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Time variations in the deep underground muon flux measured by MACRO

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More than 30 million high-energy muons collected with the MACRO detector at the underground Gran Sasso Laboratory have been used to search for flux variations of different nature. Two kinds of studies were carried out: search for periodical variations and for the occurrence of clusters of events. Different analysis methods, including Lomb-Scargle spectral analysis and scan statistics have been applied to the data.

1. Introduction

The high energy muon events collected by the MACRO apparatus at the average depth of 3600 m.w.e. represent one of the most extensive records of such kind of data. The time series of these high-energy muons can be used to search for time variations of periodic and stochastic characters, as it was done with the arrival times of EAS [1]. These variations in the underground muon flux may be due to different causes of galactic, solar and terrestrial origin. The common problem for this type of searches is to determine whether an observed effect has occurred by chance or if it signals a departure from the underlying probability model.

The MACRO detector was a multipurpose modular detector with 6 supermodules with scintillator detectors, limited streamer tubes and nuclear track detectors [2], and studied atmospheric neutrinos [3], aspects of CR physics and astrophysics [4], searched for GUT Magnetic Monopoles and other exotica [5]. Some interruptions of different kinds occurred during data taking, either randomly (e.g. power outages), or regularly (e.g. maintenance). So appropriate statistical methods have to be applied and particular care should be used in choosing periods of stationary conditions.

In the following we discuss the results of the searches for periodic variations and for time clustering of muon events.

2. Periodicity search: spectrum analysis

For this analysis we considered data recorded by the streamer tube system in the time interval November 1991 - May 2000 and selected with the following criteria:

1. run duration longer than 1 hour;
2. streamer tube efficiencies of wires and strips larger than 90% and 70%, respectively for each module;
3. all 6 super-modules in acquisition;
4. acquisition dead time smaller than 2.5% for the whole detector.

The total number of runs surviving these cuts was 6920 for a total number of 3.5×10^7 muon events.

The Fourier amplitude spectrum analysis is a powerful technique that allows a blind search for regular/persistent fluctuations in a time serie [6]. Such a technique, however, requires the input data to be sampled at evenly spaced intervals; data gaps of variable length and occurring randomly in the serie produce spurious contributions to the power that can mimic the presence of a periodicity. The Lomb-Scargle method [7] has been developed to mitigate this effect even in case of very long data series. Moreover, as indicated in [8], it allows to evaluate the significance of the "peaks" (signal) in the power distribution. The muon events were binned in 15 min time intervals and bins deviating by more than 3 σ from the monthly average rate were discarded. The total number of time bins used was 160242 corresponding to 58% of the whole sample.

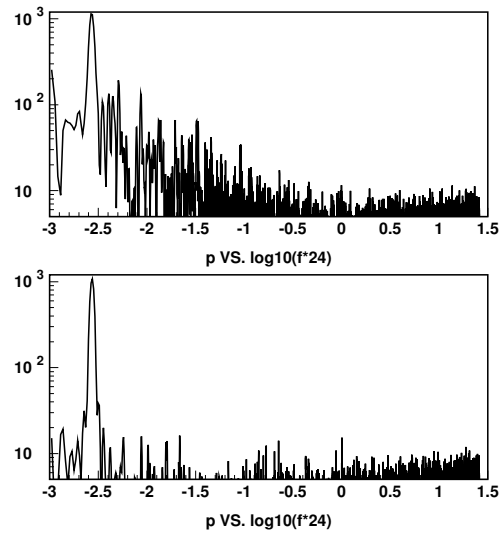

Figure 1. Lomb power as a function of the Log_{10} of the frequency [days^{-1}] for experimental data (upper panel). Note the high peak at $\sim$ -2.56 corresponding to 365 days (the seasonal flux variation). In the lower panel the results of a Monte Carlo simulation having the same noise level of real data with seasonal, solar diurnal and sidereal waves [9] added.

The results of our analysis are shown in Fig. 1. We compare the spectrum obtained for the real data with a Monte Carlo simulation having the same noise level and time intervals distributed according to the sequence of the original serie. The seasonal, solar diurnal and sidereal waves [9] were also added in the serie. The spectrum of real data shows a power distribution similar to what observed in other cosmic ray data series [6], i.e. a low frequency spectrum whose power decreases with Frequency^{-2}. The most striking feature of the spectrum is the large peak at $\sim$ -2.56 corresponding to the seasonal flux variation. Figure 2 shows a frequency region around the solar diurnal frequency where we have also indicated the frequencies corresponding to the sidereal and anti-sidereal waves. Note that peaks of similar size (or even larger) are present elsewhere in the spectrum. The claim that the sidereal and solar diurnal waves are real is based upon its occurrence at a frequency of *a priori* interest and on the stability of its amplitude and phase with time. We find that the amplitudes and the

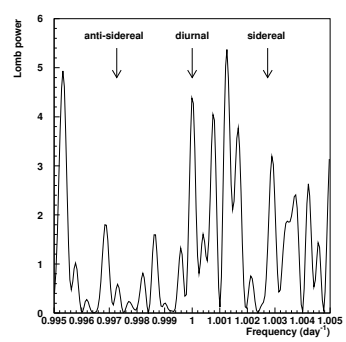

Figure 2. The frequency region around the solar diurnal wave with arrows marking its position and the sidereal and anti-sidereal peaks

probabilities for the null hypothesis is in fair agreement with the ones obtained using a standard "folding" method [9].

