Neutrino Telescopes

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Abstract. Neutrino telescopes complement gamma ray telescopes in the observations of energetic astronomical sources as well as in searching for the dark matter. This paper gives the status of the current generation neutrino telescopes projects: Baikal, AMANDA, NESTOR, NEMO and ANTARES with particular emphasis on the ANTARES telescope in the Mediterranean Sea.

INTRODUCTION

Gamma ray astronomy has significantly extended the energy range of classical photon astronomy and the resulting multi-wavelength observation of astronomical sources is greatly increasing our knowledge of many highly energetic objects in the universe. Neutrino telescopes, together with cosmic ray detectors and gravitational wave detectors aim to further extend astronomy with multi-messenger observations of the same and possibly of as yet undiscovered objects in the universe.

The neutrino telescopes, described in this paper, have numerous scientific objectives. One of the main objectives is the discovery and understanding of the sites of acceleration of high energy particles in the universe. Since their original discovery one hundred years ago the origin of the high flux of charged cosmic ray arriving at the Earth is unknown. Linked to this objective is the study of the sources discovered and measured in multi-wavelength astronomy such as: Supernova Remnants (SNR); Active Galactic Nuclei (AGN); Microquasars (MQ) and Gamma Ray Bursts (GRB). An important further objective of neutrino telescopes is the search for dark matter in the form of neutralinos. In supersymmetric theories with R-parity conservation, the relic neutralinos from the Big-Bang would concentrate in massive bodies at sites such as the centres of the Earth, Sun and Galaxy. In these sites neutralino annihilations and the subsequent decays of the resulting particles would yield neutrinos detectable in neutrino telescopes of the scale currently in operation and being constructed.

In the past decades several neutrino telescope projects have been launched. At the present time there are two operating neutrino telescopes (AMANDA and Baikal) and three projects in the Mediterranean Sea building current detectors and developing technology for future detectors (ANTARES, NEMO and NESTOR). In this paper the techniques of neutrino telescopes are presented and illustrated using mainly examples from the ANTARES telescope which is currently under construction in the deep sea.
ASTRONOMY WITH NEUTRINOS

Neutrinos provide an entirely new way to observe astronomical objects. Like photons but unlike charged cosmic rays, they propagate without deviation in electromagnetic fields; however their property of weak interaction with matter gives neutrinos unique features compared to photons of all energies. Neutrinos pass through large amounts of matter without interaction enabling probes, for example: through dust clouds in the galactic plane; through dense accretion disks of matter around massive central sources such as black holes and to the centers of stars and planets including the Sun and Earth.

Neutrinos are necessarily produced in any regions of space where high energy charged particles or gamma ray interact with matter. In extremely energetic astronomical sources, high energy neutrinos are emitted as secondary products produced in interactions of charged cosmic rays; the charged cosmic rays being accelerated in shock processes in the sources. Typically the interactions are of high energy protons with nucleons in the interstellar matter or with photons from the local radiation field, e.g.: \( p + p \rightarrow \pi^0 + \pi^\pm + \ldots \). Neutrinos are produced in decays of charged pions: \( \pi^\pm \rightarrow \nu_\mu, \mu \rightarrow \nu_e \nu_\mu e \) and high energy gamma rays are produced in the same reactions from the decay of neutral pions: \( \pi^0 \rightarrow \gamma \gamma \). The resulting fluxes of neutrinos and gammas from \( pp \) interactions is roughly the same while for \( p\gamma \) interactions it is expected that the flux of gammas is roughly four times that of neutrinos due to the dominance of the \( \Delta \) resonance in the \( p\gamma \) mode. Due to the multiple secondary particles, the neutrino only carries a fraction of the primary proton energy, typically 10% or less. These reactions can occur close to the acceleration source where the matter density is likely to be high or in interstellar space or molecular clouds in the Galaxy.

The relative fractions of neutrino flavours produced at the source is approximately \( \nu_e : \nu_\mu : \nu_\tau \cong 1 : 2 : 10^{-5} \). After propagation over large astronomical distances of the order of kpc to Earth, neutrino oscillations lead to similar numbers of each neutrino flavour, \( \nu_e : \nu_\mu : \nu_\tau \cong 1 : 1 : 1 \).

