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Neutrino astrophysics with the MACRO detector in the Gran Sasso underground laboratory

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We present the results of a search for neutrino emission from celestial objects and of a search for coincidences with gamma ray bursts. We have computed flux limits for WIMPS coming from the center of the Earth and of the Sun. For this search we used 605 upward-going muons produced by neutrino interactions in the rock below the MACRO detector in the underground Gran Sasso Laboratory.

1. INTRODUCTION

High energies neutrinos are expected to be emitted from a wide class of possible celestial objects[1]: X-Ray binary systems, young supernova remnants , active galactic nuclei,etc.. In the range of energies from several GeV to several TeV the detection of neutrinos is based on the observation of upward-going muons produced from neutrino interactions in the rock around the detector. Currently the expected signals are below the sensitivity of existing detectors. Only galactic supernovae are expected to give detectable signals some time after the supernova explosion.

Another possible emission of high energy neutrinos is due to Weakly Interacting Massive Particles (WIMPS) trapped inside the center of the Earth or the center of the Sun. WIMPS have been suggest ed as possible constituents of the dark matter. Halo WIMPs can lose enough energy to become gravitationally trapped in the core of celestial bodies through elastic scattering in the nuclei. While their density builds up inside the body, their annihilation rate increases until equilibrium is achieved between capture and annihilation. High energy neutrinos are eventually produced via the hadronization and/or decay of the annihilation products (mostly fermion-antifermion pairs, weak and Higgs bosons) and can be detected as upward-going muons in underground detectors. The most promising WIMPS is the neutralino, which is the lightest supersymmetric particle in the minimal supersymmetric extension of the standard model. Neutralinos as constituent of the dark matter can be detected with direct and indirect methods. Direct methods employ low-background detectors (e.g. semiconductors or scintillators) to measure the energy deposited when a WIMP elastically scatters from a nucleus. We will present results based on the detection of ν radiation from WIMP annihilation in the core of the Earth and of the Sun (indirect method).

Finally other possible sources of high energy neutrinos can be correlated with the emission of gamma ray bursts[2] [3].

2. DATA SELECTION

The MACRO detector[4] located in the INFN Gran Sasso Laboratory consists of 6 supermodules and has overall dimensions of 12 m x 77 m x 9 m.

The detection elements for muons are planes of streamer tubes for tracking and liquid scintillators for fast timing. The angular resolution is better than 0.5°; the time resolution is about 500 psec. Data for upgoing muons come primarily from three running periods and detector configurations: the lower half of the first supermodule from March 1989 through November 1991, the full lower half of the detector from December 1992 through June 1993 and the full detector from April 1994 until March 1997. Starting from August 1995 the apparatus is running in the final configuration.

The search for upgoing muons crossing the detector is done using the time-of-flight method and

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is described in another talk in this conference [5]. In order to maximize the acceptance for the search of neutrinos from celestial bodies we do not require the minimum amount of material as in reference[5]. Without this requirement we introduce some background due to large angle pions produced from downgoing muons and we also add events with an interaction vertex inside the detector. We also included events which were observed during periods when the detector acceptance was changing with time due to construction work. All of these data can be used for the point source search since the benefit of the greater exposure in setting flux limits offsets the slight increase in the systematic error in the acceptance. This data set contains 605 events.

3. POINT LIKE SOURCES

A very important quantity in the search for point sources is the effective angular spread of the detected muon with respect to the neutrino direction. We computed the angle between the neutrino and the detected muon for several neutrino spectral indices γ. We assume a neutrino energy distribution like $dN/dE_\nu = constant \times E^{-\gamma}$ with a full Monte Carlo taking into account the neutrino-nucleon cross sections, the muon energy loss in the rock and the detector angular resolution. Table 1 shows the fraction of events in a 3^o search cone for two different neutrino spectral indices as a function of zenith angle.

Table 1
Fraction of events accepted in a 3^o cone

Cos(Zenith)	$\gamma = 2$	$\gamma = 2.2$
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 2 shows the results of the search for several specific sources. The background was calculated from data itself, counting the events in a declination band of $\pm$ 5^o around the declination of the source and having different right ascensions. The limits were calculated including the reduction factor for a 3^o search cone and spectral index $\gamma = 2.1$. The best limit from past experiments was taken from Baksan, IMB, Kamiokande, KGF[6]. The neutrino flux limits were computed for a neutrino spectral index $\gamma = 2.1$ and with a threshold of 1 GeV on the neutrino energy.

