UNDERWATER-ICE NEUTRINO TELESCOPES

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After answering the questions: why neutrinos and why underwater-ice detectors, we present the physics goals that justify these telescopes. Then, we present the status of the projects and the first results of the running experiments.

1 Why neutrinos?

Most of our current knowledge of the Universe comes from the observation of photons. They have many advantages as cosmic information carriers: they are copiously produced, they are stable and electrically neutral and they are easy to detect over a wide energy range. We can reasonably ask the question: why trying to use neutrinos that are not so easy to detect? Because neutrinos can shed light where photons cannot.

Due to their weak interaction with matter and absence of interaction with the electro-magnetic radiations, neutrinos can travel in the Universe without being absorbed.

Because photons interact with matter, with the infra-red radiation and with the cosmic microwave background, the Universe is opaque for very high energy gammas.

Charged cosmic rays, like protons, are deflected by the galactic and extra-galactic magnetic fields. Therefore, only ultra-high energy protons are straight enough to point back to their sources. However, at these extreme energies protons also suffer from interactions with the infra-red radiation and the cosmological microwave background. These effects limit the proton free path length to about 50 Mpc.

It appears that the unique solution to explore the Universe at high distances and at high energy is to use neutrinos as cosmic information messengers.

2 Why underwater-ice detectors ?

To observe a muonic neutrino, the method is to detect the muon produced by its interaction with the matter surrounding the detector. The detection principle is based on Markov's idea [1].

The νN cross section increases with the neutrino energy and the muon range increases with the muon energy. Therefore, the probability to detect a neutrino pointing toward the detector is an increasing function of the neutrino energy. This means that high energy neutrinos will be statistically enhanced.

When the energy of the neutrino increases, the angle between the direction of this neutrino and the produced muon decreases and the direction of the parent neutrino is well determined.

Despite its increase with the neutrino energy, the νN cross section is small and the detector area must be large enough to provide sufficient sensitivity in any direction. For this reason, a detector's volume of about $1km^3$ is needed.

The main source of background is the neutrino flux coming from cascades initiated by primary cosmic rays in the atmosphere. In addition, the flux of down-going atmospheric muons is about 10 orders of magnitude higher than the flux of muons coming from atmospheric neutrinos. To suppress this high flux, the detector has to be well shielded and only up-going muons have to be considered.

The most economic way to realize such a km-scale well shielded detector is to use natural media and build a 3-D array of optical modules deep in the ocean or in the polar ice.

3 Physics goals

3.1 Astrophysical sources

High energy neutrinos could be generated by leptonic decays of mesons produced in the cascades induced by the interactions of high energy protons or nuclei with matter or electro-magnetic radiation. These protons may come from different astrophysical sources such as, for example:

- galactic sources
  Binary stars with very massive objects like neutron stars or black holes accrete matter from their companion. This process leads to plasma waves in the strong magnetic field of the compact object, and protons rise to high energy by stochastic acceleration. The interactions of these protons with the accreting matter or the companion star will then produce high energy neutrinos.
  In supernovae remnants, protons are accelerated in the expanding shell by the fermi mechanism. These protons interact with the matter of the shell, leading to high energy neutrino production.

- active galactic nuclei (AGNs)
  AGNs are supposed to be black holes with masses of about 10^6 to 10^{10} solar masses sitting in the center of galaxies. This black hole accelerates protons to ultra high energies; their interaction with the radiation

field and the matter surrounding the black hole or in the jets produces neutrinos. Acceleration mechanisms in AGN models is the subject of active debate between theorists. The observation of neutrinos coming from these sources is obviously needed.

- gamma ray bursts (GRBs)
  GRBs have puzzled astronomers since their accidental discovery in the last sixties. They are currently observed at a rate of about one event per day. GRBs are at cosmological distances and release 10^{51-53} ergs in a few seconds making them the most luminous objects in the Universe. In the current standard model of GRBs and their afterglow, the initial event deposits a solar mass in a region with a radius of about 100 km. The resulting fireball expands ultra relativistically into the surrounding medium with a Lorentz factor of the order of 100. A hadronic component is expected in such extreme phenomena. The expected neutrino fluxes are very low, but their observation could be possible by requiring a spatial and temporal coincidence with an observed GRB.

3.2 Dark matter

Neutrinos could also be produced by the annihilation or the decay of elementary heavy particles, such as neutralinos.

