MACRO as a Telescope for Neutrino Astronomy

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Abstract

We use a sample of 990 upward-going muons, induced primarily by atmospheric neutrinos, to search for neutrinos of astrophysical origin. No evidence has been found using the event direction information. Flux limits of the order of 10^{-15} cm^{-2} s^{-1} are imposed on current models for candidate point-sources. A space-time correlation search has been undertaken between 2328 BATSE gamma ray bursts (GRBs) and MACRO upward-going muons.

1 Introduction: Neutrino Astronomy:

The detection of high energy ($E_\nu > 100$ MeV) neutrinos of astrophysical origin would open an exciting field complementary to γ-ray astronomy due to their penetrating power. TeV γ-rays suffer absorption in intergalactic space on infrared light, PeV γs on the microwave background and EeV γs on radio-waves. Astrophysical source models in which radiation is due to electromagnetic processes do not produce significant ν fluxes. Sources involving "astrophysical beam dumps" (accelerated protons on a gas of matter or radiation with consequent production of neutrinos from $\pi^\pm$ decay) (Gaisser, Halzen & Stanev, 1995) are candidate ν sources. Examples are supernova remnants (SNRs) in which particles can interact with the gas in the acceleration region, and X-ray binaries made of a compact object (neutron star or black hole) and a non compact companion transferring mass to the other with consequent development of an accretion disk (Gaisser, 1996). The ν spectrum expected from "beam dump" sources is a power law with spectral differential index $\gamma \sim 2 - 2.5$ as expected from Fermi acceleration mechanisms. Neglecting γ absorption, ν fluxes are expected almost equal to γ-ray ones. Hence spectra measured by γ-ray experiments can be used to calculate expected rates of ν events. In MACRO they are $\sim 10^{-3} - 10^{-2}$ events/yr for a typical point-like source. The scenario in Protheroe, Bednarek & Luo, 1998 for young SNRs, in which particle acceleration takes place along the magnetic field (10^{12} Gauss) lines of a pulsar of 5 msec period formed during the supernova explosion, would produce ~ 5 events/yr in 10^3 m^2 for $E_\nu \geq 100$ GeV during the first 0.1 year after the explosion for a beaming solid angle of 1 sr. However the event rate drops rapidly after 0.1 years.

$\cos\theta$	$\gamma = 2$	$\gamma = 2.2$
0.15	0.77	0.72
0.35	0.90	0.85
0.55	0.91	0.87
0.75	0.91	0.87
0.95	0.91	0.87

Table 1: Fraction of events accepted in a 3° cone for various zenith angles and 2 spectral indices.

We also explore the possibility suggested by fireball models that GRBs are ν sources. GRBs are interesting as they are the most powerful objects ever observed in our Universe. For example, the total energy of GRB 980329 for isotropic emission is $> 10^{54}$ erg (Galama et al., 1999). Predicted rates are extremely low for detectors of the size of MACRO and the sensitivity needed could probably be reached only by a new generation of experiments of huge areas employing an active medium of sea water or ice. Nevertheless, MACRO is monitoring almost online the available region of sky using the detected ν events. The absence of an excess of these events with respect to the fluctuations of the background of atmospheric ν events allows us to derive flux limits that constrain some theoretical models.

2 Search for Point-like Sources:

The MACRO detector is located in the underground Gran Sasso Laboratories and has dimensions of 12×76.6 m^2 and a height of 9 m. MACRO measures ν-induced upward-going muons using a system of 12 m long boxes containing ~ 600 tons of liquid scintillator to measure the time-of-flight (time resolution ~ 500 psec) and $\sim 20,000$ m^2 of streamer tubes for tracking (angular resolution better than 1° and pointing accuracy

