Seasonal variation of the muon flux seen by AMANDA

A. Bouchta for the AMANDA Collaboration [1]
DESY Zeuthen, D-15738 Zeuthen, Germany (email: bouchta@ifh.de)

Abstract

We have measured the variation of the muon flux with the AMANDA underground detector at the South Pole. Using the data from 1997, a 10% effect has been observed. A study of the muon flux variation and the atmospheric changes yields a positive correlation between the two. For the 225-days observation period used, an effective temperature coefficient $\alpha_T = 0.86 \pm 0.05$ was found.

1 Introduction and Motivation

Atmospheric muons are produced in the decay of charged pions and kaons, which are themselves the results of the interaction of cosmic rays with air. It has been observed and it is expected that their flux is affected by atmospheric variations (Allkofer, 1975; Andreyev et al., 1990; Ambrosio et al., 1997). At the high atmospheric muon energies (> 500 GeV at the surface level) capable of triggering the AMANDA detector, the main effect that can be seen is due to the competition between interaction and decay of the parent particle, be it a pion or a kaon. A temperature rise between the layer where these particles are produced (100 mbar) and the one where they interact (200 mbar) leads to a lower atmospheric density and to a larger fraction of them decaying into muons. Therefore, the muon intensity is expected to follow the temperature fluctuations. The AMANDA detector extends in depth between 1500 and 2035 m below the surface of the glacier ice, with its center located at a depth of 1730 m (or 1590 mwe). The ice cap surface is at 2835 m above sea-level.

Detailed weather data are collected by Antarctic Support Associates (ASA) and made available by the Antarctic Meteorology Research Center (AMRC). At least one balloon is launched at the South Pole each day during the whole year and records the temperature, pressure and altitude, as well as other parameters during its ascension. There is one reading of the instruments per second. The highest altitudes are reached during the austral summer, at 40 km. Getting to high elevations is more difficult in the winter, but it is possible to reach the 20 mbar layer during most of the year.

Given the quality of the atmospheric data available, and the specific conditions prevailing at the South Pole (no 24-hour cycle, large temperature differences between summer and winter) it is of interest to search for correlations between the trigger rate recorded by AMANDA and the meteorological variations.

The temperature effect at high energy is described by (Barrett, 1952):

$$\frac{\Delta I_\mu}{I_\mu^0} = \int_0^\infty dX \alpha(X) \frac{\Delta T(X)}{T(X)} \tag{1}$$

where I_μ is the muon intensity above the detector energy threshold, ΔI_μ is the fluctuation around a nominal intensity I_μ^0, $\alpha(X)$ is the temperature coefficient and $\Delta T(X)$ and $T(X)$ are the temperature fluctuation and temperature at a given atmospheric depth X. The integration is performed across the whole atmosphere. As discussed in (Ambrosio et al., 1997), an effective temperature T_{eff} can be defined to replace Eq.1 by:

$$\frac{\Delta R_\mu}{\langle R_\mu \rangle} = \alpha_T \frac{\Delta T_{eff}}{\langle T_{eff} \rangle} \tag{2}$$

Where R_μ and T_{eff} are the counting rate and effective temperature , respectively and their mean is taken over the period of observation. The effective temperature is defined (Barrett, 1952; Ambrosio et al., 1997) as:

$$T_{eff} = \frac{\int_0^\infty \frac{dX}{X} T(X) (e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N})}{\int_0^\infty \frac{dX}{X} (e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N})} \tag{3}$$

[1] see talk of F.Halzen (HE 6.3.01) for the full author list

T_{eff} is thus a weighted average of the temperature at different depths, and Λ_π and Λ_N are the attenuation lengths for pions and for nucleons (Gaisser, 1990). Eq. 3 is valid if scaling applies and if the kaon component is neglected. As indicated in (Habig, 1996), these assumptions are reasonable for the resolution we seek to achieve in our present α_T measurement. T_{eff} is the temperature of an isothermal atmosphere resulting in the same intensity as that produced in an atmosphere having a temperature distribution $T(X)$ (Barrett, 1952). At lower energies (a few GeVs) than AMANDA is triggered by, muons are sensitive to pressure changes which alter their energy-loss by ionization. Also, temperature variations modify the altitude where muons are produced and the ground flux is thus changed due to their limited life-time. These two effects lead to a negative correlation between temperature and pressure and the muon intensity, but are negligible here.