In the Minimal SuperSymmetric Model (MSSM), the Lightest Supersymmetric Particle (LSP) is the neutralino. It is a natural candidate to the non baryonic dark matter which might constitute most of the matter of the Universe. The neutralinos might move in the galaxy halo at a few hundred km/s. They lose energy by elastic scattering on nuclei from the Sun, the Earth or the galactic center when crossing them. This can result in a high concentration of neutralinos in these bodies, and this will enhance the neutralino annihilation rate per volume unit. These annihilations will produce enhanced neutrino emission. The corresponding signal consists of an excess of neutrino flux, coming from the Sun, the centre of the Earth or the galactic center, with a typical energy around the neutralino mass.

3.3 Neutrino oscillations

Atmospheric neutrinos are an irreducible background for the study of high energy cosmic neutrinos. However, they can be used for the study of neutrino oscillation with a baseline length up to the order of the diameter of the Earth. SuperKamiokande and MACRO have published evidence for two family neutrino oscillations with the most probable mixing parameters $\Delta m^2 = 3.5.10^{-3} eV^2$

and $sin^2 2\theta = 1$. In this scenario, an atmospheric neutrino experiment sensitive to neutrino energies between 10 and 100 GeV could observe both the disappearance and the re-appearance of muon neutrinos crossing the Earth. This energy range would be available to the new generation of neutrino telescopes.

Many references on papers about all these physics goals can be found in [2]

3.4 Interdisciplinary science

To construct these underwater-ice neutrino detectors, many studies of the medium are performed, leading to interdisciplinary studies. The main concerns are optical, mechanical and thermal properties of the polar ice and deep water environmental studies such as bioluminescence and optical water properties.

4 Telescopes: status and first results

4.1 Detecting neutrinos

High energy muon neutrinos can be detected by observing long-ranged muons produced in charged current neutrino-nucleon interactions in the matter surrounding the detector.

When passing through water or ice, the high energy muons will produce Cherenkov light at an angle $\theta_c = 43°$. This light is detected by the 3-D matrix of optical modules. A precise knowledge of the position of the optical modules and an accurate measurement of the arrival time of the photons allow to reconstruct the axis of the light cone which defines the direction of the muon. The measured amplitudes lead to the determination of the muon energy and an estimate of the neutrino energy.

4.2 DUMAND

The DUMAND (Deep Underwater Muon And Neutrino Detector) project was the first attempt to build an underwater neutrino telescope. It was started in 1975 and was supposed to immerse strings of optical modules at 4000m depth offshore of Hawai island. Technical studies have been performed, that are usefull for the actual projects. DUMAND was decommissioned in 1996.

4.3 BAIKAL

BAIKAL [3] is the first demonstration of feasability for underwater neutrino telescopes. This detector (see fig 1) has been deployed in the Siberian lake Baikal at 1300m depth and 3.6 km away from the shore.

