Mem. S.A.It. Suppl. Vol. 9, 363

Memorie della
Supplementi

Experimental high energy neutrino astronomy

E. Migneco[1,2]

[1] Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud, Via S. Sofia 62, I-95123 Catania, Italy
[2] Department of Physics and Astronomy, Via S. Sofia 64, I-95123, Catania, Italy e-mail: migneco@lns.infn.it

Abstract. Neutrinos are considered promising probes for high energy astrophysics. Many indications suggest, indeed, that powerful cosmic accelerators such as AGNs, GRBs and microQSOs can produce high energy neutrinos. Travelling in straight line, without being absorbed, these particles reach the Earth carrying direct information on the source. The underwater/ice Cherenkov technique is widely considered the most promising experimental approach to build high energy neutrino detectors. The first generation detectors, BAIKAL and AMANDA, already set constraints on astrophysical source models for TeV neutrino production. The construction of larger (km^2) size detectors is started: in the South Pole, the ICECUBE neutrino telescope is going to be deployed. In the Northern Hemisphere three Collaborations (ANTARES, NEMO and NESTOR) are conducting R&D to install a neutrino telescope in the Mediterranean Sea.

Key words. Astronomy: high energy neutrino – Detectors: underwater/ice neutrino telescopes

1. Introduction

Several theoretical models predict that ultra high energy cosmic rays (UHECR), detected by several experiments, are protons accelerated in cosmic objects, e.g. GRBs and AGNs, where Fermi acceleration mechanism takes place. Such protons interacting with ambient gas or radiation can also produce high energy neutrinos from the decay of charged pions. Gaisser, Halzen & Stanev (1995); Waxman & Bahcall (1999). The flavour ratio at the source is $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$. Neutrino oscillations change the ratio at the Earth into $1 : 1 : 1$, since approximately one half of the muon neutrinos convert to tau neutrinos over cosmic baselines.

Light and neutral neutrinos are optimal probes for high energy astronomy, i.e. for the identification of astrophysical sources of high energy particles. Differently from charged particles and gamma rays (E_γ >TeV) neutrinos can indeed reach the Earth from far cosmic accelerators in straight line, allowing source detection. To fulfill this goal neutrino detectors must be design to optimise reconstruction of particle direction and energy, thus they are commonly referred as *neutrino telescopes*. High energy neutrinos are detected indirectly following weak Charged Current (CC) interaction with nucleons in matter and the production of a charged lepton in the exit channel of the reaction. The low νN cross section ($\sigma_{\nu N} \simeq 10^{-35}$ cm^2 at $\simeq$1 TeV) and the expected astrophysi-

Send offprint requests to: E. Migneco

cal ν fluxes intensities require a ν interaction target greater than 1 GTon (1 km^3 of water). In early '60s the use of natural water (lake or seawater or polar ice) was proposed to detect neutrinos using the optical Čerenkov technique to track the charged lepton outgoing the νN interaction. Underwater neutrino telescopes are large arrays of optical sensors (typically photomultipliers tubes of about 10" diameter) which permit to track charged leptons in water by timing the Čerenkov wavefront emitted by the particles. Search for neutrino point sources requires good pointing resolution, this can be obtained looking at the ν_μ channel. Muons are emitted co-linearly with the in-coming neutrino and have long range in water (kilometres at TeV energy, tens of kilometres at EeV energy). Muons emit, along their track, Čerenkov radiation that is detected by the lattice of PMTs (Photomultiplier Tubes). The Čerenkov wavefront, then the muon direction, is reconstructed using the information of photon hits and PMT positions. At PeV (10^{15} eV) muons generate showers by bremsstrahlung and pair production increasing the number of Čerenkov photons radiated in water. This is a good estimator for the muon energy. Due to the extremely high cosmic muon background, originated by cosmic ray interaction in the atmosphere, neutrino telescopes are optimised to observe up-going events: only neutrinos can, indeed, cross the Earth and generate a muon event close or inside to the detector.