2 The Data

The muon data covers 225 days in total when the detector was taking data. In 1997, AMANDA consisted of 302 PMTs, of which a small fraction was not functioning properly. The muon counting rate, with a trigger multiplicity of 16 PMTs hit in a 2 μs window, was 100 Hz (after correcting for a dead time of $\sim$25%). In order to study trigger rate variations of the order of a few percent, it is important to have a very stable behavior of the detector with respect to several variables. Each triggering event contains the complete ADC and TDC information for each PMT that produced a signal. A ”pre-cleaning” was performed to remove 117 PMT channels and 54 run periods before applying any off-line trigger calculation. Typically, PMTs behaving abnormally had a high noise and bad or missing ADC or TDC information. Runs were removed when they contained a high number of PMTs departing from their normal dark noise rate, when parts of the detector were removed from the data stream for maintenance, or when calibration tests were performed.

3 Analysis and Results

Even after the pre-cleaning procedure described above, there was still a fraction of the remaining PMTs that deviated significantly from their mean dark noise rate for certain periods of time. Therefore, a cleaning algorithm was used, to remove PMTs and/or runs completely, until a stable data-set remained. The method is iterative: in each cycle, the worst PMT or the worst run is removed. The comparison here was made between the total number of runs in which a PMT was noisy and, for a run, the total number of noisy PMTs. Applying this on the pre-cleaned data left us with a total of 181 PMTs and 425 runs (equivalent to 173 days of up-time of the detector). The time period covered extends from 5 April 1997 to 15 November 1997, with several time gaps in between.

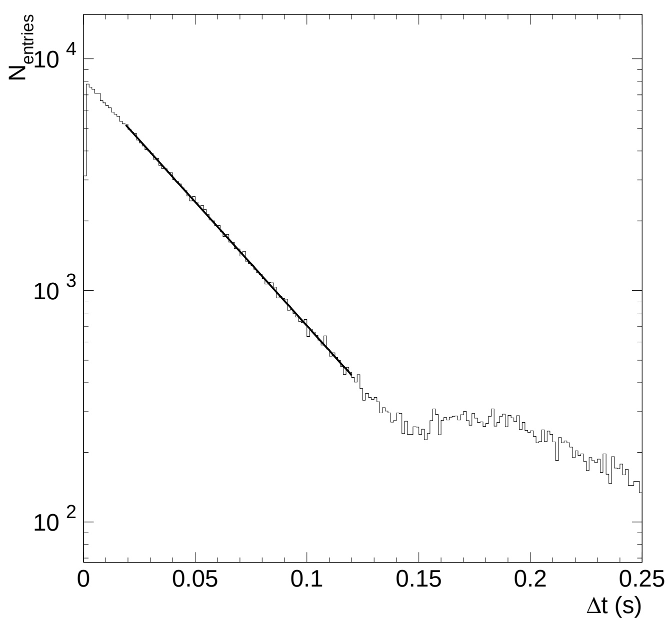

Figure 1: Distribution of the time between triggered events Δt. This figure shows the fit for data taken during day 120.

It should be noted that this hard selection is specific to the present analysis, which aims at getting a continuously stable subset of the detector. Cuts on the ADC values and on the time-over-threshold were used to remove electronics noise and cross-talk. The muon trigger was then determined off-line.

In order to compensate for the dead-time, the trigger rate for each day was calculated by fitting an exponential to the distribution of time-difference between consecutive events (see Fig. 1). Each histogram for each day contained $\sim$ 250,000 entries, corresponding to $\sim$ 4 hours of data-taking.

