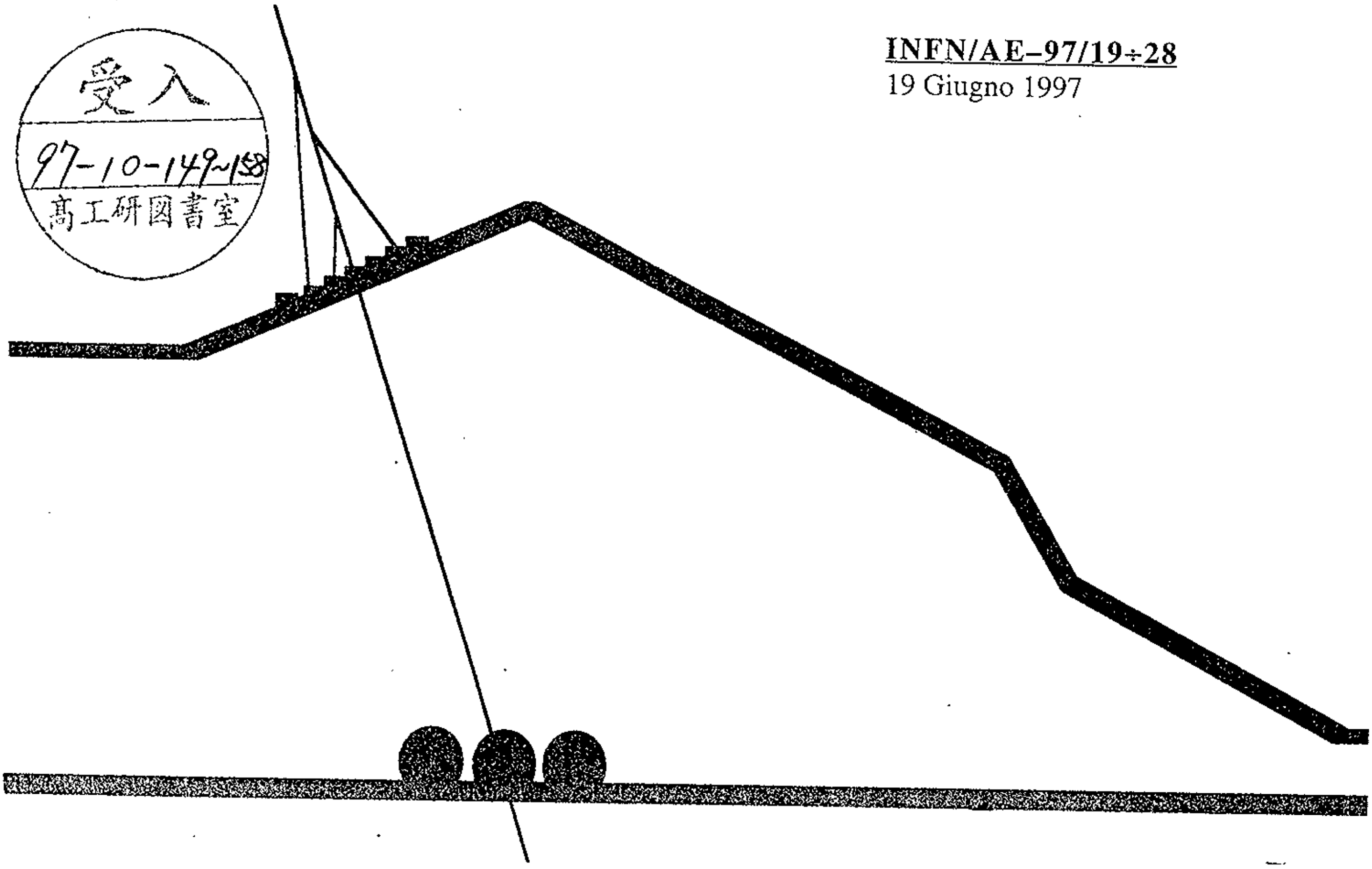
INFN/AE-97/19÷28
19 Giugno 1997



Contributions of the MACRO Collaboration to the 1997 Summer Conferences

INFN – Laboratori Nazionali del Gran Sasso

Published by ***SIS–Pubblicazioni***
dei Laboratori Nazionali di Frascati

The MACRO Collaboration

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Acknowledgements.