Apart from muon tracks, electron cascades (originated by ν_e) can also be detected. In the energy range of interest cascade develops for few tens of meters in water, thus can be considered as quasi point-like compared to the spacing of OMs. While energy reconstruction is good for these events, the total amount of light radiated is proportional to electron energy, the reconstruction of the track direction is poor, $\sim$ tens of degrees.

At neutrino energies above 1 PeV, the Earth is opaque to neutrinos all neutrino flavours except tau, which undergo regeneration ($\nu_\tau \rightarrow \tau + X \rightarrow \nu_\tau + X$). Tau events can be identified when both ν_τ interaction and τ decay happen within the detector originating two cascades ("double bang" event). Since this signature is rare, the search for astrophysical neutrinos is concentrated on events close to the horizon, where the atmospheric background is low.

2. The operating detectors: Baikal NT-200 and AMANDA

After the pioneering work carried out by DUMAND offshore Hawaii Island (Roberts et al. 1992), Baikal was the first collaboration which installed an underwater neutrino telescope and, after more than ten years of operation, it is still the only neutrino telescope located in the Northern Hemisphere. The BAIKAL NT-200 is an array of 200 PMTs, moored between 1000 and 1100 m depth in lake Baikal (Russia) (Belolaptikov et al. 1997). BAIKAL is a high granularity detector with a threshold $E_\mu \simeq 10$ GeV and an estimated effective detection area $\leq 10^5$ m^2 for TeV muons. The limited depth and the poor optical properties of water (light transmission length of 15÷20 m, high optical background rate due to bioluminescence) limit the detector performances as a neutrino telescope. The Collaboration has successfully measured the atmospheric neutrino flux and set a 90% c.l. upper limit for diffuse astrophysical neutrino fluxes of $E_\nu^2 \Phi_\nu < 4 \times 10^{-7}$ cm^{-2} s^{-1} sr^{-1} GeV (Wischnewski et al. 2005). The detector is going to be improved with an external array of few tens PMTs that will enlarge the detection volume for high energy cascades.

AMANDA is currently the largest neutrino telescope installed (Andres et al. 2001). In the present stage, named AMANDA II, the detector consists of 677 optical modules (OM) pressure resistant glass vessel hosting downward oriented PMTs and readout electronics. OMs are arranged in 19 vertical strings, deployed in holes drilled in ice between 1.3 and 2.4 km depth. Vertical spacing between OMs is 10÷20 m, horizontal spacing between strings is 30÷50 m. The ice optical properties have been mapped as a function of depth: at detector installation depth the average light (λ = 400 nm) absorption length is $L_a \simeq 100$ m, the effective light scattering length is $L_b \simeq 20$ m. This makes AMANDA a good calorimeter for astrophysical events, with a resolution 0.4 in log(E) for muons and 0.15 in log(E) for electron cascades. The detector angular resolution is between 1.5° and 3.5° for muons and $\simeq$ 30° for cascades. AMANDA data have permitted to measure for the first time the upgoing atmospheric neutrino spectrum in the energy range from few TeV to 300 TeV (see figure 1).

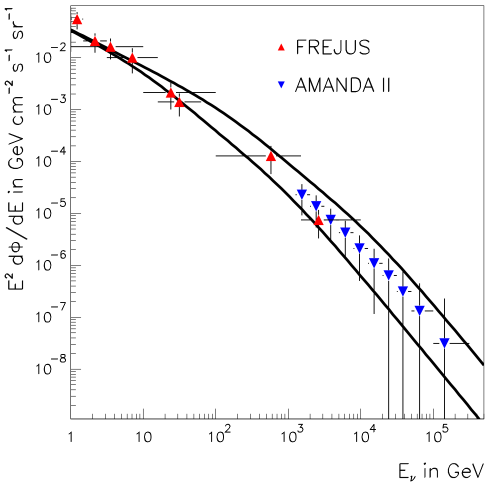

Fig. 1. Atmospheric neutrino energy spectrum (preliminary) from AMANDA data, compared to the Frejus spectrum (Daum et al. 1995) at lower energies. The two solid curves indicate model predictions Volkova (1980) for the horizontal (upper) and vertical (lower) flux.