Source	δ	Data (3^o)	Backg.(3^o)	μ-Flux limit 1 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	μ-Flux limit 2 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	Prev. best μ limit $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	ν-Flux limit $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
SMCX-1	-73.5°	3	1.87	$0.60 \cdot 10^{-14}$	$0.67 \cdot 10^{-14}$	-	$0.19 \cdot 10^{-5}$
SN1987A	-69.3°	0	1.79	$0.29 \cdot 10^{-14}$	$0.16 \cdot 10^{-14}$	$1.15 \cdot 10^{-14}$ B	$0.09 \cdot 10^{-5}$
Vela P	-45.2°	1	1.40	$0.56 \cdot 10^{-14}$	$0.53 \cdot 10^{-14}$	$0.78 \cdot 10^{-14}$ I	$0.17 \cdot 10^{-5}$
SN1006	-41.7°	1	1.21	$0.58 \cdot 10^{-14}$	$0.58 \cdot 10^{-14}$	-	$0.18 \cdot 10^{-5}$
Gal.Cen.	-28.9°	0	0.86	$0.48 \cdot 10^{-14}$	$0.35 \cdot 10^{-14}$	$0.95 \cdot 10^{-14}$ B	$0.15 \cdot 10^{-5}$
Kep1604	-21.5°	2	0.82	$1.04 \cdot 10^{-14}$	$1.15 \cdot 10^{-14}$	-	$0.32 \cdot 10^{-5}$
ScoXR-1	-15.6°	1	0.76	$0.85 \cdot 10^{-14}$	$0.90 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$ B	$0.26 \cdot 10^{-5}$
Geminga	18.3°	0	0.42	$1.34 \cdot 10^{-14}$	$1.17 \cdot 10^{-14}$	$3.1 \cdot 10^{-14}$ I	$0.41 \cdot 10^{-5}$
Crab	22.0°	1	0.40	$2.22 \cdot 10^{-14}$	$2.22 \cdot 10^{-14}$	$2.6 \cdot 10^{-14}$ B	$0.68 \cdot 10^{-5}$
MRK501	38.8°	0	0.12	$5.40 \cdot 10^{-14}$	$5.44 \cdot 10^{-14}$	-	$1.66 \cdot 10^{-5}$

Table 2: μ flux limits for some sources (90% c.l.) calculated using the classical Poissonian method (μ flux limit 1) and the prescriptions in Feldman, & Cousins, 1998 (μ flux limit 2). Previous best limits (Gaisser, 1996): B is for Baksan, I for IMB. Neutrino flux limits are given.

checked with the moon shadow measurement (Ambrosio et al., 1999)). The rock absorber inside the lower half of MACRO imposes an energy threshold to vertical muons of ~ 1 GeV. The data used for the upward-going muon analysis has been collected since Mar. 89 with the incomplete detector (Ahlen et al., 1995); since Apr. 94 the full detector has been taking data (Ambrosio et al., 1998). In addition to $\sim 33 \cdot 10^6$ atmospheric μs, 990 upwardgoing μs with $-1.25 < 1/\beta < -0.75$ are selected with an automated analysis. $1/\beta = \Delta T c/L$, ΔT being the measured T.o.F. and L the track length, is ~ 1 for downward-going muons and ~ -1 for upward-going muons. Among these 990 events, 890 are measured with the full detector. The T.o.F. measurement is used to select upward-going μs produced in the rock below and inside the apparatus by atmospheric neutrinos of average energy $\langle E_\nu \rangle \sim 100$ GeV and $\langle E_\nu \rangle \sim 4$ GeV, respectively, from atmospheric downward-going muons. The main requirement to reject events with incorrect β measurement is that the position along the scintillation boxes measured using the times at the 2 ends (spatial resolution ~ 11 cm) and the position obtained using the streamer track (spatial resolution of ~ 1 cm) are in agreement within 70 cm.

The sample used for this analysis is larger than the one used for the neutrino oscillation analysis (Ronga et al., 1999) because we remove the requirement that 2 m of absorber are crossed in the lower part of the MACRO and we include a period in which MACRO was under construction. In fact, when calculating upper limits, the benefit of increasing the exposure offsets the slight increase of the background. We look for statistically significant excesses of upward-going muons in the direction of known sources (a list we have compiled of 40 selected sources, 129 Egret sources (Thompson et al, 1995), 220 SNRs (Green, 1998), 7 sources with γ emission above 1 TeV, 2328 GRBs in the BATSE Catalogue (Meegan et al., 1997)) or around the direction of any of the detected neutrino events. For this directional search it is important to consider the angular spread between the detected μ and the parent ν due to the ν spectrum which determines the kinematics of the charged current interaction, the μ propagation from production to detection and the angular resolution of the apparatus. In Tab. 1 we show the fraction of events accepted in a cone of 3° for various differential ν spectral indices γ and muon directions. We have considered cones with half- widths of 1.5°,3°,5° and 10° around the direction of