We gratefully acknowledge the support of the director and of the staff of the Laboratori Nazionali del Gran Sasso and the invaluable assistance of the technical staff of the Institutions participating in the experiment. We thank the Istituto Nazionale di Fisica Nucleare (INFN), the U.S. Department of Energy and the U.S. National Science Foundation for their generous support of the MACRO experiment. We thank INFN, ICTP (Trieste) and NATO for providing fellowships and grants (FAI) for non Italian citizens.

97-10-157

A SKY SURVEY USING MUONS IN THE MACRO DETECTOR

INFN/AE-97/27
19 Giugno 1997

ABSTRACT

During 1991 - 1996 we have detected more than 2×10^7 muons in MACRO, which is located at the Gran Sasso Laboratory. Our effective livetime is 26,400 h. Using this sample of data we have defined and evaluated MACRO's properties as a muon telescope. First we observed the Moon shadowing effect. This is the first statistically significant detection of the moon using muons detected deep underground. Our detection of this signal has established that the pointing errors of MACRO are less than 0.1 degree and that the angular resolution of the apparatus is about 1 degree. Next we studied the arrival directions of muons, looking for excesses above the expected background in any direction of the sky. Finally we have also done a detailed search for possible muon point sources (and diffuse sources) in the galactic plane using double muons. We will present all three results; the Moon shadowing, the sky survey, and the flux limits for muon sources in the galactic plane.

INTRODUCTION

In this work we have used the directionality of the muons seen by the MACRO detector to survey the sky for steady sources of muon excesses. The analysis has been done using the muons collected during 1991-1996. We have thus collected more than 2×10^7 muons. The interest for this analysis arises from the old observations of excesses of underground muons in the direction of Cygnus X-3. More recently no signal has been detected from this kind of source but several observations of X or γ ray bursts have been reported from other sources like Mkn 421 (Bradbury et al. 1997). Therefore the interest for a monitoring of any possible source of cosmic rays is still present. However the underground detectors can detect only the secondary muons produced in the interactions of the primary cosmic rays with the atmosphere. So their sensitivity to cosmic ray sources is lower than that of surface and satellite experiments. Nevertheless MACRO can detect very small variations of underground muon intensity. In fact we have reported the measurement of a seasonal variation of the intensity (Ambrosio et al., 1997), in which a modulation of the intensity with an amplitude of less than 3% is found. We have also observed the moon shadowing effect on the intensity (Ambrosio et al., 1997). This last effect is extremely important in establishing the correctness of the pointing ability and at the same time the good angular resolution of the apparatus.

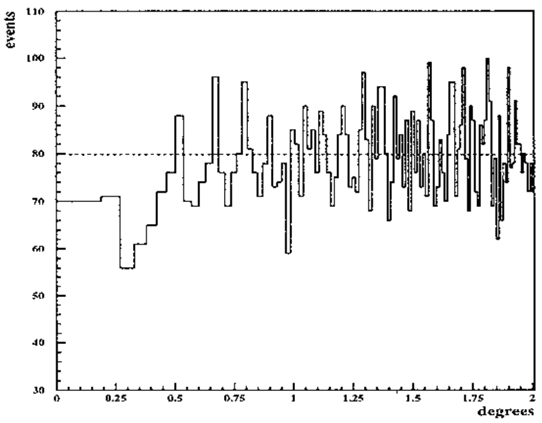

Fig. 1: Muon density versus the angular distance from the Moon. Superimposed as a dashed line is the expected density for the background events. A variable bin width is used in order to have the same solid angle for each bin.

THE MOON SHADOWING EFFECT

To verify the pointing accuracy of the MACRO detector, we have searched for the Moon shadowing effect in the high energy primary cosmic rays. This analysis has been done using all muons collected by the detector from 1989 to the beginning of 1997. The resulting sample is about 30×10^6 muons. The analysis has been done selecting single or multiple muons having the arrival directions close to the moon center, and comparing the distribution of these events with the distributions of random background events. The analysis has been done using two different methods: the first one is a simple comparison of the density of the real and simulated event distributions versus the angular distance from the Moon center. The results are shown in Figure 1. A deficit is visible at about 0.25 ° from the computed Moon position and the maximum resulting deficit is about 130 events on a background of 2218 ±47 events contained in a cone of about 1° radius centered on the Moon position.