3. Burst serach: time interval distribution

The first method used in searching for correlations in the arrival times was the study of the time interval distribution. For each muon arriving at time t_0 we calculated the distribution of the time interval elapsed between the first muon t_0 and the next five muons: t_i-t_0, i=1,...,5. A complete analysis was published in [10]. Here we report the results for the direction bands with 0< RA<360 and 25< decl <50 that include the Cyg X-3 region. The distributions show some deviations from the expected probability model. The probability computed using the Kolmogorov-Smirnov test show some disagreement (prob=0.38) but the available statistics is too poor to reach clear conclusions.

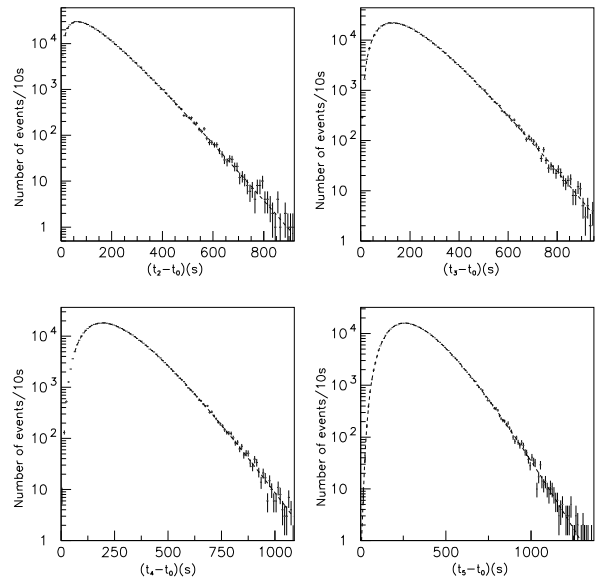

Figure 3. Time interval distributions (from top left to bottom left clockwise) for t_2-t_0,t_3-t_0,t_5-t_0 and t_4-t_0 respectively for a cone of arrival directions with declination $25° < \delta < 50°$.The dashed lines represent the fits to the Erlangen function of the order 2, 3, 5, 4 respectively (see [10]).

4. Burst serach: scan statistics

Scan statistics is a powerful method to search for bursts of events over an *a priori* known underlying distribution. It is a bin-free method, well suited to perform blind analyses and it provides unbiased results when data are analysed *a posteriori*, i.e. after data taking (see [11] and references therein). We used scan statistics in the following way: for each run i, let $[A_i, B_i]$ be the time interval ranging from the start to the end of the run. We open a "time window" of fixed length w and we scan the interval $[A_i, B_i]$ counting the number of events falling inside w. k_i is the maximum number of events recorded during the scan. Finally, for each run, we compute the probability P_i that a statistical fluctuation would produce a burst of events as large as k_i. The only *a priori* choice is the size of w. We tried different sizes (w=30 s, 5 m and 15 m) and, for each of them, we analysed the probability distribution P_i, i=1, N_{run}. In Fig. 4 we show the probability distributions for the 6113 runs surviving our cuts: w=30 s above, 5 m at the centre and 15 m below. No significant deviation from the null hypothesis is found; we also inspected the unusual runs with small probabilities and we found that the "bumps" of events were concentrated during the "stabilization phases" of the runs, i.e. near their beginning or shutdown.

5. Conclusions

We analysed the time series of MACRO muons using two complementary approaches: search for periodicities and search for burst of events. The Lomb-Scargle method was used in the first case, scan statistics in the second. The two tecniques complete early analyses performed with "folding" methods in searching for periodicities and time differences for burst events. No deviations from the expected distributions was found.

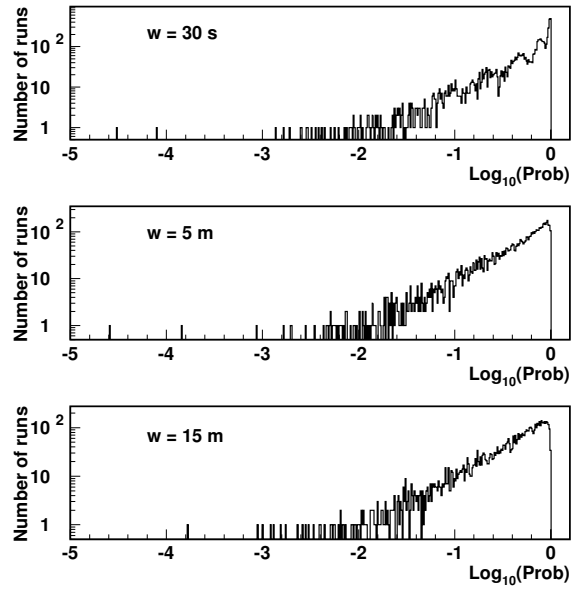

Figure 4. Scan scatitistics probability distribution for all runs. In the upper panel a time window w=30 s was used; w=5 m in the central panel and w=15 m in the bottom panel.

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