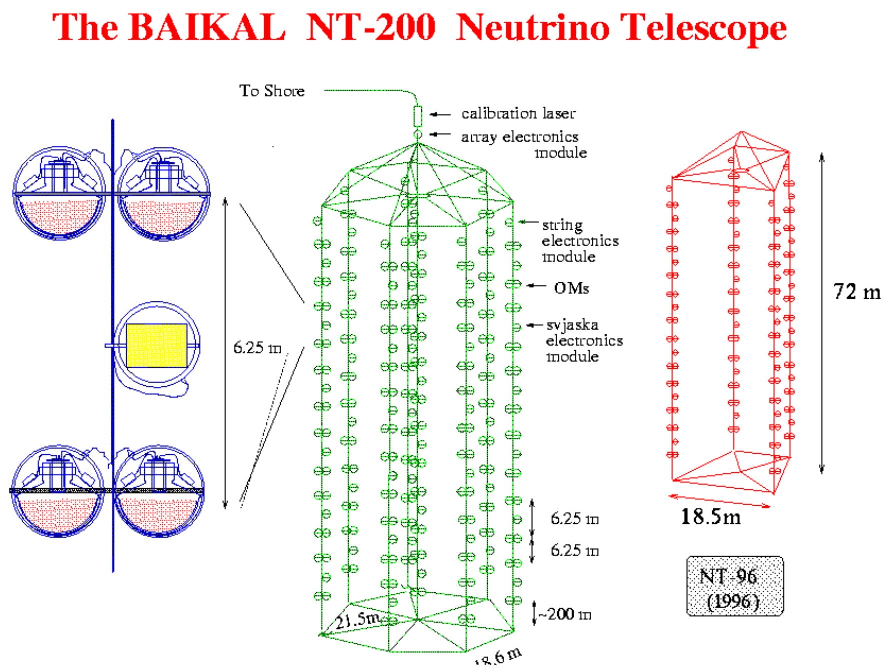


Figure 1: The BAIKAL setup

This Russian-German project is underway since 1981. It uses the thick ice cover of the lake as a platform to deploy instrumented strings in late winter. Via cables to shore, the detector is operated over the full year. Baikal was built in several phases. The two main phases are NT96 and NT200. The first one corresponds to 96 optical modules on four strings deployed in 1996. The last one corresponding to 192 optical modules on 8 strings is operating since 1998.

Using the data taken in 1998 by NT200, the rate (35 neutrino candidates) has been found compatible with the rate (31 Monte-Carlo events) expected for atmospheric neutrinos. Baikal is able to put limits on magnetic monopoles fluxes, comparable with other experiments like Amanda, Macro and Baksan. Baikal is also looking for neutrinos coming from the annihilation of WIMPS and for very high energy neutrinos. The analysis of the data taken since 1998 are still in progress.

Research and developpement activities of Baikal focus now on acoustic detection for very high energy neutrinos, new versions of optical modules and data taking system.

4.4 AMANDA

The AMANDA[4] (Antarctic Muon and Neutrino Detector Array) collaboration consists of institutions from the USA and Europe (Belgium, Germany and Sweden). Amanda uses the Antartic ice as target and Cherenkov medium. Strings are deployed into holes drilled with hot water in the 3 km thick ice sheet of the south pole. Amanda profits from the infrastructure of the Amundsen-Scott station.

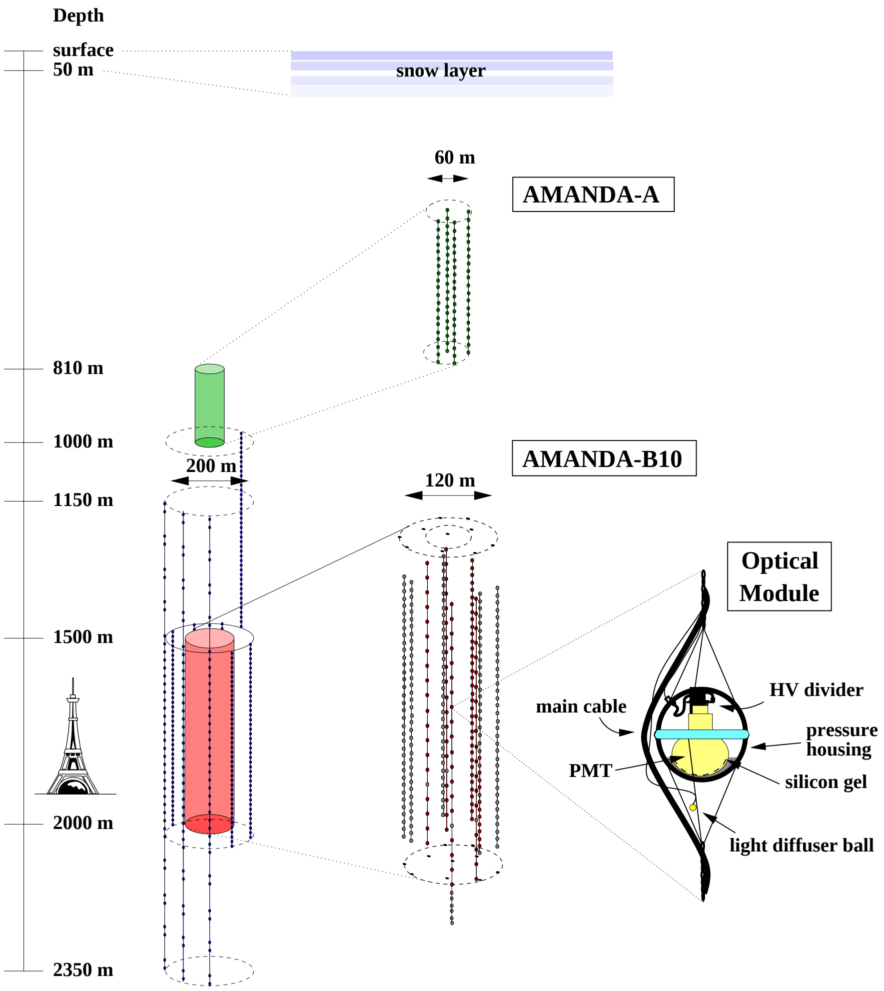
Amanda has been constructed in 3 phases (see fig 2 for a schematic diagram of the detector). AMANDA-A consists of 4 strings holding 80 optical modules (OMs) at depth of 800 to 1000m. The first analysis of data taken by AMANDA-A in 1993-94 showed a high concentration of air bubbles, leading to a strong light-scattering and making an accurate track reconstruction impossible. AMANDA-B was installed deeper in the ice and the bubble density at that depth was shown to be 50 times smaller than for Amanda-A.