A second analysis has been done using bidimensional histograms and taking into account the point spread function of the apparatus. This analysis is based on the maximum-likelihood method of COS-B (Pollock et al., 1993) to evaluate the significance of the signal (Ambrosio et al., 1997). The results of this analysis are shown in Figure 2, where the χ^2 in each bin has been computed as a function of the Altitude versus Azimuth distances from the Moon center. The amount of the displacement found can be attributed to the geomagnetic displacement of the primary protons, which have energies of about 10 TeV. We found therefore a westward displacement of 0.25° of the Moon shadow with a χ^2=14.2 corresponding to a significance of 3.7σ. We have compared this number with an analysis done on random fake moons. We found that the probability to find random fluctuations having a $\chi^2 \geq 14.2$ is 0.02%, in agreement with the previous estimation of the significance. Thus this positive identification of the moon shadowing effect in an undergound experiment establishes the correct pointing ability of the detector.

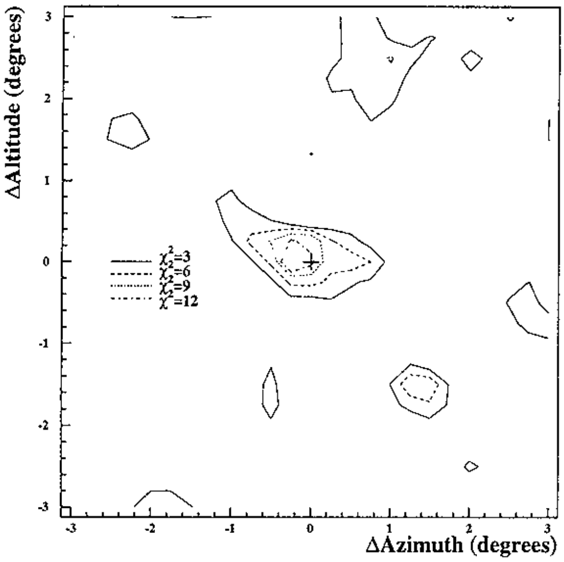

Fig. 2: χ^2 levels in the window centered on the Moon. Four levels starting from χ^2=3 with a step of 3 are shown. The maximum value is χ^2=14.2 in the position (-0.25°,0°)

ALL-SKY SURVEY USING SINGLE MUONS

We have grouped the events in sky bins of equal solid angle ($\Delta\Omega = 2.3\times10^{-4}, \Delta\alpha = 1°, \Delta sin\delta = 1/75$). These bins have approximately the solid angle of a cone of half-angle 1.°, a value obtained to maximize the signal to noise ratio for our apparatus. Removing from the sample the bins having few events, we compute for each bin the standard deviation using the simple Gaussian statistics $(n_{obs} - n_{bck})/\sqrt{n_{bck}}$, where n_{obs} and n_{bck} are the observed and expected events respectively. This distribution is well fitted by a Gaussian curve and no excess is evident. The result of the fit gives χ^2/Dof=0.86. We have repeated the survey by displacing the center of these bins, in both the coordinates, of half of the bin width, in order to search for possible sources close to the neighborhoods of the bins. No excess has been found also in this case. We thus confidently say that no significant "point source" has been observed.