To give an idea of the physical implications of those limits we recall that we expect from the supernova remnant Vela Pulsar[6] a muon flux of the order of 0.03 x 10^{-14}cm^{-2} s^{-1} (about one order of magnitude lower than the existing limits).

We also looked at the gamma ray sources listed in the Second Egret Catalog[7]. We found no statistically significant excess from any of the sources. We compared the results with the predictions obtained from a Monte Carlo simulation using the events themselves, changing randomly the association between times and angles (zenith, azimuth) and adding a smooth variation to the angles. We have found 5 sources with ≥ 2 events in the search cone to be compared to 8.4 sources expected from the Monte Carlo.

We also looked for possible clusters of events counting the number of events in a 3^o cone centered around a given event; we found 22 clusters of $\geq$ 3 events around a given event, to be compared with 21 expected from the Monte Carlo.

4. CORRELATION WITH GAMMA RAY BURSTS

We looked for correlations with the gamma ray bursts in the Batse Catalog [8] containing 1762 events in the time window between April 21th 1991 and March 24th 1997, overlapping with 585 upward-going muons collected from MACRO during this time. The area for upgoing muon detection in the direction of the bursts averaged over all the bursts in the catalog is $107m^2$; the number is small because MACRO is sensitive to neutrinos only in one hemisphere and because MACRO was not completed in the period between 1991-1994. We found no statistically significant correlation

Table 2
Limits for Selected Sources at 90% CL. Muon flux limits in unit 10^{-14}cm^{-2} s^{-1}. Neutrino flux limits in unit 10^{-5}cm^{-2} s^{-1} for $E_\nu \geq 1$GeV and spectral index $\gamma = 2.1$.

Source	δ	Events in 3^o	Background	Muon flux limit	Old best limit (muons)	Neutrino flux limit
Cyg X-3	40.8	0	0.06	9.9	4.1 Baksan	5
MRK 421	38.1	0	0.07	9.1	3.3 IMB	4.6
Her X-1	35.4	0	0.14	6.4	4.3 IMB	3.2
Crab Nebula	22	1	0.25	3.8	2.6 Baksan	1.9
Geminga	17.8	0	0.21	2.1	3.1 IMB	1
SS433	5	0	0.34	1.4	1.8 Baksan	0.72
Sco X-1	-15.6	1	0.47	1.57	1.5 Baksan	0.78
Kepler 1604	-21.5	2	0.51	1.92	-	0.96
Galact Cent	-28.8	0	0.5	0.76	0.95 Baksan	0.37
Vela XR-1	-40.5	0	0.65	0.67	0.45 Baksan	0.33
SN 1006	-41.7	1	0.66	1.12	-	0.56
Vela pulsar	-45.3	0	0.76	0.64	0.78 IMB	0.32
CEN XR-3	-60.6	1	1.04	0.84	0.98 IMB	0.42
LMCX-4	-66.4	0	1.15	0.46	0.36 Baksan	0.23
SN1987 A	-69.4	0	1.1	0.46	1.15 Baksan	0.23

between neutrino events and gamma bursts. We particularly looked in a search cone of 20^o around the gamma burst direction (determined from the Batse angular accuracy) and in a time window of ±200 sec: we found no events, compared with 1 expected from the background. The corresponding upper limit at 90% C. L. is 1.2×10^{-9}cm^{-2} upward-going muons per burst. This limit is five orders of magnitude lower than the flux of the "extreme" model of reference[2] .

5. WIMP SIGNAL FROM THE EARTH AND THE SUN

In the search for WIMPS the SUN is a point like source moving in the sky. The background can be computed using the data itself changing the association between angles and times. So for the Sun we have used a data set with the same cuts used in the astronomy. For the Earth the situation is different. We must compare with an absolute theoretical prediction and therefore for the Earth we have used the more reliable data set of the atmospheric flux measurement[5]. For both sorces the background is normalized from the expectations outside the maximum search cone (30^o).

