High Energy Neutrino Telescopes in the Northern Hemisphere

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Abstract

We review the status and results of the high energy neutrino telescopes in the Northern Hemisphere, namely ANTARES and Baikal (NT200+). After a brief introduction to Neutrino Astronomy, we describe these telescopes in their past and present configurations and report briefly on the results obtained in several areas, such as the search for high energy cosmic neutrino diffuse fluxes and point sources, the indirect search for dark matter, the multimessenger studies and the search for exotic particles, such as monopoles and nuclearites.

Keywords: Neutrino Telescopes, Neutrino Astronomy, High Energy Astrophysics
PACS: 95.55.Vj, 95.85Ry, 96.50 Pw

1. Introduction

The detection of high energy cosmic neutrinos can help solve the problem of the origin of high energy cosmic rays and be a new tool to elucidate the mechanisms of hadronic acceleration in astrophysical objects. In the low energy domain (few MeV to several GeV) the observation of extraterrestrial and atmospheric neutrinos gave rise to the discovery of neutrino oscillations and to one of the most direct experimental tests of our models of supernova explosions. In the high energy regime (several GeV to EeV), neutrinos have several advantages as cosmic messengers and can provide information on the particle acceleration mechanisms in the Universe. Experimental methods to detect them exist and have been technologically proven. The major challenge in the field of Neutrino Astronomy is at present to reach a sensitivity high enough to detect the first cosmic neutrino sources.

Let us briefly summarize the advantages of neutrinos as cosmic messengers. They are neutral particles, therefore they are not deflected by magnetic fields and point back to their sources. They are weakly interacting and thus can escape from very dense astrophysical objects and travel long distances without being absorbed by matter or background radiation. Moreover, in cosmic sites where hadrons are accelerated, it is likely that neutrinos are generated in the decay of charged pions produced in the interaction of those hadrons with the surrounding matter or radiation, being therefore a smoking gun of hadronic acceleration mechanisms.

The observation of neutrinos in a Cherenkov neutrino telescope is based on the detection of the muons produced by the neutrino charged current interactions with the matter surrounding the telescope by means of the Cherenkov light induced by the muons when crossing the detector medium, natural ice or water. Cascades produced in charged or neutral current interactions of neutrinos inside or nearby the detector can also be detected.

A typical neutrino telescope consists of a three dimensional array of light sensors, photomultipliers (PMTs), that record the position and time of the emitted Cherenkov photons, enabling the reconstruction of the muon track or the cascade. To avoid the huge background of muons produced by cosmic ray showers in the atmosphere, the telescopes look at the other side of the Earth, i.e. they use it as a shield against the muons produced in normal atmospheric showers. The increase in the range of muons in the rock at high energies (from kilometres to several kilometres) together with the increase of the neutrino cross section gives rise to an approximately exponential increase of the effective areas of these devices in the GeV to PeV energy range. Above a few TeV the telescopes can determine the direction of the incoming neutrinos with angular resolutions better than $1°$, hence the name "telescope". At energies above the PeV, the Earth becomes opaque to neutrinos, but the atmospheric muon flux decreases dramatically so that the neutrino telescopes can look for downgoing neutrinos. Other neutrino flavours can be observed through the detection of hadronic or electromagnetic showers or, in the case of tau neutrinos, via the observation of its interaction and the subsequent decay of the produced tau lepton.

The first attempt to build a neutrino telescope in natural water, namely the DUMAND project, dates back to the 60's [1]. DUMAND paved the way for subsequent projects. NT200 in Lake Baikal and then ANTARES in the Mediterranean Sea benefited from the experience of DUMAND.

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We will cover in this article these two last experiments which are the first underwater neutrino telescopes ever built.

The first efforts to install a neutrino telescope in Lake Baikal started in the 80's [2]. After some site tests, the first single string arrays were operated between 1984 and 1990. Already since 1987 the construction of a telescope with 200 PMTs was envisaged. Between 1993 and 1994, the so-called NT-36 version of this telescope with 36 PMTs was operated. Since then the detector has been growing gradually: NT-72 (1995-1996), NT-96 (1996-1997), NT-144 (1997-1998) and NT-200 (since 1998). In 2005 three outer strings were added to form the so-called NT-200+.