The atmospheric neutrino spectrum recorded by AMANDA-II was then used to set a 90% c.l. upper limit on a diffuse muon neutrino flux of $E^2_{\nu_\mu}\Phi_{\nu_\mu} < 2.6\times10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} ($100 < E_\nu < 300$ TeV). AMANDA can also detect cascades originated by the leptonic vertex of electron and tau neutrino charged current interactions, and hadronic vertex cascades from all-flavor neutral current interactions. The measured 90% c.l. upper limit with respect to the flux of all three flavors is $\Phi_{\nu_e+\nu_\mu+\nu_\tau}E^2_\nu = 8.6\cdot10^{-7}$cm^{-2}s^{-1}sr^{-1}GeV (50 TeV $< E_\nu <$ 5 PeV) Ackermann et al. (2004). No excess above background is observed for horizontal events, the measured 90% c.l. upper limit on all flavors neutrino flux is $\Phi_{\nu_e+\nu_\mu+\nu_\tau}E^2_\nu < 9.9\times10^{-7}$cm^{-2}s^{-1}sr^{-1}GeV (1 PeV $< E_\nu <$ 3 EeV) (Ackermann et al. 2005a).

For point sources AMANDA reached a sensitivity $E^2_{\nu_\mu}\Phi_{\nu_\mu} \simeq 7\times10^{-8}$ GeV cm^{-2} s^{-1} calculated over 807 days live time (years 2000-2003) (Ackermann et al. 2005b). The search for 33 pre-selected sources yielded no evidence for extraterrestrial point sources. The strongest excess was observed from the direction of the Crab nebula, with 10 events where 5 were expected (Spiering 2005). A much larger array like a km^3 scale detector is therefore necessary to detect astrophysical sources.

3. The future km3 neutrino telescopes

AMANDA and BAIKAL have demonstrated the possibility to use the Čerenkov technique to track muons induced by $E_\nu >$100 GeV neutrinos. This success opened the way to the construction of km^3 neutrino telescopes such as IceCube (Ahrens et al. 2003), that will extend the AMANDA detector at South Pole.

3.1. IceCube

The IceCube telescope will be the natural extension of AMANDA to the km^3 size. When completed (expected in 2010), it will consist of 4800 downward looking PMTs arranged in 80 strings. The distance between PMTs will be 16 m with a spacing of 125 m between the strings. IceCube will be able to identify muon tracks from muon neutrinos with $E_{\nu_\mu} >$ 100 GeV. Simulations run by the IceCube Collaboration show that in three years of live time, the detector will reach a sensitivity $E^2_{\nu_\mu}\Phi_{\nu_\mu} = 4.2\times10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1} for a diffuse E_ν^{-2} neutrino spectrum and a sensitivity $E^2_{\nu_\mu}\Phi_{\nu_\mu} = 2.4\times10^{-9}$ GeV cm^{-2} s^{-1} for a point-like source (Ahrens et al. 2003). Besides, IceCube will be able to detect cascades from electron neutrinos with $E_{\nu_e} >$ 10 TeV and from tau neutrinos with $E_{\nu_\tau} >$ 1 PeV.

It is also worthwhile to mention that the under-ice detectors are not affected by radioactive and biological optical noise which is present in natural sea or lake waters. This makes them suitable for the search of low energy neutrino fluxes from Galactic SuperNova explosions.

3.2. The Mediterranean km^3

The contemporary observation of the full sky with at least two neutrino telescopes in opposite Earth Hemispheres is an important issue. A telescope in the Northern Hemisphere, has also the possibility to observe the Galactic Centre (not seen by IceCube), already observed to be an intense TeV gamma source (Aharonian et al. 2004) and the sources. In the Northern Hemisphere a favourable region is offered by the Mediterranean Sea, where several abyssal sites (> 3000 m) close to the coast are present and where it is possible to install the detector near scientific and industrial infrastructures. An underwater detector offers also the possibility to be recovered, maintained and/or reconfigured. Detector installation at depth ≥3000 m will reduce the atmospheric muon background by a factor ≥5 with respect to 2000 m depth, where IceCube is located. The long light scattering length of the Mediterranean abyssal seawater preserve the Čerenkov photons directionality and will permit excellent pointing accuracy (order of 0.1° for 10 TeV muons). On the other hand the light absorption length in water is shorter than in ice, then it reduces the photon collection efficiency for a single PMT. In the following we discuss the project conducted by three collaborations operating in the Mediterranean Sea (ANTARES, NEMO and NESTOR).