At present the only observations of extra-terrestrial neutrinos have been from the sun and from SN1987a in the Large Magellanic Cloud. These neutrinos originate in nuclear reactions and have energies in the MeV range. The neutrinos which are searched for by the present generation of neutrino telescopes from the reactions mentioned in the last paragraph are of much higher energy in the TeV to PeV range. The potential sources of these neutrinos include Active Galactic Nuclei, Gamma Ray Bursts, Supernova Remnants and Microquasars and some predictions of rates for these sources will be given later.

TECHNIQUES OF NEUTRINO TELESCOPES

Neutrino telescopes are sensitive to all three flavours of neutrinos but the detection efficiency of each mode can be very different depending on the detection technique of the telescope. In all techniques the neutrinos are detected via the secondary particles produced in interactions with matter, either inside or around the
detector. For charged current interactions of neutrinos with nucleons the lepton produced corresponds to the flavour of the neutrino: \( \nu_e N \rightarrow eX, \nu_\mu N \rightarrow \mu X, \nu_\tau N \rightarrow \tau X \), where \( X \) represents the hadrons resulting from the nucleon recoil. In neutral current reactions the neutrino scatters inelastically: \( \nu N \rightarrow \nu X \), and the event topology is similar for all flavours. In neutrino telescopes the lepton plays the main role in the detection efficiency and while the hadrons, \( X \), are detected they usually have little effect on the efficiency. Due to this, the charged current modes generally dominate the efficiency and the \( \nu_\mu \) mode dominates over the other flavours due to the long range of muons in matter.

While neutrino data exist from underground detectors in caverns, this paper only discusses neutrino telescopes using large volumes of water or ice in the deep sea, deep lakes or deep glacier. These telescopes are based on the detection of Čerenkov from the secondary particles produced in the neutrino-matter interaction. As mentioned above the detection mode with the highest sensitivity is that of \( \nu_\mu \) and figure 1 illustrates the principle of a deep sea neutrino telescope using this channel. A matrix of light detectors, in the form of photomultipliers in glass spheres, "optical modules", is deployed near the sea bed.

FIGURE 1. Principle of detection of high energy neutrinos in an underwater neutrino telescope

This matrix of light detectors enables the direction of the muon track to be measured with a precision of a few tenths of a degree and at high energies the muon track direction is closely aligned with that of the neutrino such that the neutrino direction is measured with similar precision. As an example figure 2a shows the simulated angular resolution for the ANTARES neutrino telescope. This figure shows the angular resolution for muons and for neutrinos, the difference being due to the deep inelastic scattering interaction where at higher and higher energies the neutrinos follow more and more closely the muon direction. Above 10 TeV the angular resolution becomes \( \sim 0.2^\circ \). By using the total light collected in the detector it is possible to obtain a measurement of the energy of the muon track and hence that of the neutrino. The accuracy of this measurement is limited by the fluctuations in the energy loss measurements of the muon. The resolution possible is shown in figure 2b where
the error on the logarithm of the muon energy is plotted. The achievable energy resolution is \( \sim 0.4 \) in \( \log(E_\mu) \) at 10 TeV, decreasing to \( \sim 0.3 \) in \( \log(E_\mu) \) at 100 TeV which corresponds to a factor 2 in \( E_\mu \).

**FIGURE 2.** Simulated resolutions for ANTARES underwater neutrino telescope: a) angular resolution showing the difference between the reconstructed muon direction and the true muon direction and the muon and the true neutrino direction as indicated on the figure; b) energy resolution.