AMANDA B consists of 10 strings holding 302 OMs at depth of 1500 to 2000m. The array forms a cylinder of 400m height and 120m diameter. A cable provides the high voltage and transmits the anode current signal of the 8-inch photomultiplier to the data acquisition electronic at the surface. Amanda B is now surrounded by the nine 800m long strings of AMANDA II, holding 677 OMs at depth of 1300 to 2400m. These additional strings, located on an outer ring of 200m diameter, use optic-fiber cables for calibration and for analog signal transmission of the photomultiplier pulses.

The analysis of the data collected by AMANDA-B during 1997 yields 188 atmospheric neutrino candidates after quality cuts. Their zenith angle distribution agrees with expectations based on Monte-Carlo simulations.

Searches for neutrinos from point sources and gamma ray bursts, for magnetic monopoles and for cold dark matter signal from the center of the Earth are in progress and yield limits that begin to impact models.

Now, AMANDA-II is taking data and a proposal exists to construct the Icecube detector which would consist of 4800 OMs to be deployed in 80 strings. Icecube will reach a $1km^2$ effective telescope area.



AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

Figure 2: The AMANDA setup

4.5 ANTARES

ANTARES [5] (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) is a collaboration between France, Italy, Russia, Spain, The Netherlands and UK, including physicists, astronomers and oceanologists. This project aims to construct, deploy and operate a detector about $0.1km^2$ off-shore of Toulon in France at 2400m depth. This location allows a 3.5π coverage of the sky and the survey of the galactic center. The detector (shown on fig. 3) will consist of 10 strings, equipped with about 1000 optical modules containing 10-inch phototubes. The minimum spacing between two strings will be around 60m. Strings will be 450m high, with only the top 350m instrumented. Each string will be equipped with 30 storeys spaced by 12 m and containing 3 OMs each. These three OMs look down at 45° with respect to the vertical. This design ensures a good efficiency for upgoing muons and a marginal acceptance for