NESTOR (NESTOR web page 2000), the first Collaboration that operated in the Mediterranean Sea, proposes to deploy a modular detector at 3800 m depth in the Ionian Sea, near the Peloponnese coast (Greece). Each module is a semi-rigid structure (*the NESTOR tower*), 360 m high and 32 m in diameter, equipped with ≃ 170 PMTs looking both in upward and downward directions. After a long R&D period, in March 2003 NESTOR has successfully deployed 1 tower floor, with a diameter of 12 m and equipped with 12 PMTs. This module was deployed at a depth of 3800 m in order to test the overall detector performance and particularly that of the data acquisition systems. It acquired, on-shore, underwater optical noise and cosmic muon signals for about 1 month. From data acquired during this time, 745 atmospheric muon events have been reconstructed, making it possible to measure the cosmic ray muon flux as a function of the zenith angle (Aggouras et al. 2005). In the next future the Collaboration aims at the deployment of the first tower with 2×10^4 m^2 effective area for E_μ >10 TeV muons.

ANTARES will be a *demonstrator* neutrino telescope with an effective area of 0.1 km^2 for astrophysical neutrinos (ANTARES web page 2000). It will be located in a marine site near Toulon (France), at 2400 m depth. ANTARES will be a high granularity detector consisting of 12 strings, each equipped with 25 equidistant stories made of 3 PMTs (total 75), placed at an average distance of 60 m. The PMT are 45° downward oriented, in order to avoid their obscuration by sediments and bio-fouling. The whole detector installation is scheduled to be completed in 2007 (Korolkova et al. 2004). After a first operation of two prototypal lines in spring 2003, a new improved version of a short line instrumented with oceanographic sensors and optical modules has been put in operation in April 2005 and it is taking data since then. Data recorded by optical modules show an unexpectedly high optical background ranging from 60 to several hundreds kHz, well above the one produced by ^{40}K decay, then probably due to bioluminescence.

The NEMO Collaboration was formed in 1998 with the aim to carry out the necessary R&D towards the km^3 neutrino telescope. The activity has been mainly focused on the search and characterization of an optimal site for the installation and on the development of a feasibility study of the detector (Migneco et al. 2004). NEMO has intensively studied the oceanographic and optical properties in several deep sea (depth ≥ 3000 m) sites close the Italian coast. Results indicate that a large region located 80 km SE of Capo Passero (Sicily) is optimal for the installation of the km^3 detector. The bathymetric profile of the region is extremely flat over hundreds km^2, with an average depth of $\simeq$ 3500 m. Deep sea currents are, in the average, as low as 3 cm s^{-1}, and never stronger than 12 cm s^{-1}. The average value of blue (λ =440 nm) light absorption length is L_a = 66 ± 5 m. The same device measured L_a(440nm)$\simeq$ 48 m in Toulon site (Riccobene et al. 2003) and L_a(488nm)= 27.9 ± 0.9 m in Baikal lake (Balkanov et al. 2003). The optical background noise was also measured at 3000 m depth in Capo Passero. Data show that optical background induces on 10" PMTs (0.5 s.p.e.) a constant rate of 20 ÷ 30 kHz (compatible with the one expected from ^{40}K decay), with negligible contribution of bioluminescence bursts. These results were confirmed by biological analysis that show, at depth> 2500, extremely small concentration of dissolved bioluminescent organisms (Riccobene et al. 2003).

