A MACRO SAMPLER*

(Presented by M. J. Longo for the MACRO Collaboration)

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Abstract

We present results from approx. 2 years running with the MACRO detector. Most of these data were taken with one of the six supermodules of the final detector in operation. Using a sample of 1.8 x 10^6 muons with E>1.4 TeV we have searched for an excess of muons of celestial origin over cosmic ray background. No evidence for steady point sources was found. The upper limit on the muon flux at 95% CL is typically 2 x 10^{-12} $cm^{-2}sec^{-2}$. No evidence for time modulated point sources was found. The muon multiplicity distribution favors a "light" composition for cosmic ray primaries with ≈75% protons above ~10^3 TeV. We have also searched for neutrino bursts from supernovae in our Galaxy. None were observed during the period Oct. 1989 to Feb. 1992. Our sensitivity to neutrino bursts from collapsing stars extends to ≈60% of the stars in the Galaxy.

INTRODUCTION

The MACRO detector is a large-area underground experiment located in the Gran Sasso Laboratory 120 km east of Rome at a minimum depth of 3200 m water equivalent. The detector is composed of six supermodules (SMs) which when completed will have dimensions 72 m x 12 m x 9 m. The main features of the streamer tube information. The uncertainty

*This work was supported in part by the Italian National Institute for Nuclear Physics (INFN), the U.S. Department of Energy, and the U.S. National Science Foundation. Complete addresses for the institutions are in Ref. 1.

the detector are summarized in Table I. One supermodule is illustrated in Figure 1. The first supermodule is fully described in Reference 1.

SEARCH FOR MUON POINT SOURCES

Muon track directions can be reconstructed in MACRO to an accuracy of approx. 1° using was determined from the distribution in space angle between double muon events and is mainly due to multiple Coulomb scattering in the rock above. The data presented here come from a period of approx. 9 months of running with 1 SM and 9 months with 2 SMs. The total sample includes approx. 2 x 10^6 single muons.

Table I—Complete MACRO Detector

General (complete detector)

Acceptance: $11000\ m^2sr$

Dimensions: 72 m x 12 m x 9 m high

Average depth: 3600 m. water equiv.

Principal elements: Streamer tubes, liquid scint. tanks, track-etch detectors

Streamer Tubes

18 hor. layers interspersed with 0.35 m absorber of low radioactivity rock, 5 layers on sides.

Cells are 3 cm x 3 cm x 12 m

Gas mixture: He + CO_2 + n-pentane, operated in limited streamer mode

Spatial resolution: Approx. 1 cm

Angular resolution: <0.2°

Time resolution: 150 ns (50 ns after reconstruction)

Liquid Scintillator Counters

3 horizontal layers with 4.5 m separation between layers. Sides closed with one layer

Horizontal tanks are 75 cm x 50 cm x 12 m long; side tanks are 25 cm x 50 cm x 12 m long.

Interior of tanks is lined with clear teflon so that light is collected by total internal reflection.

