Observations of high energy neutrinos with water/ice neutrino telescopes

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Abstract. The search for high energy neutrinos of astrophysical origin is being conducted today with two water/ice Cherenkov experiments. New instruments of higher performance are now in construction and more are in the R&D phase. No sources have been found to date. Upper limits on neutrino fluxes are approaching model predictions. Results are reported on the search for point sources, diffuse fluxes, gamma ray bursts, dark matter and other sources.

1. Introduction
High energy neutrino astronomy will offer a new view of the Universe. The observation of the highest energy cosmic rays and the detection of galactic and extragalactic sources of gamma rays are proof that very energetic sources of non-thermal radiation exist. The detection of sources of high energy neutrinos will provide insights into the origin of the highest energy radiation. Neutrinos have been detected from the Sun and from Supernova 1987a; both observations representing fundamental breakthroughs in astrophysics and physics. Neutrino telescopes now in operation and construction aim at higher energies. This report will focus on the energy range aimed for by under water/ice neutrino telescopes: $\approx 10^{11}$ eV to $\approx 10^{18}$ eV. At the same time an increasing effort is underway to detect neutrinos at the highest energies to beyond $10^{20}$ eV. Markov and Zheleznikh [1] suggested the detection of neutrinos in water via the process $\nu_l (\bar{\nu}_l) + N \rightarrow l^\pm + X$ of upward or horizontal neutrinos interacting with a nucleon $N$ of the matter surrounding the detector. A significant fraction of the neutrino energy will be carried away by the produced lepton. For the important case of the muon the angle between the parent neutrino and the muon is less than $1^\circ$ at $1$ TeV energy and it becomes very small at higher energies providing the basis for astronomy.

In the past decade high energy neutrino astronomy has evolved from exploratory experiments to the first generation of neutrino telescopes with substantial neutrino detection rates. The first attempt was made by the DUMAND project [2] in the deep Pacific Ocean near Hawaii. This pioneering effort opened the road to the realization of the first working neutrino telescopes, AMANDA-B10 (1997, [8]), Baikal (NT-200 1998, [3]) and AMANDA-II (2000). Two telescopes are in construction, IceCube [15], at the South Pole, and ANTARES [5], in the Mediterranean Sea, and two projects are in the planning and prototyping phase in the Mediterranean Sea: NESTOR [4] and NEMO. The sensitivity of some of the current experiments, Baikal and AMANDA-II, is already below some model predictions. This report will focus on the current status of observations.

2. Detection principle and energy ranges
Water Cherenkov detectors detect the Cherenkov photons that are emitted by relativistic particles. Strings of optical sensors which are deployed in a transparent medium detect the
Cherenkov photons of muon tracks or cascades. Measuring the photon arrival times with a resolution of a few nanoseconds allows an accurate reconstruction of the muon track.

Neutrino telescopes cover a wide energy range for two reasons. The first reason is that the neutrino-nucleon cross section increases substantially with energy. The second is that the muon range and energy loss increase substantially with energy. We single out muons because they allow the best angular resolution. The cascade channel (e’s, τ’s and neutral currents) however allow in many areas a comparable sensitivity. Figure 1 shows the effective detection area for muon neutrinos in AMANDA-II and ANTARES [6] for point source selection, for the Ultra High Energy (UHE) analysis of AMANDA B10.

3. Detectors

3.1. AMANDA
AMANDA is a neutrino telescope built and operated at the Geographic South Pole. The final detector configuration, called AMANDA-II, consists of 677 optical modules (OM) arranged on 19 vertical strings deployed at depths between 1300-2400 m. Most of the OMs are deployed at a depth of 1500-1950 m and arranged within a diameter of 200 m. All analog pulses of the 20 cm photomultipliers are transmitted to the surface on individual cables, with most of the channels using fiber optic cables. The analog transmission on fibers allows low dispersion (PMT pulse FWHM about 20 nsec), high time resolution and a high dynamic range while keeping the electronics in the ice at a minimum.

