Search for Steady, Modulated, and Variable Cosmic Ray Sources Using Underground Muons in MACRO

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Abstract

Using a sample of 38.5 million underground muons collected by the MACRO detector we have performed an all-sky search for pointlike sources producing excesses of muons above the expected background. The d.c. muon flux upper limit at the Earth coming from selected sources is of the order of 10^{-13} cm^{-2} s^{-1} or less. Futhermore we discuss searches for possible modulated and variable sources of muons using different techniques.

1 Introduction:

In this work we present the results on the study of muon arrival directions, as seen by the MACRO detector (Ahlen et al., 1993), looking for excesses above the expected background in every sky direction. We have also searched for steady and pulsed signals from potential cosmic ray sources.

Features of the MACRO detector are an excellent angular resolution and a large collecting area, when compared to other deep underground detectors. Because of these properties, MACRO can be used as a good muon telescope. The interest in this kind of analysis arises from the old observation of underground muon excesses from the binary system Cygnus X-3, as reported from the SOUDAN and NUSEX collaborations (Marshak et al., 1985; Battistoni et al., 1985). On 1991 January, SOUDAN2 reported the observation of unmodulated muon signals from Cyg X-3, correlated with the radio-burst occurring in the same period. These muon excesses had fluxes of $7.5\times10^{-10} cm^{-2} s^{-1}$ (Marshak, 1993). Recently, no experiment detected signals from this kind of source, but several observations of X and γ-bursts were reported from other celestial objects. During 1997, several γ-bursts from AGN objects, like Markarian 421 and Markarian 501, were reported by the Whipple and Hegra experiments (Punch et al., 1992; Quinn, 1997).

2 Data Selection and Reduction:

The data set used for this analysis is from a long period of acquisition, from the first MACRO run (February 1989) until January 1999. In order to optimize the track reconstruction and to eliminate possible detector malfunctions, strict selection criteria were defined. After all cuts, we selected a sample of 38.5 million events (single and doubles), collected over 55248 h of live time.

2.1 Angular Resolution and Background Simulation: The MACRO pointing precision was calculated from the distribution of the double-μ angular deviation. We assume that these events at the Earth's surface are parallel muon pairs. Then, the overburden rock produces their deviation at the MACRO level through multiple Coulomb scattering processes. The space angle θ, containing 68% of the events, defines the detector angular resolution. We found $\theta = 0.8^o$, consistent with the value derived from the Moon shadowing of primary cosmic rays (Giglietto, 1999).

For the present search, we assume that our signals are muons produced in atmospheric photoproduction processes and the background (or *noise*) is produced by primary interactions with the terrestrial atmosphere. The background has been determinated by a Monte Carlo simulation, assuming an isotropically distributed cosmic ray flux. For each run we generated the background events by coupling the arrival direction of each muon with 25 arrival times, randomly extracted from the same run.

3 All-sky d.c. Survey:

In the search for point-like sources we first started an all-sky survey, without *a priori* assumptions about the source locations; then, we examined selected celestial objects known as potential cosmic ray sources.

Therefore, we examine sky regions looking for deviations from the expected background larger than random fluctuations.

3.1 Search for d.c. Muon Excesses: As a first step, we generated the sky map with muons collected by MACRO by dividing the sky into bins of equal solid angle ($\Delta\Omega$= 2.1 $\times$ 10^{-3} sr; $\Delta\alpha$ = 3^o, Δsinδ = 0.04). These bins have the same $\Delta\Omega$ as a narrow cone of half-angle 1.5^o. Then, assuming that a potential source is located at the center of the bin, we obtained a sky survey in absolute astronomical coordinates α and sinδ (*map(1)* in Table 1). However, if the source is near a bin edge, its signal will be spread between adjacent bins. Then, to reduce the possibility of missing sources close to the bin edges, three other surveys were also done: *map(2)* shifted the grid one-half bin in α, *map(3)* shifted the grid one-half bin in sinδ and *map(4)* which contains the *map(2)* and *map(3)* shift. For each solid angle bin in the four surveys, we calculated the deviation from the mean in units of standard deviations:

	MEAN	SIGMA	χ^2/Dof	N.deviations
map(1)	-0.13$\times10^{-1}$	0.99	62/35	4(+) 3(-)
map(2)	-0.6$\times10^{-3}$	1.01	24/34	5(+) 3(-)
map(3)	-0.22$\times10^{-3}$	1.01	36/34	4(+) 4(-)
map(4)	0.3$\times10^{-2}$	1.02	34/35	5(+) 4(-)

Table 1: *Best-fit parameters of the Gaussian fit for the four sky surveys.The last columns gives the number of positive and negative deviations larger than 3.2σ.*

$$\sigma(i) = \frac{N_{obs}(i) - N_{exp}(i)}{\sqrt{N_{exp}(i)}} \tag{1}$$

where $N_{obs}(i)$ is the observed number of events in the bin and $N_{exp}(i)$ is the number of events expected from the background simulation. Bins having less than 20 events were removed.

If the observed muons are distributed according to Gaussian statistics, the $\sigma(i)$ distributions will be a Gaussian curve with zero mean and unit standard deviation. Table 1 shows the Gaussian best fit for the four surveys: the means are close to zero and the half widths near one. The best-fit parameters and the number of fluctuations larger than 3.2σ are also given. We found the larger positive and negative deviations are in similar number. We conclude that all deviations are consistent with random background fluctuations.

3.2 Steady Flux Limits: We calculated the upper limits to the muon flux from the all-sky survey, following the Helene method (Helene, 1983). The steady upper limit at 95% confidence level to the muon flux for each bin was computed from:

$$\mathrm{J}_\mu^{stdy}(95\%) \leq \frac{n_\mu(95\%)}{KA_{eff}T_{exp}}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\,. \tag{2}$$

Here n_μ(95%) represents the muon number we would observe at 95% C.L. in each bin, if $N_{obs}(i)$ and $N_{exp}(i)$ are the number of events observed and expected in that bin, respectively. A_{eff} is the average effective area for every bin computed by averaging the projected area seen by each muon

$$\mathrm{A}_{eff}(i) = \frac{1}{N_{obs}(i)} \sum_{j=1}^{N_{obs}(i)} A(\alpha_i, \delta_i) \tag{3}$$

where α_i and δ_i are the muon arrival directions. The A_{eff} calculation takes into account the geometrical and tracking reconstruction efficiencies. T_{exp} is the exposure time, computed bin-by-bin and the factor K takes into account the scattering of some muons out of the bin. We found K=0.78 for the selected bin dimension (1.5^o half-angle).

We found, for the majority of the bins, J_μ^{stdy}(95%) $\leq 5{\times}10^{-13} cm^{-2} s^{-1}$.

3.3 Search for Modulated Signals: Searches were also made for modulated signals coming from those sources that in the past showed variability (Cyg X-3 and Her X-1). We found no evidence for excesses in any of the phase bins into which the characteristic period was divided. The 95% C.L. upper limits to the modulated muon flux from the directions of Cyg X-3 and Her X-1 are, respectively, $1.8{\times}10^{-13} cm^{-2} s^{-1}$ and $2.2{\times}10^{-13} cm^{-2} s^{-1}$.

4 Point-like d.c. Source Study:

To study muons coming from specific celestial objects, we selected only events contained in a narrow cone (1.0^o half-angle) around the source direction. The selected windows are centered on the Cyg X-3, Mrk 421 and Mrk 501 positions. Table 2 gives the muon number observed and expected from the Monte Carlo simulation. Since there is no significant excess from Cygnus X-3, we calculated its steady flux limit following the Helene formula (Helene, 1983) and the classical method (Hikasa et al., Particle Data Group, 1992).

	N_{obs}	N_{exp}	σ	Area m^2	T_{exp} 10^6 sec	Flux 1 $cm^{-2}s^{-1}$	Flux 2 $cm^{-2}s^{-1}$
Cyg X-3	4242	4234.2	-0.1	691	109	3.4 10^{-13}	1.9 10^{-13}
Mrk 421	4328	4250.4	1.2	704	105.4	4.4 10^{-13}	2.0 10^{-13}
Mrk 501	4630	4496.1	2.0	699	107.4	5.4 10^{-13}	2.0 10^{-13}

Table 2: *Number of events observed and expected, the standard deviation calculated as in (1), the average effective area and exposure time for three selected sources. For these we give also the flux upper limits calculated with the Helene formula (Flux 1) and with the classical method (Flux 2).*

For Mrk 421 and Mrk 501 we have small steady excesses at the level of 1.2σ and 2.0σ respectively. For these sources the steady flux limits are given in Table 2.