The rate of neutrino detection in a neutrino telescope is the product of several factors characterizing the neutrino interactions with matter and the detector properties. For the \( \nu_\mu \) mode the long range of the muon contributes to increase the event rate. The observed event rate is given by: \( N_\nu = \Phi_\nu \times A_\nu \) where \( \Phi_\nu \) is the flux of neutrinos arriving at the Earth and \( A_\nu \) is the effective area of the detector for neutrinos. For \( \nu_\mu \) events: \( A_\nu = P_{\text{Earth}} \times \sigma_\nu \times \rho N_{AV} \times R_\mu \times A_\mu \), where \( P_{\text{Earth}} \) is the survival probability that the neutrino crosses the Earth to the detector; \( \sigma_\nu \) is the neutrino interaction cross-section; \( \rho N_{AV} \) is the number density of target nucleon in the rock or water; \( R_\mu \) is the range of the muon and \( A_\mu \) is the effective area of the detector for muons. The geometry and properties of the neutrino telescope enter only in \( A_\mu \) and this quantity is obtained from detailed simulations of the detector. Figure 3a and 3b show the effective muon area and the corresponding neutrino effective area for ANTARES.

**FIGURE 3.** Effective areas for the ANTARES detector: a) effective area for muons averaged over all neutrino incident directions, the different symbols are for selection cuts on the quality of the events, the triangles are the standard cuts, squares are events with angular resolution better than 0.3° and the circles for resolution better than 1°; b) effective area for neutrinos, the different symbols indicate different incidence angles as given in the figure.
There are currently two neutrino telescopes in operation in the world: Baikal[1] at a depth of 1200 m in the water of Lake Baikal in Siberia and AMANDA[2] at a depth of 2000 m in the ice at the South Pole in Antarctica. In addition there are a number of groups developing neutrino telescopes in the deep sea: ANTARES, NEMO and NESTOR. A deep sea-water telescope has significant advantages over ice and lake-water experiments due to the better optical properties of the medium. There are however, serious technological challenges to overcome to deploy and operate a detector in the sea. The pioneer sea-water project, DUMAND which worked from 1980 to 1995 to build a detector off the coast of Hawaii, did not overcome these challenges and the project was cancelled. In contrast the projects AMANDA and Baikal which deploy from the solid glacial ice and the frozen ice surface of the lake, respectively, have developed workable deployment systems. The advantages of sea-water neutrino telescopes are significantly better angular resolution e.g. ~0.2°, as shown earlier, for ANTARES compared to ~3° for AMANDA, as well as more uniform efficiency due to the homogeneous medium. A disadvantage of a sea-water detector is the higher optical background due to radioactive decay of $^{40}$K and light emission from living organisms: bioluminescence. These backgrounds can be overcome in the design of the detector by having a higher density of optical modules and high bandwidth data readout.

The Baikal detector started operating in 1993 with 36 optical modules and was finished in 1998 with 192 optical modules. The detector is located in the Southern part of Lake Baikal at a point where the lake has a depth of 1366m and the distance to the shore is 3.6 km. The light transmission properties of the lake water vary greatly depending on the season due to sedimentation due to river in-flow. Typical light absorption lengths are 20m and light scattering lengths 15m. The optical modules are deployed on 8 strings arranged at the edges and centre of an equilateral heptagon supported from above by a rigid frame. The detector is deployed into the water using the platform of frozen surface ice during the winter months.

AMANDA was installed in stages in holes in the glacial ice made with a hot water drilling technique. The first detector elements were deployed in 1993 at depths of 810 to 1000m; however, measurements of the ice transparency at those depths showed that the light scattering was unacceptable for operation of a detector. Subsequent strings were deployed at depths of 1500 to 2000m where the ice properties are better. In 1997 the AMANDA B10 detector had 300 optical modules on 10 strings and the data so far published from AMANDA comes from this detector. Since then extra strings have been added with improved signal readout technology. The present AMANDA II detector has 19 strings and about 700 optical modules. A much large neutrino telescope, ICECUBE, with 4800 optical modules will begin installation at the South Pole site at the beginning of 2005.

In the Mediterranean Sea there are three sites, shown in figure 4, under evaluation for Neutrino Telescopes. A review of the neutrino telescope developments underway at these sites can be found in reference [3]. The most advanced project is that of the ANTARES collaboration which is building a detector with initially 900 optical modules at a site off the south coast of France near Toulon. The NEMO
collaboration is exploring a site off Sicily and developing technology for a future large detector. Since 1990 the ANTARES and NEMO collaborations have been working together on the detector at the Toulon site with the intention to choose the best site for a future larger telescope. The NESTOR collaboration intends to build a detector with 168 optical modules at a site near Pylos off the coast of Greece.