The IceCube neutrino observatory at the South Pole will consist of 4800 optical sensors, installed on 80 strings between the depths of 1450 m to 2450 m in the Antarctic Ice, and 320 sensors deployed in 160 ice Cherenkov tanks (referred to as IceTop) on the ice surface directly above the strings. Each sensor consists of a 25 cm photomultiplier tube, connected to a waveform-recording data acquisition circuit capable of resolving pulses at nsec time resolution and high dynamic range. In January 2005 76 such sensors were installed as a first part of the IceCube array. The collaboration reported first results which show that the detector system works as expected [15]. The collaboration hopes to do first science with an array of 10 or more strings in 2006 and complete construction in 2010/11.

3.2. Baikal
The Baikal neutrino telescope is located 30 km off the shore of Lake Baikal, Siberia, at a depth of 1.1 km. The configuration NT200 [3] was commissioned in April, 1998. It consists of 192 optical modules (OMs), mounted on 8 vertical strings, which form a structure of 40 m diameter and 72 m height. Each OM contains a 37 cm diameter photomultiplier. For installation and maintenance, the Baikal collaboration takes advantage of the cold winters in Siberia, which cause the Lake to freeze over for several months allowing easy access to the deployment site.
Figure 2. Schematic view of currently running detectors (AMANDA and Baikal) and of detectors currently in construction: ANTARES and IceCube.

The Baikal Collaboration added three outer strings in 2005 to increase the sensitivity at high energies for cascades.

3.3. ANTARES
Antares is a neutrino telescope under construction in the Mediterranean Sea at a depth of 2500 m near Toulon, France. The project aims to complete the full array, consisting of 12 lines with 75 photomultipliers each, by 2007. Simulations indicate a very good angular resolution of 0.3° for 1 TeV $\mu$'s (0.6° degrees with respect to the neutrino direction). The neutrino effective area is expected to be similar to the AMANDA array as shown in fig. 1.

3.4. Other projects and initiatives
NESTOR is a neutrino telescope with a proposed location near Pylos, on the Greek Ionian Sea coast. A calibration and engineering run of a test detector was carried out in 2003 [21]. The detector was operated for more than one month and data was continuously transmitted to shore. With the data collected, the collaboration was able to reconstruct muon events at a rate consistent with predictions and produce a muon zenith angle distribution [20].

The initial goal of the NEMO project is research and development to lay the technological foundation for a future km scale detector in the Mediterranean. The collaboration has identified a possible site for a 1 $km^3$-scale instrument at a depth of 3500 m, at a distance of about 80 km from the Sicilian coast. The NEMO architecture for a 1 $km^3$ detector is based on 5832 optical sensors. Finally, it should be mentioned that the groups involved in the Mediterranean projects have formed a European consortium called KM3Net to further the development of a kilometer scale neutrino telescope in the Mediterranean Sea.

4. Atmospheric muons and neutrinos
Cosmic ray muons form a background for neutrino telescopes. The background is rejected in two ways which illustrate two fundamental modes of operation:
At low energies - below a few PeV: Reject downgoing muons by zenith angle and use upward muons as reliable neutrino messengers.

At very high energies: Reject cosmic ray muon background by direction and energy. At energies above \( \approx 10^{15-16} \text{eV} \), (depending on the depth of the instrument) the down going background is negligible, especially at larger zenith angles. This allows to accept more downgoing signal events.

At the depth of AMANDA it is found that the down-going cosmic ray muon flux is about 5 orders of magnitude larger than the expected neutrino flux. At greater depth the muon flux is significantly smaller and vice versa. Neutrino telescopes can use the cosmic ray muon flux to study the detector response, possible systematic effects and also to perform physics measurements. The cosmic ray muon angular and vertical intensities were measured in AMANDA-II and they agree well with simulations and with other experimental measurements [15]. AMANDA was able to use down-going muon events, which are in coincidence with SPASE surface array, to make a measurement of the cosmic ray mass composition as a function of the primary energy near the knee [7].

In order to measure the atmospheric neutrino component, a rejection factor of more than \( \approx 10^6 \) is needed to eliminate the cosmic ray muon background. The AMANDA collaboration records about 4 well reconstructed neutrino events per day in AMANDA-II. The preliminary unfolded \( \nu_\mu \) sea-level energy spectrum was determined and is in agreement with the expectations up to above \( 10^4 \) GeV [9]. The observed spectrum is shown in figure 3.