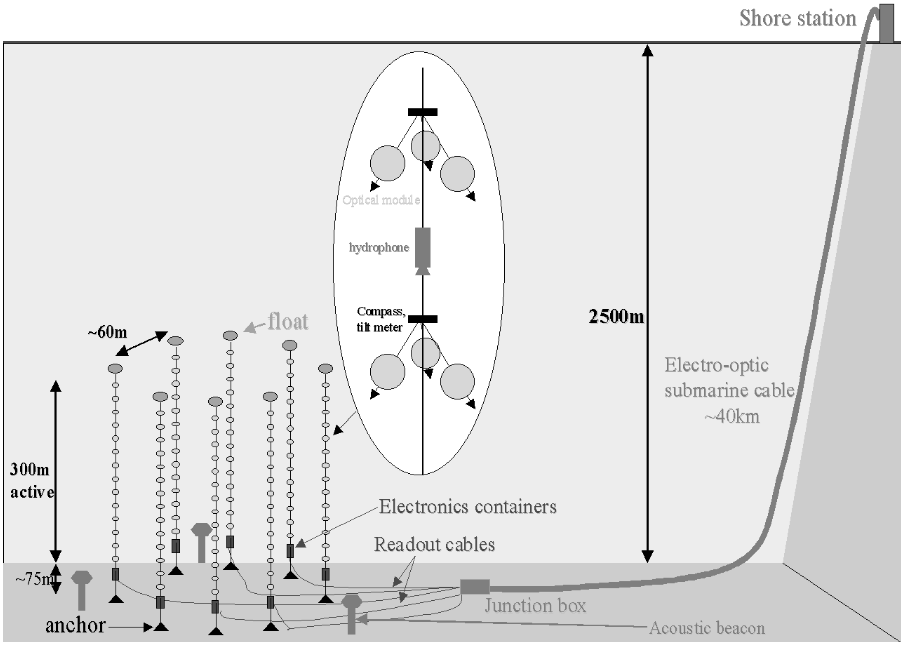


Figure 3: The ANTARES setup

downgoing ones. The strings will be anchored to the sea-bed and kept tout by a buoy at the top; they will be connected to a junction box by a manned submarine. The junction box will be linked to the shore-station via a 40 km long electro-optical cable. The relative positions of all OMs will be provided with an accuracy better than 10cm by acoustic beacons and hydrophones, compass and tiltmeters. The major part of the detector will be deployed in 2003.

To be able to deploy such a detector, deep-sea technologies have to be mastered by the collaboration, and an excellent knowledge of the submarine environment is necessary. To achieve these goals, ANTARES did an extensive program of research and developpement on: electronic, data read-out, power supply, connection to shore, mechanical structure, deployment and recovery procedures, choice of the optical modules, and study of the environmental parameters. This program extended over 4 years and more than 30 deployments have been done during that period. A full prototype structure has been fully deployed; the operation has been repeated to verify the precision of the deployment that was found to be a few meters. A test of submarine connection and disconnection has been successfully performed with the IFREMER's Nautile. The site parameters have been measured in situ with different autonomous systems. The results can be summarized as: absorption length greater than 50m - scattering length larger than 200m for large scattering angles - loss of transparency of the glass spheres due to biofouling less than 2% in one year, thanks to the downward orientation of the OM - ^{40}K optical background around 60 kHz for 10-inch PMTs - dead-time due to bioluminescence less than 5%. These parameters have been used to perform simulations that show that the expected angular resolution is better than 0.4° for $E \geq 5$ TeV. The muon energy is estimated with an accuracy of a facor 3 below 10 TeV and of a factor 2 above 10 TeV.

In November 1999, a demonstrator string has been deployed 37 km off the coast of Marseille at 1200m depth and has been connected to an undersea electro-optical cable. The string has been operated for several months and has been recovered in june 2000. This string had 16 storeys separated by 14.6m and two glass spheres on each storey. Seven of these spheres were instrumented with a PMT. Contrary to the ANTARES detector design, these PMTs were looking horizontaly to increase the sensitivity to downgoing muons. A complete positionning system was present, allowing to test the positionning system of the ANTARES detector. More than 50000 coincidences of the 7 PMTs have been recorded leading to more than 1350 reconstructed events per day. The obtained angular distribution agrees with expectation from atmospheric muon distribution.

The ANTARES R&D program has shown that a submarine neutrino telescope deployed in the Mediterranean sea is a feasible project. The collaboration has moved now into the construction phase.

4.6 NESTOR

The NESTOR[6] (Neutrino Extended Submarine Telescope with Oceanographic Research) project is a Germany-Greece-Italy-Russia-Switzerland-USA collaboration. The NESTOR project foresees to deploy in the Ionian see, off-shore of Pylos in Greece, at 3800m depth, a tower made of 12 hexagonal stars with 16m long arms. The distance between the stars will be 30m. Each star will be equipped with 7 pairs of optical modules: one pair at each arm and one pair at the center of the star. Each pair consisting of two OM placed back to back, the detector is fully symmetric. The tower will be connected to the shore with an electro-optical cable.

The collaboration has performed in situ measurements, showing that the transmission length in the blue part of the spectrun is about 55m. The underwater currents have been measured over many years and have been found to be minimal. i.e. a few cm per second. The sedimentology analysis is also performed.

All the phototubes (15-inch) and glass spheres necessary to the detector are available. The shore station is operational. Five stars are available: 2 in titanium and 3 in aluminium.

The estimated effective area for a full tower is $2000m^2$ for muons above 10 TeV.

4.7 NEMO

The NEMO[7] project is aimed to identify the best site to install a km^3 detector in the Mediterranean sea. A programme of measurements of the water parameters has already started off-shore of Sicily and of the Ponza Island in Italy. First results have already been obtained, for example on water transparency, sedimentation and biofouling.

5 Conclusions

The detection of high energy cosmic neutrinos is a great experimental challenge. A broad field of physics is offered to the running and future experiments, and correlations with other probes will yield interesting observations. The projects in construction and the already running experiments demonstrate the feasibility of such detectors. They will certainly provide the first encouraging physical results and show the way toward km^3 detectors.

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