Table 3 shows the number of events detected and expected inside 6 arbitrary cones around the direction of the vertical of the apparatus and of the Sun.

Due to the deficit of the measured events with respect to the predicted upgoing events induced by the atmospheric neutrino background near the vertical of the apparatus [5], we give conservative flux limits for the Earth assuming that the number of events measured equals the number of events expected.

The signal of upgoing muons produced by WIMP annihilation has an angular shape that is due to several factors: dimension of the source, $\nu - \mu$ angle due to ν CC-interaction in the Earth, multiple scattering of muons in the path from the neutrino interaction point to the detector, detector angular resolution. The angular dimension of the Sun is negligible (about 0.5^o), this is not the case for the Earth, for which we expect wider angular distributions. The distribution of the $\nu - \mu$ angle is of course dependent on the shape of the neutrino energy spectrum. The energy spectrum of neutrinos produced in the annihilation of a WIMP of mass m_χ depends in principle on the

Table 3
Selected and expected events and 90% C.L. muon flux limits for 6 cones around the Earth and Sun directions.

EARTH				SUN		
Cone	Data	Background	Flux Limit ($cm^{-2}s^{-1}$) Exp. = 1900 m^2yr	Data	Background	Flux Limit ($cm^{-2}s^{-1}$) Exp. = $710m^2yr$
30^o	48	87.2	2.67×10^{-14}	46	40.8	7.1×10^{-14}
25^o	36	61.9	2.14×10^{-14}	30	28.5	5.0×10^{-14}
20^o	23	40.2	1.72×10^{-14}	20	18.3	4.4×10^{-14}
15^o	16	22.7	1.44×10^{-14}	9	10.3	2.6×10^{-14}
10^o	7	10.2	1.08×10^{-14}	2	4.6	1.4×10^{-14}
5^o	1	2.7	5.98×10^{-15}	2	1.2	1.9×10^{-14}
3^o	0	1.1	5.4×10^{-15}	2	0.4	2.2×10^{-14}

details of the final states produced in the annihilation. However, the most important parameter in determining the shape of the spectrum is simply the neutralino mass, which sets the maximum neutrino energy $E_{max} = m_\chi$.

Table 4
Muon flux limits as function of the neutralino mass computed for angular window containing 90% of the signal. Limits at 90% C. L. in units $10^{-14}cm^{-2}\,s^{-1}$.

	EARTH		SUN	
mass (GeV)	window (90%)	limit	window (90%)	limit
20	23.2^o	2.2	16.1^o	3.6
60	15.5^o	1.6	12.2^o	2.0
120	9.8^o	1.1	7.8^o	1.8

The neutrino fluxes induced by 20, 60 and 120 GeV neutralinos computed in reference[9] have been used as input to a full Monte Carlo to study the shape of the expected signal. Table 4 shows the results of such calculation together with the limits computed using angular windows containing 90% of the signal. Some improvement in the limits can be obtained from a fit to the data using the shape of the expected distributions.

The limits in table 4 are already of physical interest because can exclude several sets of allowed values of the parameters of the minimal super-symmetric extension of the standard model [10],[11].

REFERENCES

1 Gaisser, T. K., Halzen, F. and Stanev, T. Physics Reports 258 (1995) 173
2 Halzen, F. and Jaczko Phys Rev D54 2779 (1996)
3 Bahcall, J. and Waxman, E., Phys Rev Lett 78 2292 (1997)
4 Ahlen S. P. et al., MACRO Collab., Nuclear Instruments Methods A324 337 (1993)
5 Surdo A. (MACRO Collab.):Talk at this conference.
6 Gaisser, T. K. Nucl Phys B (Proc Suppl) 48 (1996) 405
7 Thompson D.J.et al Astr Journ. Suppl. (1995) and http://cossc.gsfc.nasa.gov /cossc/egret/egretcatalog
8 Meegan,C.A. et al. http:://www.batse.msfc.nasa.gov /data/grb/catalog (1997)
9 Bottino, A., Fornengo, N., Mignola, G., Moscoso, L., Astrop. Physics 3 65 (1995).
10 Bottino A.: Summary Talk at this conference
11 Bergstrom,Edsjo,Gondolo Phys Rev D55 1765 (1997)