The Baikal neutrino telescope NT-200 is located in Lake Baikal at a latitude of around 52° North [3]. The detector is around 3.6 km from the shore and at a depth between 1115 m and 1185 m. The NT200 configuration is composed of 8 strings that are held by an umbrella shaped mechanical structure (see Fig. 1). Each string has 24 optical modules (OMs) arranged in pairs adding up to a total of 192 OMs. Each OM contains a 37-cm diameter QUASAR photomultiplier [4] specifically designed for this detector. The two photomultipliers (PMTs) of a pair are operated in coincidence in order to supress background from bioluminiscence and PMT noise. The upgraded version NT200+ includes three new lines that surround the old NT200 detector and are located at 100 m from its centre, thereby increasing its sensitivity by a factor four for very high energy cosmic neutrinos.

The ANTARES neutrino telescope is located 40 km offshore from Toulon at 2475 m depth at a latitude around 43° North [5]. It consists of 12 mooring lines anchored to the sea bed and held taut by means of buoys (see Fig. 2).
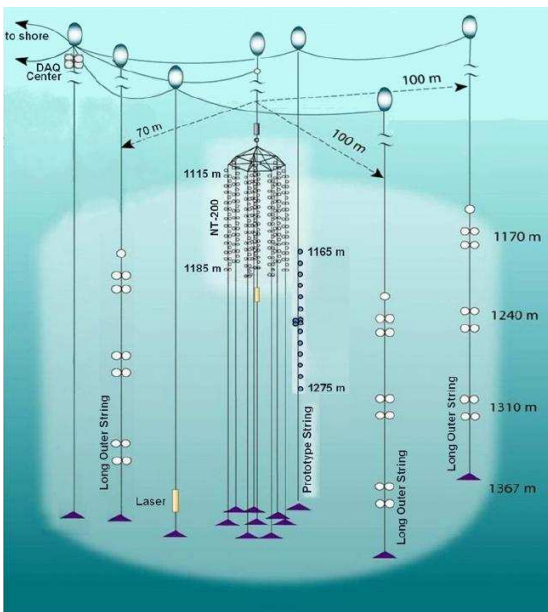

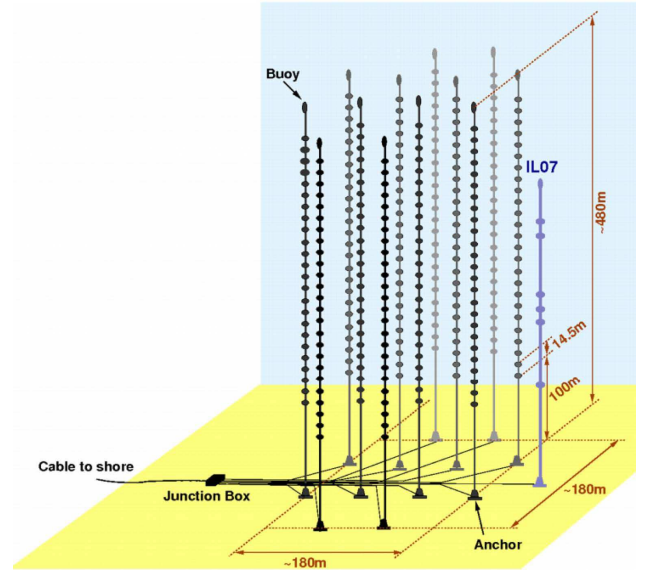Figure 1: Schematic view of the Baikal Neutrino Telescope

Figure 2: Schematic view of the Antares Neutrino Telescope

Each line contains 25 storeys. The lowest storey is 100 m above the sea bed and the vertical distance between consecutive storeys is 14.5 m. The total line length is 480 m. Each storey has a triplet of OMs and an electronics module. The OMs contain a 10-inch photomultiplier looking 45° downwards [6, 7]. In addition, several optical beacons [8] are distributed throughout the lines for calibration purposes [9]. The horizontal separation between lines is between 60 and 80 m. Each line is connected to a junction box by means of interlink cables and the junction box is connected to the shore by the main electro-optical cable.