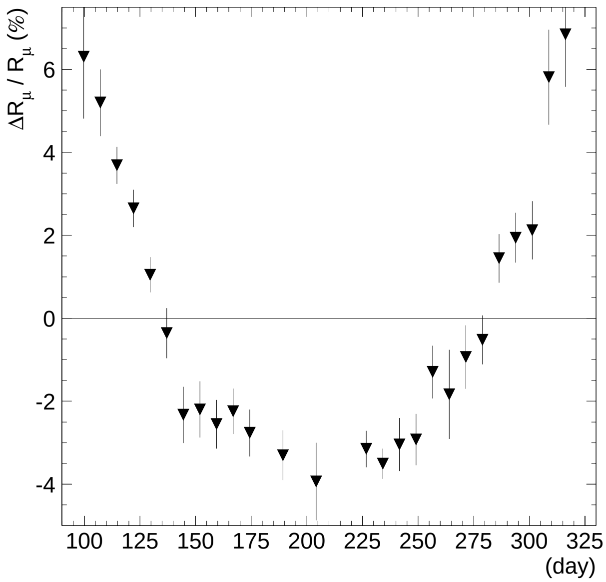

Figure 2: The measured relative variation of the trigger rate around its mean $\Delta R_\mu/\langle R_\mu\rangle$ as a function of day number, for the 225 days used. The data is sorted in bins of 7.5 days.

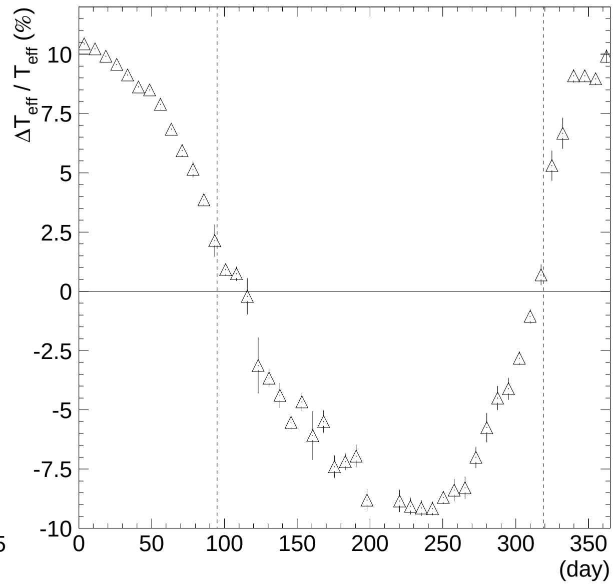

Figure 3: The relative variation of the effective temperature around its mean $\Delta T_{eff}/\langle T_{eff}\rangle$ as a function of day number for the full year 1997. The dotted lines show the 225-days period when our muon data was taken.

Two prominent features have to be avoided by the fit: the first is the time gap apparent at times less than 1 ms; this is the expected dead time of the detector due to the electronics. The other is the peak at the foot of the exponential, at times differences ~ 0.14 s, due to a periodical time-consuming CPU activity holding up the data-taking. The fits were performed in the time interval between 0.02 s and 0.12 s, yielding an error of 0.05 to 0.2 Hz. In order to get a one-to-one correspondence between the muon trigger rate and the effective temperature, both quantities were binned in time-bins of equal length over the period of 225 days available (see Figs. 2, 3). Only those bins were considered which contained information for both variables. The mean trigger rate obtained this way was 23.78 Hz and the mean effective temperature was 201.2 K. The errors were calculated using errors on the daily measurements of 0.05 to 0.2 Hz for the trigger rate R_μ and 1 K for T_{eff}. The statistical fluctuation and fluctuation due to the time variation inside one bin was also taken into account in the error calculation. A comparison between the two variables (see Fig. 4) shows that the overall agreement in shape is good. However, there are a few deviations. A discrepancy starting at day 139 has been found to correspond to a period of large noise ($>$ 200 kHz) for several PMTs. Although they were removed before the trigger calculation they might have disturbed the DAQ system, because of remaining cross-talk. Another feature is a shift in time between $\Delta R_\mu/\langle R_\mu\rangle$ and $\Delta T_{eff}/\langle T_{eff}\rangle$.
Fitting the relative trigger rate to the relative variation of T_{eff} according to Eq. 2, taking into account the errors shown in Figs. 2 and 3 for both variables, we get $\alpha_T = 0.86 \pm 0.05$. As can be seen in figure 5, this result agrees well with the theoretical prediction given by the formula (Barrett, 1952; Ambrosio et al. 1997):

$$\langle \alpha_T \rangle = \left\langle 1/\left(1 + \frac{\gamma}{\gamma+1} \times \frac{\epsilon_\pi}{1.1 E_{th} cos\theta}\right)\right\rangle \tag{4}$$

Monte Carlo simulations of atmospheric muons were made for a few selected days. Only incident protons were considered and the South Pole atmospheric data was used. The variation of the resulting simulated muon rates are consistent with the observed trigger rates.