5 Search for Bursting Episodes:

During 1997, surface experiments reported several γ-bursts from celestial objects like Mrk 421 and Mrk 501. Therefore we have made also a search for pulsed muon signals in a narrow window (1^o half-angle), around the position of these possible sources of U.H.E. photons. We studied bursting episodes following two different methods.

First, we searched for daily excesses of muon flux above the background: because the daily observed events are few, we plotted the cumulative excesses day by day, over a long observation period (Clay, Dawson, & Meyhandan, 1994). Fig.1 shows the progressive accumulation of our excesses above the computed background for Mrk 501. Periods are present in which excesses accumulated rapidly but after that, the cumulation rate reduced.

We observe the cumulated signal is every day above the background: fluctuations are contained in 2σ for Mrk 421 and for Mrk 501.

For the same sources, we have also searched for statistically significant daily excesses of muons, following a second method (Padilla et al., 1998). From our complete data set we

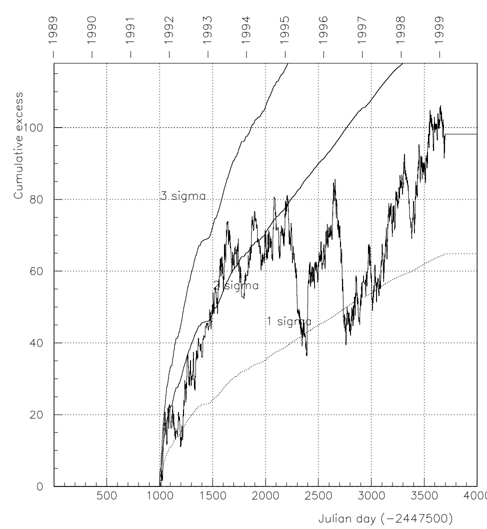

Figure 1: Cumulative muon excesses from the direction of Mrk 501 (1^o half-angle). The selected time period is from January 1992 until January 1999

computed, day by day, the quantity $-log_{10}$ P, where:

$$\mathrm{P} = 1 - \sum_{n=0}^{N_{obs}-1} \frac{\alpha^n}{(1+\alpha)^{n+N_{bck}+1}} \frac{(n+N_{bck})!}{n! \times N_{bck}!} \tag{4}$$

N_{obs} is the number of observed muons in a day and N_{bck} is the number of background events in the same day, computed by Monte Carlo simulation. α is the ratio of the on-source time to the off-source time (0.04 for the present analysis) and P represents the probability of observing a burst at least as large as N_{obs} due to background fluctuations. We assume that the background has a Poissonian distribution about N_{bck}. If no bursts are observed, we expect that the cumulative frequency distribution of P is a power law of index -1. In Table 3 we report the statistical parameters for Mrk421 to be compared with the observations from surface experiments (Shubnell et al., 1996). For comparison, we created a sky survey by computing the quantity -log_{10} P for every bin of the sky map: this distribution has slope -1.1 and the superposed line fits the data well.

6 Conclusions:

Since February 1989, the MACRO detector has collected a sample of about 38.5 million muons. Using this sample, we searched for muon excesses above background from every sky direction and from single cosmic ray sources. No significant excesses have been found from the all-sky survey and we computed the upper steady limit to the muon flux. At 95% confidence level, we found this limit at 5×10^{-13} $cm^{-2}s^{-1}$. The search for steady emission from different sources does not indicate for Mrk 421 and Mrk 501 a muon excess above the background, as the statistical significance of the excess is 1.2σ and 2σ respectively.

Date	N_{obs}	N_{exp}	$-log_{10}P$	P
7 Jan 93	9	1.88	3.58	2.6×10^{-4}
14 Feb 95	9	1.96	3.46	3.6×10^{-4}
27 Aug 97	8	1.72	3.16	6.9×10^{-4}
5 Dec 98	8	1.52	3.48	3.3×10^{-4}

Table 3: *Statistical parameters for possible excesses from Mrk421.* $N_{exp} = \alpha \times N_{bck}$ *and P represents the probability per day to observe a burst at least as large as* N_{obs}*, due to background fluctuations (*1^o *half-angle). The total number of observations was 3660.*

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