5. Search for sources of astrophysical neutrinos

5.1. Diffuse fluxes

The search for diffuse astrophysical neutrino fluxes is in many respects the most challenging. The reason is that atmospheric neutrino background rejection is almost entirely based on energy reconstruction, and misreconstructed downgoing cosmic ray muons can complicate the analysis. A diffuse flux can only be measured if the spectrum is significantly harder than the steeply falling atmospheric neutrino spectrum.

Models of cosmic ray shock acceleration based on the Fermi mechanism naturally produce energy spectra with a power index \( \gamma \approx 2 \). \( E^{-2} \)-type spectra are often used as a reference flux. However, each specific model needs to be optimized and analyzed separately and the energy cut will move higher or lower depending on the hypothetical signal flux. The limits discussed here are not differential limits, instead they refer to an assumed \( E^{-2} \) spectrum extending over the whole energy range. The accelerated protons interact with each other or with ambient photons. Pion decay yields a \( \nu^- \)-flux with roughly the same spectral index as the protons. At the production site, the \( \nu^- \)-flavors are distributed according to the ratios \( \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0 \). Due to neutrino oscillations, an approximate equipartition of flavors is predicted to be observed at the detector. However, the assumption of a \( \nu_e : \nu_\mu : \nu_\tau = 1:1:1 \) ratio is indeed a simplification, which is not accurate at energies above \( \approx 10^{14} \text{eV} \) [22].

We categorize the results in three groups and give the current results for Baikal and AMANDA. The reported results are compiled in the figure 3. AMANDA has reported results on all three channels, Baikal on the third one.

- Through-going upward muon events:
  For the through-going upward muons AMANDA reports results in two analyses. In one analysis, an energy cut is applied and observed events above the energy cut are compared to the signal and background prediction. The optimization is done before the data is unblinded. The collaboration reported a sensitivity at the level of \( \approx 10^{-7}\text{GeV}/(\text{cm}^2\text{sr}) \) [15] for a data set currently being analyzed. The other result is based on a neutrino energy spectrum analysis with a differential limit at about 30 TeV based on an energy unfolding method [9].

- Contained cascade events:
  This analysis aims for the measurement of the diffuse flux of \( \nu_e, \nu_\tau \) and due to neutral current interactions. In order to determine a generic astrophysical flux limit the assumption is made that astrophysical neutrino fluxes appear in a \( \nu_e : \nu_\mu : \nu_\tau = 1:1:1 \) ratio. While the directional
resolution is relatively poor, a comparable flux limit is obtained due to the better energy resolution for cascades compared to $\nu_\mu$.

- Not through-going muon and not contained cascade events:
  The Baikal collaboration was able to develop an analysis technique which allowed the effective detector volume for very bright cascade events to increase substantially over the geometric volume. Even though non contained events are accepted with a vertex up 200 m outside the instrument, the technique allows to reject downgoing background effectively by using a combination of energy and directionality of the timing pattern. The atmospheric neutrino background is easily rejected based on energy. An upper limit is reported based on 806 days of livetime. AMANDA developed a technique to detect non-contained events of very high energy. In this analysis the 2 billion cosmic ray muon events are rejected using the energy. This UHE analysis is sensitive to signal flux in the region from about 10 PeV to 1000 PeV.

5.2. Search for point sources

The detection of astrophysical point sources of neutrinos is perhaps the most prominent and also name bearing goal of neutrino astronomy. Numerous sources of TeV energy gamma rays have been detected in the past decade. Neutrino telescopes not only overlap at low energies with the energy range of current ground based gamma ray telescopes, but also extend in sensitivity to much higher energies.

Results are available from the underground detectors MACRO and SuperKamiokande and also from Baikal and AMANDA.