The ANTARES initiative started in 1998 and after a period of site evaluation, detector design, tests and construction, the first line was deployed in 2006. The detector was operated with 5-lines during several months in 2007 and was fully deployed in 2008. Taking advantage of the possibility of detector maintenance offered by water, the ANTARES collaboration has recovered and repaired some of the lines and fixed problems in some of the detector's interlink cables.

2. Search for a diffuse flux of cosmic neutrinos

The term diffuse flux refers to the search of cosmic neutrinos without requiring precise directional information. An excess over the expected atmospheric neutrino background is looked for and if none is found limits are customarily set on the normalization of signal fluxes with energy spectra of the type E^{-2}.

The Baikal collaboration has performed several searches for diffuse fluxes of cosmic neutrinos [10–12]. They looked for cascades produced both in charged and neutral current interactions of neutrinos in the medium surrounding the detector. Initial cuts were applied to the energy

of the reconstructed cascades in order to select neutrino events. The number of upward going cascades detected agrees with those expected from background. A cut on energy of 10 TeV and 130 TeV for upgoing and downgoing cascades, respectively, was then introduced to select the final neutrino signal. No events were observed for an expected background of around 2 events. From this lack of signal an upper limit of $E^{-2}\Phi < 2 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} was set for the flux of all flavours of neutrinos of cosmic origin in the energy interval 20 TeV $< E_\nu <$ 20 PeV. As usual, a flavour ratio $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ was assumed.

Using the data collected by ANTARES during the period from December 2007 to December 2009, corresponding to a total live time of 334 days with different detector configurations (9, 10 and 12 lines), a search for a diffuse flux of astrophysical muon neutrinos was performed [13]. In addition to the cuts on the quality of the reconstructed track and on the number of hits, an energy cut was also applied. A novel technique based on the repetition rate of photoelectrons on a given PMT averaged over all the PMTs was used. This variable is a good proxy of the energy of the track and is well described by the Monte Carlo simulation. After unblinding of the data, the number of events above the optimized cut in repetition rate was found to agree with background expectations. From the compatibility of the observed number of events with the expected background and assuming an E^{-2} flux spectrum for the signal, a 90% C.L. upper limit on the $\nu_\mu + \bar{\nu}_\mu$ diffuse flux of $E^2\Phi < 5.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} in the energy range 20 TeV to 2.5 PeV was obtained.

The 90% C.L. upper limits on a diffuse flux of muon neutrinos (plus antineutrinos) from several experiments [14] are given in Fig. 3. The original limits given by BAIKAL NT-200 and Amanda-II UHE are for all flavours and are divided by 3 in this plot for the sake of comparison. The recent limit on the diffuse flux of astrophysical ν_μ from the IceCube experiment, $E^2\Phi < 8.9 \times 10^{-9}$ GeV cm^{-2} s^{-1} [15], is not shown in this figure. The grey band represents the expected variation of the atmospheric ν_μ flux: the minimum is the Bartol flux from the vertical direction and the maximum is the Bartol+RQPM flux from the horizontal direction. The central line is averaged over all directions. The phenomenological upper bounds of W&B and MPR [16] are also given, dividing by 2 the original values in order to take into account neutrino oscillations.

3. Search for point-like sources

A search for point sources was performed by ANTARES using the data taken from 2007 to 2010. After the selection of data runs requiring that most of the detector was operating and that the optical background from bioluminiscence was low, the final data sample amounted to a total of 813 live days. Only events with upgoing muons were kept for further analysis, requiring in addition that the corresponding track had a good reconstruction quality and an estimated angular error lower than 1°. The cut in quality
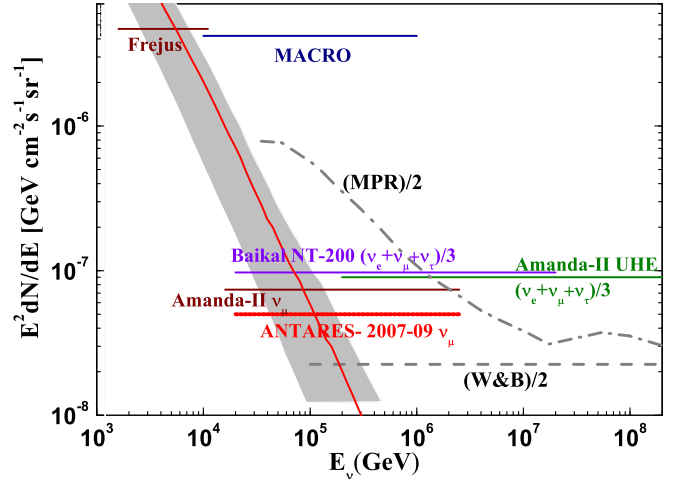