Total of approx. 600 metric tons of scintillator

Instrumentation: ADC's, TDC's, waveform digitizers

Time resolution ~ 1 ns

Track-etch Detectors

3 layers of CR-39 and 4 of lexan

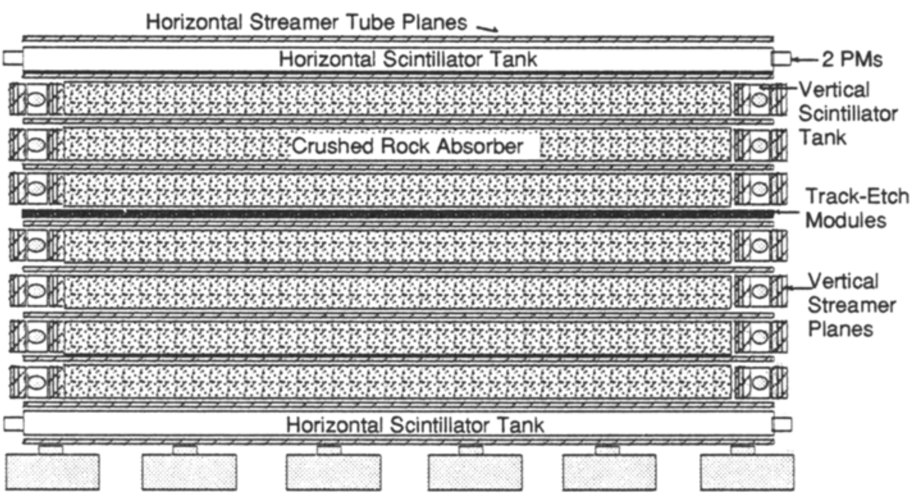

Figure 1. Vertical section through lower half of one MACRO supermodule

All-Sky Survey for Point Sources

To search for point sources of single muons the single muon events were sorted into bins of equal solid angle with $\Delta\alpha = 3°$ and $\Delta(\sin\delta) = 0.04$. This gave 3960 bins with occupancy >16 events. A "background" was calculated for each bin on a run-by-run basis by generating a large number of simulated events according to the observed two-dimensional distribution of zenith and azimuthal angles with event times chosen to mimic the actual time distribution. Figure 2 shows the distribution of $(n_{obs}-n_{expec})/\sqrt{n_{expec}}$ for these bins where n_{obs} is the observed number of events and n_{expec} the number expected from the background. This distribution is expected to be Gaussian if the angular distribution of muons is random. The best-fitting Gaussian distribution is superposed in Fig. 2. This fit has a χ^2/DoF = 87.7/68 with the mean of the Gaussian near zero and the σ is 1.0, as expected for a distribution of random fluctuations. The largest deviation in this distribution is $+3.82\sigma$. There is an *a priori* probability of 14% of finding a deviation at least this large from random fluctuations in the background. Thus we find no evidence for point sources of muons in our data. The 95% confidence limits to the muon flux for all bins are shown in Figure 3 as gray-scale intensity levels mapped in equatorial coordinates.

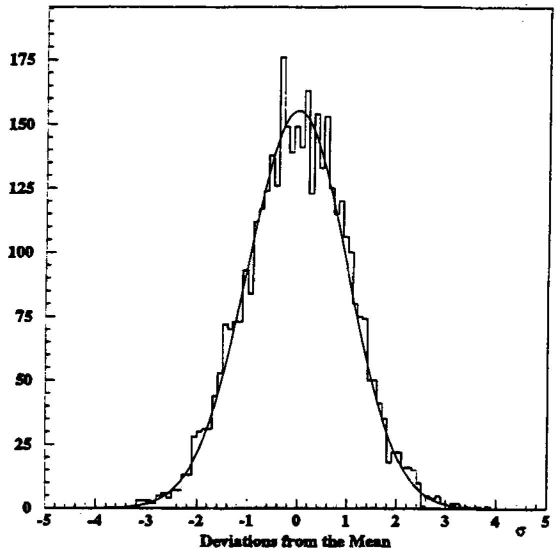

Figure 2. Distribution of $(n_{obs}-n_{expec})/\sqrt{n_{expec}}$ for 3960 equal solid angle bins where n_{obs} is the observed number of events and n_{expec} the number expected from the background. The best-fitting Gaussian distribution is superposed.

Periodicity Search for Selected Point Sources

There have been reports[2,3] of statistically significant muon excesses from the X-ray binary system Cyg X3. This muon excess appeared at a particular phase in the orbital period of the binary. Thus we have made periodicity analyses of the muons from the direction of Cyg X3 and several other sources with well-established periods.

For muons with directions pointing back to a 1.5° half-angle cone centered on Cyg X3 we have constructed a phase diagram based on an extrapolation of the ephemeris of van der Klis and Bonnet-Bidaud.[4] Our data show no evidence for a modulated muon signal with the orbital period from Cyg X3 or from several additional X-ray binaries and the Crab pulsar.

The 95% confidence level limits on the flux are given in Table 2 for these sources. In Fig. 4 we compare our flux limit plotted vs. detector depth with flux limits from other experiments including the positive reports from the Soudan 1 and NUSEX detectors[2,3]. Our limit is conservative in that if we were to assume that all the flux were concentrated in one phase bin as reported by Soudan 1[2], then our upper limit would be a factor of 10 below this.