None of the current observations have indicated any significant excess above the background of atmospheric neutrinos. Limits are reported for individual sources of special interest, which are also sources of gamma rays at TeV energies. Figure 4 shows a number of individual limits for point sources from 4 years (807 days of livetime) of AMANDA in the northern hemisphere. The limits are at the level of $E^2 \cdot 6 \cdot 10^{-7}$GeV cm$^{-2}$sec$^{-2}$ [15]. In a few cases, for example the active galaxy Mrk 501, the limits on neutrino fluxes approach the observed gamma ray flux at TeV.
Figure 4. Limits on $E^{-2}$-neutrino fluxes for point sources of high energy neutrinos are shown for MACRO and AMANDA. Also shown are average sensitivities for ANTARES and IceCube.

energy of these sources in their high states. Also shown are limits of the MACRO experiment from more than 10 years of data. The average sensitivity for point sources with an $E^{-2}$-spectrum is shown for the lifetime of MACRO, for 4 years of AMANDA and for one year of IceCube.

AMANDA reported an upper limit from a search for neutrinos from the galactic plane in the Northern hemisphere [15]. A larger km scale neutrino telescope will be needed to detect the a neutrino flux from the galactic plane. The Northern hemisphere large instrument will be ideally positioned to search for the higher flux in near the galactic center.

5.3. Neutrinos from Gamma Ray Bursts, dark matter and other searches
Gamma-ray bursts (GRBs) are among the most energetic phenomena in the universe. The observation of high energy neutrinos in gamma ray bursts would confirm hadronic acceleration in the fireball; possibly revealing an acceleration mechanism for the highest energy cosmic rays. AMANDA reported searches for neutrinos from a total 451 GRBs, most of which were triggered by the BATSE telescope during 1997 to 2000. The short duration, typically 10 to 100 seconds, of the bursts makes background rejection easy. AMANDA observed zero neutrino events at an expected background of approximately 2 events for all bursts. Upper limits have been reported at the level of $3 \cdot 10^{-8}$ GeV cm$^{-2}$ sr$^{-1}$ s$^{-1}$ [19, 15] for 139 bursts from 2000 to 2003. This limit is about an order of magnitude above the Waxman-Bahcall prediction [23].

5.4. Dark matter and other searches
Minimally Supersymmetric extensions to the Standard Model predict the existence of the neutralino, in the mass range GeV-TeV, which is a candidate for the cold dark matter. The particles will lose energy and become gravitationally trapped in the centers of object like the earth, the sun, or the center of the galaxy where they annihilate to produce neutrinos. These neutrinos may be detected in a high-energy neutrino telescope. The energy range of the predicted neutrino fluxes is from about $10^{10}$ eV to a few times $10^{12}$ eV. AMANDA has performed a search for dark matter in the center of the Earth and the Sun [24]. No excesses of events have been observed and upper limits were placed. Baikal reported an upper limit (see for example [29]) at a comparable level on the neutrino flux from WIMPs annihilating in the Earth. SuperKamiokande holds the lowest limit by a factor of 2 [28] on the muon neutrino flux from the Sun at a level of $2000$ km$^{-2}$ yr$^{-1}$ for neutralino masses around $10^{12}$ eV (based on a data set from many years). Limits from underground detectors like Baksan [26] and MACRO [27] are still comparable or lower, especially for lower neutralino masses around $10^{11}$ eV. ANTARES is expected to have a sensitivity of a factor 10 below the current limits; IceCube is expected to have a final sensitivity of about 2 orders of magnitude below the current AMANDA limit. Northern hemisphere telescopes will be in a good position to also search for dark matter from the center of the Galaxy.
5.5. Neutrinos of highest energies

New techniques are being explored to search for neutrinos in the energy range from $10^{18}$eV to beyond $10^{21}$eV. Some exploratory experiments are already underway. A recent overview of sensitivities of techniques and instruments can be found in ref. [30]. Most of the current efforts have focused on the use of radio signals from highest energy events in ice. The application of the radio technique in salt domes is being investigated. Acoustic techniques are being explored to measure the acoustic pulse of GZK events. First data are available from a prototype version of ANITA, which has performed a first scan of the Antarctic ice sheet for neutrino radio pulses from a balloon [31]. RICE [32] uses radio sensors deployed in the deep ice near the South Pole. The techniques are still in rapid development and a substantial increase in sensitivity at highest energies can be expected in the next decade.

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