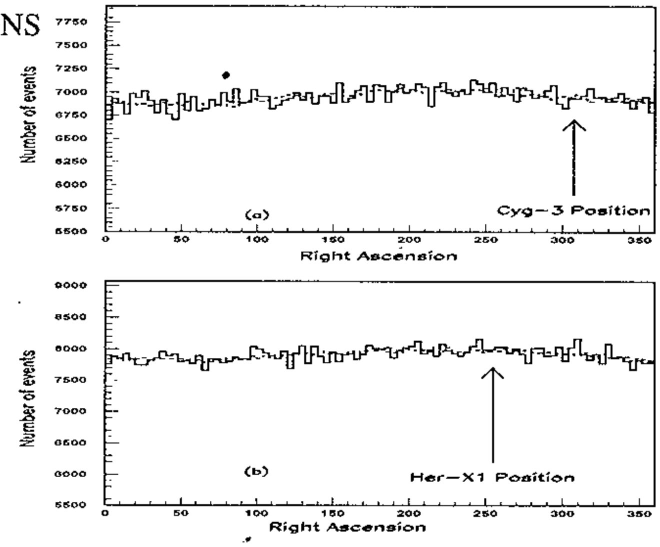

Fig. 3: Right ascension distributions for muons coming from a 1.5° half angle declination window centered on (a) Cyg X-3 and (b) Her X-1. Solid lines represent the experimental data and dashed the background simulation.

against the seasonal modulation, the fit to the antisidereal diurnal data gives the parameters in the relation: $K_2 \cos\{2\pi[(N_{sol}-1)t+\phi_1-\phi_2]\}$. In this fit, ϕ_{max} in Table 1 was shifted to account for the arbitrary zero point of phase used in constructing Figure 2. As shown in Ambrosio et al. (1997), the phase of maximum modulation for the seasonal variation is $\phi_2 \approx 0.6$, which implies that $\phi_{max} \approx 0.45$ for the antisidereal modulation. Finally, the sidereal modulation seen in Figure 3, parameterized as $K_3 \cos\{2\pi[(N_{sol}+1)t+\phi_3]\}$, is the 'apparent sidereal modulation' and represents the sum of two terms,

$$\begin{aligned} K_3 \cos\{2\pi[(N_{sol}+1)t+\phi_3]\} &= K_4 \cos\{2\pi[(N_{sol}+1)t+\phi_4]\} + \\ &\quad K_2 \cos\{2\pi[(N_{sol}+1)t+\phi_1+\phi_2]\}. \end{aligned}$$

The amplitude, K_4, and the phase, ϕ_4, of the 'true sidereal modulation' can be found from the fits in Table 1. The results of this analysis, including the correction for the zero point of antisidereal phase and the converstion from Julian days to solar time, are given in Table 2. The errors on K_4 and ϕ_4 were computed by combining the errors in quadrature.

Table 2: Analysis of Underground Muon Data

	Amplitude (%)		Phase of Maximum (hr)	
Solar Diurnal	0.093 ± 0.063	(K_1)	13.2 ± 2.6	(ϕ_1)
Antisidereal	0.17 ± 0.05	(K_2)	10.8 ± 1.4	$(\phi_1-\phi_2)$
Apparent Sidereal	0.19 ± 0.06	(K_3)	5.9 ± 1.3	(ϕ_3)
True Sidereal	$0.34 \pm .26$	(K_4)	4.8 ± 3.2	(ϕ_4)

CONCLUSIONS

We have used the method of Farley and Storey (1954) to search for the first harmonic of the sidereal modulation in the underground muon data collected by MACRO. The result at this time must be considered preliminary. In order to achieve a result with high statistical significance, several more years of MACRO data must be analyzed.

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POINT SOURCE STUDIES

Steady Flux Limits

As a first step, we selected only muons coming from two windows $\pm1.°$ wide in declination centered on Cyg X-3 and Her X-1 and we searched for dc excesses in the muon flux above the expected background in the Right Ascension distributions around those positions. No excess was found around the two source positions.

We also searched the data for other particular point sources (see Table 1). We analyzed the data contained in a narrow cone (0.5° radius) around the source position and found no dc excess. The dc upper flux limits, using the formula (Ahlen et al., 1993):

$$J_{\mu}^{stdy} = \frac{n_{\mu}(95\%)}{0.41\epsilon A_{eff} f t_{expos}} cm^{-2}s^{-1} \qquad (1)$$

are presented in Table 1, with $n_{\mu}(95\%)$ the 95% CL for the undetected number of muons calculated according to Helene (Helene, 1983), ϵ the average efficiency, A_{eff} the average effective area, f is the fraction of time that the source is visible, and t_{expos} the total exposure time.