E_ν (GeV)	$P_{\nu\to\mu^-}$	$P_{\bar\nu\to\mu^+}$
10	1.27×10^{-10}	9.25×10^{-11}
10^2	9.73×10^{-9}	6.68×10^{-9}
10^3	5.99×10^{-7}	4.12×10^{-7}
10^4	1.56×10^{-5}	1.14×10^{-5}
10^5	1.39×10^{-4}	1.21×10^{-4}

Table 3: Probabilities for νs and $\bar\nu$s with energy E_ν to produce a μ with $E_\mu \geq 1$ GeV.

known sources or of the detected upward-going muons. The expected atmospheric ν background is calculated by mixing 100 times the local coordinates and times of the detected upward-going μs in declination bands of $\pm 5^{\circ}$ around the source declination. We find 111 clusters of ≥ 3 events and we expect 114 clusters from atmospheric νs in a 3° cone (see Fig. 1 (a)). For the 40 selected sources we find 10 sources with ≥ 2 events and we expect 11 in a 3° cone. Muon flux limits for 40 selected sources for 3° cones are calculated using the correction factors in Tab. 1 for $\gamma = 2.1$. MACRO area is calculated using a GEANT-based full simulation of the detector described in Ambrosio et al., 1998, and it is shown as a function of declination in Fig. 1 (b). We have derived flux limits (some of them are given in Tab. 2) calculating the upper limit from the Poissonian probability for processes with background (classical method) (Barnett et al., 1996).

The corresponding ν flux limits are obtained considering the conversion probability of ν_μ and $\bar{\nu}_\mu$ into

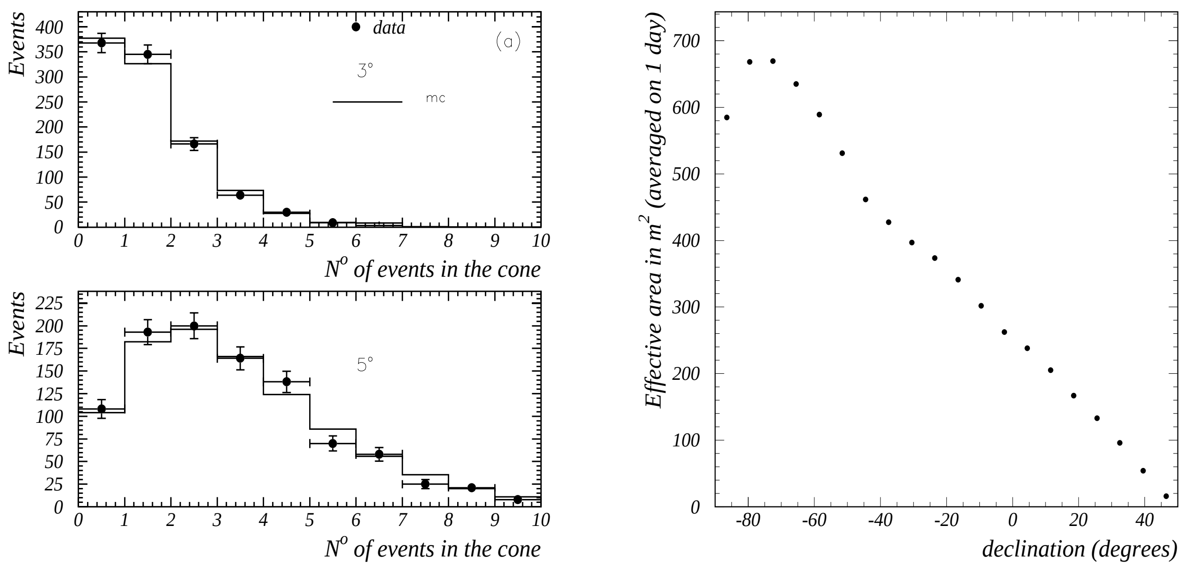

Figure 1: (a) Distribution of the number of events inside cones of 3° and 5°. (b) MACRO effective area as a function of declination averaged on 1 day for high energy events ($E_\mu \geq 10$ GeV).

muons for an energy threshold of 1 GeV (see Tab. 3). Moreover, in Tab. 2 we compare these flux limits with that obtained with a recent method suggested in Feldman & Cousins, 1998 now preferred by the Data Particle Book (Caso et al., 1998).