One of the peculiarities of the Cyg X3 system is that it exhibits episodes of flaring activity at radio wavelengths; on average once or twice a year the radio emission jumps rapidly in intensity by a factor $\sim 10^3$ and remains at the high level for a few days. Several flares occurred during the period December 1990 to February 1991 including one around January 1991. MACRO was taking data over this period and no muon daily excess was observed. A detailed descrip-tion of the single muon results is given in Ref. 5.

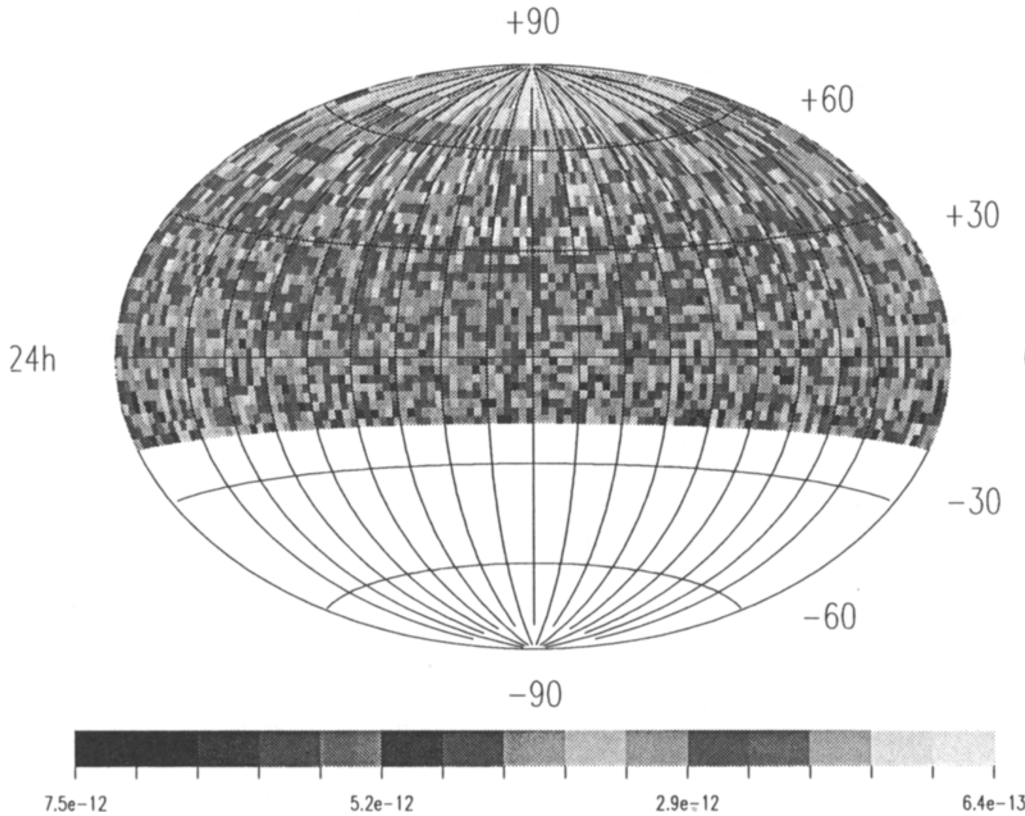

Figure 3. 95% confidence limits on the muon flux for the all-sky survey in equatorial coordinates. Units are $cm^{-2}sec^{-1}$.

Table 2. Search for modulated muon signals from point sources; J^{mod} is the 95% C.L. flux limit. The ephemerides used are shown below.