Concerning the detector design, NEMO proposes an innovative structure to host OMs: the NEMO *tower*. It is designed to deploy, during a single operation, a large number of PMTs (≥ 60) arranged in a 3-dimensional shape in order to locally permit event trigger and track reconstruction (Musumeci et al. 2003). The structure is mechanically flexible, being composed by a sequence of 16 ÷ 20 stories hosting OMs, interlinked by a net of syntectic fiber ropes. Each storey is 15 ÷ 20 m long and hosts two optical modules (one downward looking and one looking horizontally) at each storey end. The vertical inter-spacing between stories is $\simeq$ 40 m. One of the detector geometries proposed by the Collaboration is the NEMO140dh. It consists of a squared of 9 × 9 NEMO towers equipped with 5832 optical modules (10" diameter PMTs). The distance between the towers is 140 m. This configuration reaches an effective area of 1 km^2 at muon energy of about 10 TeV, with an angular resolution lower than 0.1 degrees (Sapienza et al. 2005). Figure 2 shows a preliminary result of the expected sensitivity to a E_ν^{-2} muon neutrino spectrum coming from a point-like source, obtained for a search bin of 0.3 degree (Distefano et al. 2005). The same figure reports, as a comparison, the sensitivity of the IceCube detector, obtained for a search bin of 1 degree (Ahrens et al. 2003). The NEMO140dh detector has, therefore, a better sensitivity and smaller search bin, allowing a better identification of point-like sources.

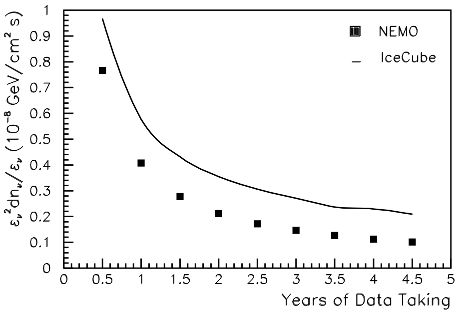

Fig. 2. Preliminary result of the NEMO140dh sensitivity to a E_ν^{-2} muon neutrino spectrum coming from a point-like source (Distefano et al. 2005), as a function of years of data taking, and comparison with the IceCube detector (Ahrens et al. 2003).

As an intermediate step towards the km^3, the Collaboration has decided to realize a technological demonstrator including most of the critical elements of the proposed detector. This project, called NEMO Phase 1 (Migneco et al. 2004), is under realization at the Underwater Test Site of the Laboratori Nazionali del Sud in Catania. The facility consists of a shore infrastructure, a 28 km long electro-optical cable, connecting the shore to the abyssal test site, and the underwater laboratory. The shore building hosts the land termination of the cable, mechanics and electronics workshops, the data acquisition room and power supplies for underwater instrumentation. The 28 km long electro-optical (e.o.) cable that connects the DAQ room to deep sea is a telecom cable, containing 10 optical fibers and 6 electrical conductors (3 mm^2) protected with external steel armor, specifically designed for high bandwidth data transmission and power feeding of deep sea installation. A sea campaign was conducted on January 2005 to install, on the cable, submarine terminations with electro-optical connectors mounted on titanium frames. The frames were deployed on the seabed at $\sim$ 2050 m depth (see figure 3). The installed connectors permit to plug and unplug underwater experimental instruments by means of Remotely Operated Vehicles (ROV) avoiding further operations on the main e.o. cable. During the sea campaign two experimental devices were deployed and connected. The INGV (Istituto Nazionale di Geofisica e Vulcanologia, Italy) attached the seismic monitoring station Submarine Network 1, which is the first node of the ESONET project. The NEMO Collaboration operated an array of hydrophones for the measurement of the deep sea acoustic background . The installation is fully operational and transmits data to shore. The completion of Phase 1 is foreseen by the end of 2006.