3 Coincidences between Gamma-ray Bursts and Upward-going Muons:

We search for correlations between 990 MACRO upward-going muons and 2328 GRBs in the BATSE 3B and 4B Catalogues (Meegan et al., 1997) detected from 21 Apr. 91 to 21 Feb. 99 (see Fig. 2(a)). Considering the BATSE angular accuracy we estimate that a half-cone of 10° includes 96.9% of the neutrinos from GRBs. We estimate that the fraction of signal lost due to the angular spread between the μ and the parent ν in a cone $\geq 10^{\circ}$ is negligible. The area for upgoing muon detection in the direction of the GRBs averaged over all of them is 118 m^2 (this value is small because MACRO is sensitive to neutrinos coming from the lower hemisphere only and because during 91-94 MACRO was not complete). We find no statistically significant correlation between MACRO and BATSE events considering their direction and time of detection. As shown in Fig. 2(b), we find no ν events in a window of 10° from GRB directions and inside a time interval of $\pm$200 s from its detection. We have examined the event measured after 39.4 s from the BATSE event of 22 Sep. 95 and angular separation of 17.6°. This separation is much larger than the BATSE positional error box of 3.86° around the GRB. The expected number of atmospheric ν background events in these windows is calculated using the delayed coincidence technique and it is 0.04 for 10° and $\Delta t = \pm 200$ s. The corresponding upper limit (90% c.l.) on the upward-going μ flux is 0.84 in units of 10^{-9} upward-going μs cm^{-2} per burst. This limit excludes an extreme cosmic string-type scenario in Halzen & Jaczko, 1996 which would produce 10^{-1} μ cm^{-2} for ν energies of some tens of TeV, while it does not exclude the fireball scenario model in Bahcall & Waxman, 1999.

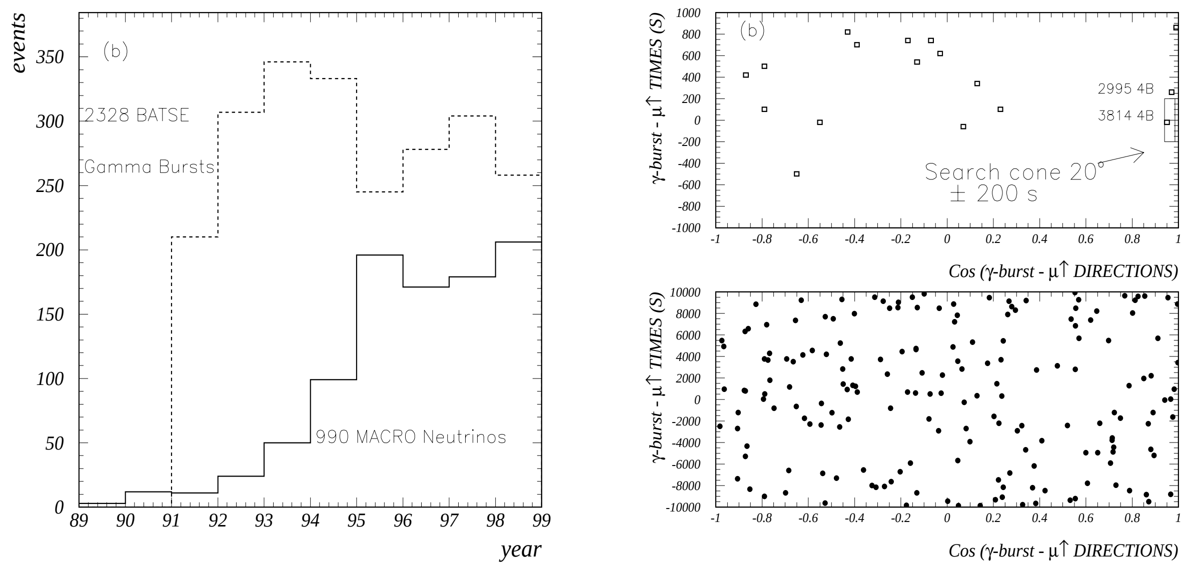

Figure 2: (a) Upward-going μs and BATSE GRBs vs year. (b) Difference in detection times vs cosine of the angular separation between the BATSE GRBs and upward-going μs. The 2 plots correspond to different time scales. The ± 200 s and 10°-20° windows are indicated in the plot on the top.

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