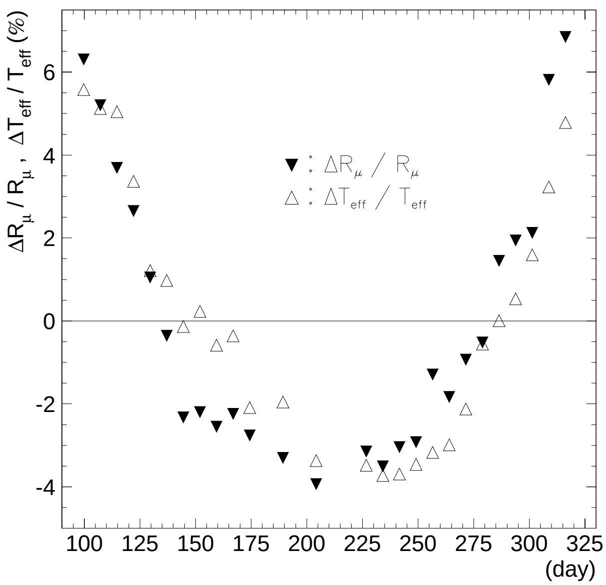

Figure 4: Temperature and rate variations superimposed, with $\Delta R_\mu / \langle R_\mu \rangle$ scaled by the value of α_T determined in this analysis.

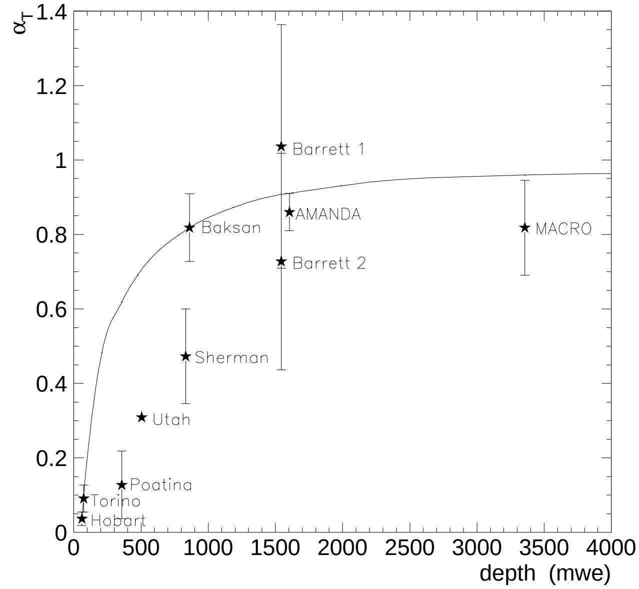

Figure 5: Measurements of α_T by detectors at different depths, with the expected curve and with the AMANDA value added. Taken from (Ambrosio et al., 1997).

4 Conclusions and Prospects

This study is the observation of a known phenomenon and is thus a test of the achievable stability of the AMANDA detector. Some improvements could be made to the analysis. The long dead time of the DAQ, e.g., might be a concern in terms of systematic errors. This problem will however be of less importance in the 1998 analysis, since it is absent in the data taken with the new DAQ system installed that year. The time coverage of the detector also increased in years following 1997. The observation of a full cycle and not only the winter-period would make the α_T measurement more robust (see Fig. 3). Also, the maximum altitude and the number of successful balloon launches is higher during the austral summer.

Furthermore, the trigger rate can be increased. This could be done by keeping more PMTs in the selection, even at the cost of having to remove more runs. Such a compromise is probably possible, since the main concern is to have a sample of runs covering as large a fraction as possible of the year and not to maximize the up-time of the detector. A better stability of the PMTs will be achieved by advanced monitoring, leading to more precise measurements. With such improvements it might be possible to ensure a trigger rate measurement precisely for the hour duration of a balloon flight.

By cutting on the declination angle of reconstructed muons, one could probe different depths. Finally, it has been pointed out (Ambrosio et al., 1997; Habig, 1996; Barrett, 1952) that since the temperature effect studied here depends on the critical energy of the parent particle, it could therefore potentially indicate its identity.

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