Source	δ	f	$(\epsilon \cdot A_{eff}) \times 10^4 cm^2$	$J_{\mu}^{stdy}(95\%)\ (cm^{-2}s^{-1})$
Cyg X-3	40°55′46″	0.57	724	3.9×10^{-13}
Her X-1	35°20′32″	0.52	738	4.7×10^{-13}
Crab	21°59′	0.48	758	5.5×10^{-13}
3C273	2°3′8″	0.37	618	7.0×10^{-13}
MRK 421	38°12′31″	0.58	730	4.5×10^{-13}
Geminga	17°47′	0.46	743	5.1×10^{-13}

Table 1: *Steady Flux Limits for selected sources. Limits were obtained using formula (1).*

Since there is no excess in all other bins in the sky, we have also calculated the flux limits using (1). The results of this all-sky map give flux limits in the interval 8.2 $\times10^{-14}cm^{-2}s^{-1} \rightarrow$ 8.5 $\times10^{-13}cm^{-2}s^{-1}$.

Searches for Modulated Signals

A careful search has been done for modulated signals coming from those sources that in the past showed variability (Cyg X-3). We found no evidence for an excess in any of the phase bins into which the characteristic period was divided. The flux limit for modulated signals at 95% C.L. found for Cyg X-3 is 9.7 $\times 10^{-14}cm^{-2}s^{-1}$.

We conclude that the present data are consistent with background fluctuations and show no evidence for a modulated muon signal from Cyg X-3.

A Galactic Plane Survey Using Double Muons

A different point source investigation has been performed selecting only double muons in the apparatus. There are two reasons to select these events in underground detectors. The primary cosmic-ray average energy necessary to produce underground muons is higher for multiple muons respect to single muons. In addtion, it has been suggested (Stanev 1986, Berezinsky 1988 and Halzen 1997) that primary gamma rays would produce double muons through photoproduction processes. However the limits of this kind of search are related to the efficiency to have muons starting from γ rays. In fact the probability to produce muons by means of γ rays is about 1% at TeV energies. For this analysis therefore we have used the subsample of events taken between 1991 and 1996 and analyzed the region of the galactic plane delimited by $20° \leq l^{II} \leq 220°$ and $-5° \leq b^{II} \leq 5°$. The analysis has been performed using the same COS-B technique used for the Moon shadowing effect, but using the point spread function in galactic coordinates. The results of this survey are shown in Figure 4.

CONCLUSIONS

A search for cosmic ray point sources has been performed using underground muons and different analyses. No evidence for point sources has been found. Nevertheless the MACRO detector has shown its ability to detect a small variation of the muon fluxes, having detected the moon shadowing effect with 3.7 σ significance and the seasonal variation effect.

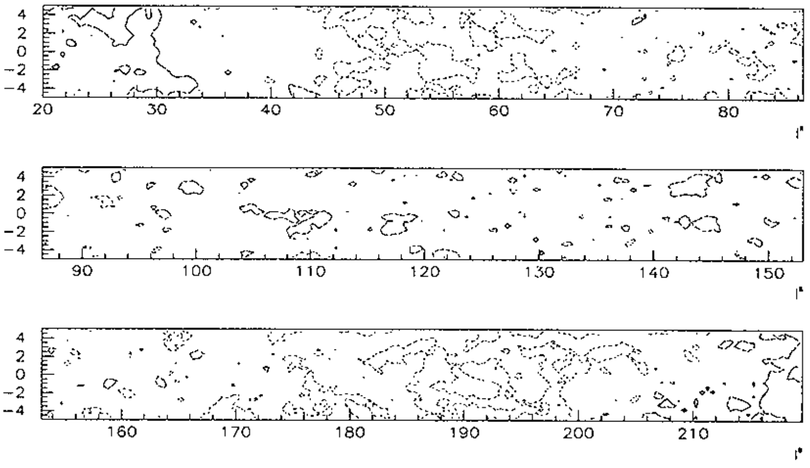

Fig. 4: Distribution of the upper limits for $\Phi_{2\mu}$ in galactic coordinates. The contour levels are from 2.0 to 8.0 $\times 10^{-14} cm^{-2} s^{-1}$.

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