The ANTARES collaboration started in 1996 to develop and construct a detector at a site off the French coast with a depth of 2400m. The first phase of the ANTARES project was to fully evaluate this site in terms of water quality, sedimentation rate and geological stability. The absorption length light at the site was measured to be 45-60 m in the blue and 25-30 m in the ultra-violet, the scattering length for large angle scatters is greater than 100m and the loss of light transmission through the glass housings of the optical modules has been evaluated in measurements lasting 8 months to be less than 2 % / year. Extensive studies of the bioluminescence

FIGURE 4. Sites of the three Neutrino Telescope projects in the Mediterranean Sea.

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rate at the site have been carried out and lead to the conclusion that this background will give an acceptable dead time in the photo-multipliers given the electronics design of the detector.

The design of the ANTARES detector array is to have optical modules suspended on individual mooring lines, with readout via cables connected to the bottom of the lines. This technology is similar to the solution originally chosen by the DUMAND collaboration. As with DUMAND, the ANTARES detector requires connections made on the seabed by underwater vehicles but since in the last 10 years the relevant underwater technology has advanced dramatically due to the needs of the offshore-oil industry, the ANTARES instrumentation is based on industrial products and more reliable. Currently a wide range of suitable deep-sea connectors is available and extensively used in industry, including electro-optical connectors wet mateable on the site. Many commercial underwater vehicles exist capable of making these connections. The ANTARES readout design maximizes the reliability of the detector by dividing the system into independent sections such that there is no single active component in the sea whose failure causes the loss of the whole detector. The detector signals are digitized in local electronics in the sea and than transmitted to the shore on high bandwidth optical links. On the shore, a computer farm makes the trigger decisions to decide which data is recorded to tape. A major aspect of the ANTARES approach is the possibility to recover and repair all elements of the detector deployed in the sea.

The NESTOR detector is planned to be installed in a site 4100m deep. An important concept of the NESTOR project, and a significant difference with ANTARES, is the arrangement of the optical modules on a tower structure with all internal connections made on the surface during deployment so as to avoid the need for submarine connections. The towers have 12 hexagonal floors of 16m in radius with photo-multipliers looking both upward and downward. Test deployments have been performed and many detector elements exist.

POTENTIAL SOURCES FOR NEUTRINO TELESCOPES

High energy neutrino astronomy is in its infancy and as yet no high energy sources have been observed [4]. The neutrino telescopes situated at the South Pole and in the Mediterranean will provide full sky coverage with the Mediterranean site allowing observations of the Galactic Centre. Figure 5 illustrates the sky coverage of neutrino telescopes at these two geographic locations using the assumption that they have full efficiency in the whole lower hemisphere of view. The positions of a number of potential cosmic sources of neutrinos are indicated in this figure and below some predictions of fluxes are described.

Among the major objectives of neutrino astronomy is the search for the origin of cosmic rays. In 2002 a paper [5] appeared from the CANGAROO collaboration using a 3.8m Gamma Ray Telescope located in Australia making the claim of the observation of the acceleration of cosmic ray protons in the supernova remnant RX J1713.7-3946. The observation was of gamma rays up to 10 TeV with an energy spectrum $E^{-2.8}$ where the observed energy spectrum could not be explained only with
\( \pi^0 \) decay from hadronic interactions. The positive observation of TeV gamma rays from this source has recently been confirmed by the HESS collaboration; however with a different energy spectrum [6]. A subsequent paper by J. Alvarez-Muñiz and F. Halzen [7] calculated the expected neutrino flux from this source assuming the integral energy carried in neutrinos was the same as that in gamma rays with a neutrino flux spectrum \( E^{-2} \). The conclusion of this later paper is that a northern hemisphere detector such as ANTARES would observe a few events per year from this source and in a few years of operation would have a clear signal with a probability less than 1\% that the events seen were background from atmospheric neutrinos. It seems likely that other similar supernova remnants are present in the Galaxy hence providing more possibilities for clear observations.