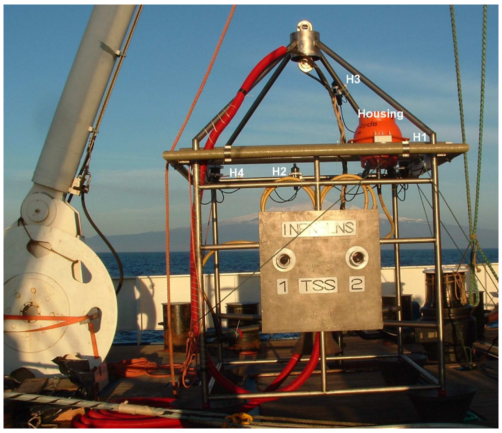

Fig. 3. The titanium frame installed on Test Site. The ROV operable electro-optical connectors are visible on the front panel. The hydrophones and electronics housing of the acoustic station are also shown (see text). The frame height is about 3.5 m)

4. Conclusions

The first generation of underwater/ice Čerenkov neutrino telescopes, BAIKAL and AMANDA, are successfully running. The atmospheric neutrino spectrum was measured up to 100 TeV demonstrating the feasibility of the high energy neutrino detection. These detectors have also set first constraints on astrophysical models which foresee TeV neutrino production in cosmic sources. The forthcoming km^3 neutrino telescopes will be *discovery* detectors that could widen the knowledge of the Universe. In the South Pole the km^3 detector IceCube detector is under construction, extending the AMANDA detection area. The detector will be completed within year 2010, being probably the first km^3 telescope running. In the Mediterranean Sea, ANTARES is going to install a 0.1 km^2 neutrino telescope demonstrator, NESTOR has deployed 12 PMTs in deep water, aiming at a 2×10^4 m^2 tower and NEMO is installing a technological demonstrator for a neutrino telescope and proposed Capo Passero as an optimal installation site for the Mediterranean km^3. The research and development activities conducted by the three Mediterranean collaborations can represent a valuable experience in the construction of the underwater km^3 detector, which will be the result of their efforts.

References

Ackermann M. et al. 2004, Astrop. Phys., 22, 127
Ackermann M. et al. 2005, Astrop. Phys., 22, 339
Ackermann M. et al. 2005,Phys. ReV., D077102
Aggouras G. et al. 2005, Astrop. Phys., 23, 377
Aharonian F. et al. 2004, A&A, 425, L13
Ahrens J. et al. 2004, Astrop. Phys., 20, 507
Andres E. et al. 2001, Nature, 40, 441 AMANDA web page http://amanda.uci.edu.
ANTARES: A Deep Sea Telescoper for High Energy Neutrinos, astro-ph/9907432, http://antares.in2p3.fr
Balkanov V.et al. 2003, NIM, A498, 37231
Belolaptikov I. et al. 1997, Astrop. Phys., 7, 263
Daum K. et al.1995, Z. Phys., C66, 417

Distefano C. et al. 2005, LNS Activity Report, http://www.lns.infn.it/info/Report2004

Gaisser, T.K., et al., Phys. Rep. 1995, D258, 173

Korolkova E.V. 2004, for the ANTARES Collaboration. Proc. of the CRIS 2004, Catania, Italy

Migneco E. et al. 2004, Proc. of the CRIS 2004, Catania, Italy

Musumeci M. 2003 for the NEMO Collaboration. Proc. of VLVνT Workshop, Amsterdam

NESTOR web page, http://icecube.wisc.edu.

Riccobene G. 2003 for the NEMO Collaboration. Proc. of VLVνT Workshop, Amsterdam

Riccobene G. 2005 for the NEMO Collaboration. Proc. of 29^{th} ICRC, Pune, India

Roberts A. et al. 1992, Rev. of Mod. Phys., 64, 259

Sapienza P. et al. 2005, LNS Activity Report, http://www.lns.infn.it/info/Report2004

Spiering C. 2004, Proc. of the Nobel Symposium on Neutrino Physics, Haga Slott, Sweden

Volkova L.V. 1980, Sov. J.Nucl.Phys., 31, 784

Waxman, E. & Bahcall, J. 1999, Phys. Rev., D64, 023001

Wischnewski R. 2005 for the BAIKAL Collaboration, Proc. of 29th ICRC, Pune, India