Source	P_0		$W(> \Re)$	F_{mod} (95%) ($cm^{-2}s^{-1}$)
4U0115+63	24.32^d (1)	orbital	0.79	$< 7.2 \times 10^{-13}$
Crab	33.3^{ms}(2)	pulsar	0.90	$< 9.3 \times 10^{-13}$
Her X1	1.70^d (3)	orbital	0.98	$< 7.6 \times 10^{-13}$
4U1907+09	8.38^d (4)	orbital	0.57	$< 1.1 \times 10^{-12}$
Cyg X1	5.60^d (5)	orbital	0.68	$< 7.3 \times 10^{-13}$
Cyg X3	4.79^h (6)	orbital	0.06	$< 8.8 \times 10^{-13}$

(1) Ricketts *et al.* (1981)
(2) Massaro *et al.* (1991)
(3) Ögelman (1987)
(4) Bolton (1975)
(5) Makishima *et al.* (1984)
(6) van der Klis and Bonnet-Bidaud (1989)

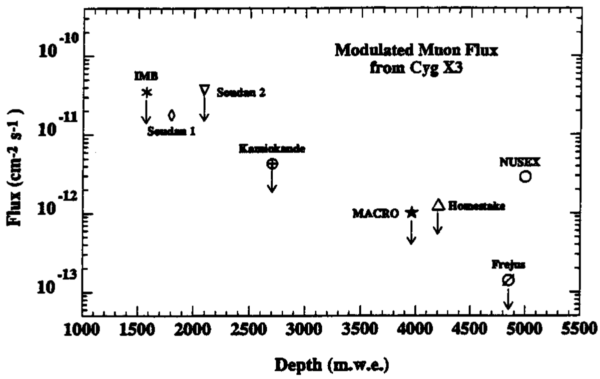

Fig. 4. The MACRO limit to the modulated muon flux from Cyg X3 compared to the results from other underground detectors.

STUDY OF THE UHE PRIMARY COSMIC RAY COMPOSITION

Multiple muon rates in underground detectors are sensitive to the composition of the primary cosmic rays. At the depth MACRO is situated, it is sensitive to primary energies between ~50 TeV and several thousand TeV. The observed multimuon rates were compared to expected rates from two composition models: a "light" composition (i.e., 50% protons below $\approx 10^2$ TeV, rising to 75% above 10^4 TeV) and a "heavy" composition (i. e., 20% Fe at 10 TeV rising to 80% above $\sim 10^3$ TeV. The predictions are based on a Monte Carlo simulation of the hadronic interactions of cosmic ray nuclei in the atmosphere, followed by detailed tracking of the muons through the rock and the apparatus.

In Figure 4 we compare the Monte Carlo distributions for the two models with the data. The light composition is clearly favored. A detailed discussion is given in Reference 6.

SEARCH FOR NEUTRINOS FROM GRAVITATIONAL COLLAPSE

The MACRO detector has been used to perform a search for bursts of neutrinos from Galactic supernovae from October 1989 to February 1992. Most of this running was with one SM and an active mass of 45 tonnes of liquid scintillator. We estimate that the detector would have been sensitive to core collapse supernovae occuring within 11 kpc. This volume contains ~60% of the stars in the Galaxy. No signal consistent with a supernova neutrino burst was observed during this approx. two year period.[7]

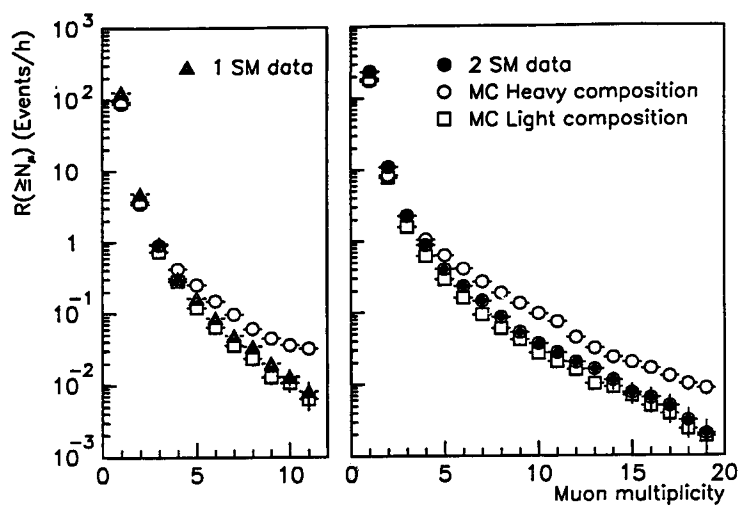

Figure 5. Comparison of MC with "heavy" and "light" compositions with the data taken with one and two supermodules.

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