Predictions from supernova remnants with central pulsars: plerions, such are the Crab Nebula give rather low events rates in neutrino telescopes. Rates have been calculated by Bednarek [8] with a model for pulsar wind nebulae in which most of the observed gamma ray emission comes from leptonic processes and hadronic processes only contribute to the high energy part of the spectrum. This model gives around 1 event/year/1km\(^2\) for the Crab Nebula and for the Vela Nebula: negligible rates for detection in ANTARES. Another model by Guetta and Amato [9] assumes that the observed gamma rays with energies above 2 TeV originate from pion decay implying hadronic processes which also give neutrinos. This assumption gives higher event

**FIGURE 5.** Sky coverage of Neutrino Telescopes geographically located at the South Pole and in the Mediterranean Sea. The upper diagrams illustrate the percentage of time the sky region is visible on a shade scale between 0\% for black and 100\% for the lightest shade. The lower diagrams illustrate this sky coverage on a sky map of gamma rays observed by EGRET together with various potential high energy neutrino sources.
rates for neutrino detection up to 10 event/year/1km² for some plerions and so a possibility for detection in ANTARES.

While in the Galaxy there are 220 supernova remnants in the catalogue of Green with about 10% having central pulsars, the rate of supernova explosions in the Galaxy is believed to be 1-3 / 100 years. If chance were to give a galactic supernova explosion during the lifetime of a neutrino telescope the observable signals would be very large. In the initial stages of the supernova the neutrinos are in the MeV energy range giving high rates of uncorrelated counts in the optical modules. These MeV neutrinos will be detectable in ice neutrino telescopes but not in sea water detectors because of the higher optical noise backgrounds. At later stages of the supernova explosion higher energy neutrinos are emitted which could be detectable in all types of neutrino telescopes. Waxman and Loeb [10] predict the rate of TeV neutrinos originating when the shock of a type II supernova breaks out of the envelope of the massive star. This break out occurs about 10 hours after the original explosion and the burst of neutrinos last around 1 hour giving ~100 events/km², a signal easily detectable in any neutrino telescope because of the short time window which would make the background negligible. An energetic pulsar in young supernova remnants can power high energy acceleration of particles and several predictions exist for such processes. For instance, a model by Protheroe et al. [11] where a young pulsar accelerates iron nuclei which photo-disintegrate to produce hadrons and so neutrinos. This model gives high rates of neutrinos but only for a few months after the supernova explosion.

Among other galactic sources with predictions of high observable neutrino rates are microquasars. The rate calculations presented by Distefano et al. [12] are based on model predictions by Levinson and Waxman [13]. This model assumes that inhomogeneities in the microquasar jet can cause internal shocks which accelerate protons and electrons. The maximum proton energy attainable is of the order of 10 PeV in the jet frame and the protons interact with a photon field around the object to produce secondary neutrinos. Using measured properties of several known microquasars and a number of assumptions for the parameters in the model, including a fraction of 10% of the jet energy carried by protons, the rates of neutrinos from two microquasars (GX339-4 and SS433) are high (respectively 183 and 252 events /km²/year) leading to a positive detection in ANTARES in around one year.

A review of neutrino rate predictions from galactic sources has been made by W. Bednarek et al. [14] explaining in more detail the prediction for sources described above together with others. Table 1 gives a summary of the neutrino rate predictions from this paper. The range of numbers for the event rate illustrates the uncertainties and the large variation of the predictions from different models.

