variation that complicated our analysis.

The positive outcome of this investigation strengthens the idea to install and use simple cosmic ray detectors at the Physics Department site and in several high schools, in order to perform a continuous recording of the cosmic ray intensity. This collaboration may be very fruitful because Physics teachers and associated groups of students could have the possibility to come into contact with the world of experimental high-energy physics, as well as to participate to the analysis of the data collected (contributing to a measurement of the barometric effect on local scale).

In the future it would be interesting to study the barometric effect in other experimental conditions: for example we could increase the detecting area using two or more Geiger counters arranged side by side, or alternatively we could define a particular orientation of detection using a telescope of Geiger counters, or even arrange two or more Geiger counters in a plane array some distance apart and probe the effect of the atmospheric pressure upon extended air showers.

6 REFERENCES

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