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Neutrino events/ km²/yr</th>
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</thead>
<tbody>
<tr>
<td>Supernovae</td>
<td>50-1000</td>
</tr>
<tr>
<td>Plerions</td>
<td>1-10</td>
</tr>
<tr>
<td>Shell SNR</td>
<td>40-100</td>
</tr>
<tr>
<td>Pulsars+Clouds</td>
<td>1-30</td>
</tr>
<tr>
<td>Binary Systems</td>
<td>a few</td>
</tr>
<tr>
<td>Microquasars</td>
<td>1-300</td>
</tr>
</tbody>
</table>
Beyond the local galaxy there are also point sources where the flux of neutrinos could be large enough to be detected by the neutrino telescopes in operation and under construction. The known extragalactic sources of high energy cosmic radiation are AGN’s and GRB’s and in neutrino telescopes individual sources could be observed as discrete point sources. In addition, the integral over all such sources in the universe could give an observable diffuse flux of neutrinos. This later diffuse flux must be distinguished from the background of atmospheric neutrinos by a harder energy spectrum, necessitating a good knowledge of the high energy contributions to the background flux. Predictions of fluxes from individual GRB sources are generally lower than for AGN sources, however coincidences with observations from gamma ray detector in space can be used to vastly reduce the atmospheric neutrino background by searching for events within a short (~second) time window relative to the gamma ray signal.

As well as observations on known sources, it is well possible that neutrino telescopes could discover hitherto unknown sources. The unique penetrating properties of neutrinos allow many speculations; only neutrinos can exit from regions of high matter density which might completely obscure certain objects from observations with other cosmic messengers. Sources observable with TeV gamma rays are limited to distances of tens of kilo parsecs while charged cosmic rays in this energy range do not point to the source. Further, the large acceptance in solid angle of neutrino telescopes opens the possibility to discover close sources, in principle observable with TeV gamma ray telescopes but as yet unobserved due to the narrow angular acceptance and necessary pointing strategy of most gamma ray detectors. The new chance discovery of a TeV gamma source HESS J1303-63 reported at this conference [15] emphasises these possibilities for neutrino telescopes.

**EXISTING RESULTS**

At the present time all observations of high energy neutrinos observed in the past and present generation of neutrino telescopes are consistent with the flux of neutrinos from the atmosphere of the Earth; there is as yet no evidence for high energy neutrinos from extra-terrestrial sources. Figures 6 and 7, from T. Montaruli [16], summarize existing and future limits for neutrino point sources and diffuse fluxes respectively. The measured diffuse fluxes are consistent with the expectations of atmospheric neutrinos based on models using measurement of cosmic ray fluxes.

The existing limits on both point sources and diffuse fluxes both start to test interesting model predictions. The forthcoming neutrino telescopes in the Northern Hemisphere such as ANTARES will be able to probe for source at and close to the centre of the galaxy, a region of the rich in sources of high energy gamma rays. Complementary searches with neutrinos will give conclusive evidence on the nature of the acceleration mechanisms for the gamma ray observations, being able to distinguish between hadronic and leptonic processes.
FIGURE 6. Existing limits, expected limits and some predictions of rates for discrete sources of neutrinos assuming an $E^{-2}$ neutrino flux. The squares are published limits from the MACRO experiment [17]. The lines indicate expected limits from AMANDA II for the 2000-2001 data and for ANTARES after one year of data taking. The inverted triangles are rate predictions for microquasars from Distefano et al. [11].

FIGURE 7. Existing limits, expected limits and some upper limit predictions of rates for a diffuse flux of neutrinos with an $E^{-2}$ spectrum. The points are measured fluxes of atmospheric neutrinos from the AMANDA experiment. The solid lines are measured limits from MACRO, Baikal and AMANDA as indicated with the expectation from ANTARES as a dotted line. The grey lines are predicted limits from Mannheim et al. [18] and Waxman and Bahcall [19].
CONCLUSIONS

The field of neutrino astronomy has made rapid advances in the last decade. Two large neutrino telescopes, AMANDA and Baikal, are operating and publishing results. Both projects are in the process of expanding their detectors, AMANDA with IceCube and Baikal with extra outlier lines. In the deep sea, the three Mediterranean projects have all made very significant progress in recent years and ANTARES and NESTOR will have completed detectors in the next few years. Together with the NEMO group they have combined in the “KM3NET” design project for the next stage towards a km³ Mediterranean Neutrino Telescope.

REFERENCES

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