Figure 3: 90% C.L. upper limits for an E^{-2} high energy cosmic neutrino diffuse flux from several experiments(see text for explanations).

was chosen so as to optimize the discovery potential. A total of 3058 events were selected. According to Monte Carlo simulations around 15% of them were atmospheric muons wrongly reconstructed as upgoing tracks.

Clusters of events with a large enough significance above that expected from background fluctuations were looked for with a likelihood ratio method. The likelihood used the distribution in declination of the atmospheric background obtained by scrambling the data in right ascension and an angular resolution of $(0.46 \pm 0.15)°$, as given by Monte Carlo simulation. The full sky was searched for possible sources and then a list of 51 pre-selected directions in the sky corresponding to possible astrophysical neutrino sources were scrutinized. No significant excess was found in either case. An alternative search method [17] was used as a cross-check obtaining similar results.

In Fig. 4 the direction in Galactic coordinates of all the selected tracks are shown as (blue) dots. The hue of the yellow background of the figure indicates the percentage of visibility of the corresponding region of the sky, white corresponds to no visibility and dark yellow to 100%.

The most significant cluster in the full-sky search was found at $\alpha = -46.5°$ and $\delta = -65.0°$ and is indicated in Fig. 4 by a (red) ellipse. The post-trial p-value for this cluster was 2.5%, a value not significant enough to claim a signal.

The (red) stars in the figure correspond to the sky position of the 51 pre-selected sources for which the dedicated candidate search was carried out. The most significant source of the predefined list (HESS J1023-575) was fully compatible with a background fluctuation (p=41%). The corresponding limits for neutrino sources emitting with an E^{-2} energy spectrum are given in Fig. 5. This limit is 2.5 times better than the one previously published [19]. Limits from other experiments are also given [18]. As can be seen, these results are at present the most stringent for the Southern Sky, except for the case of the IceCube detector for which in this hemisphere very high energy neutrinos
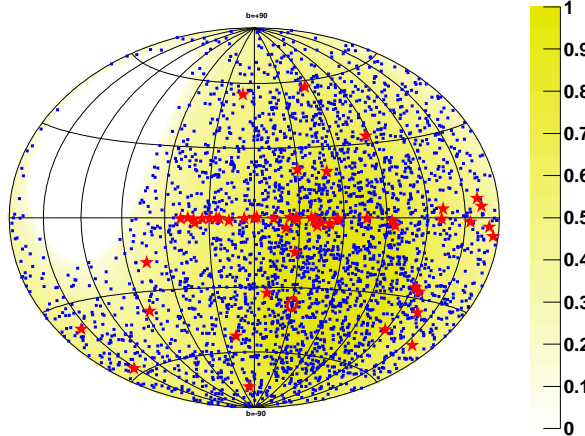
Figure 4: Skymap in Galactic coordinates. The grade in the hue of the (yellow) background indicates the visibility of the corresponding region according to the scale on the right (white: 0%; darkest yellow: 100%). Blue dots: position in the sky of the 3058 selected neutrinos candidates. Red stars: position of the 51 pre-selected sources. Red ellipse: the most significant cluster of events.

Figure 5: 90% C.L. upper limits for a neutrino flux with an E^{-2} spectrum for 51 candidates sources (blue points) and the corresponding sensitivity (dashed blue curve). Results from the MACRO, Amanda II, Super Kamiokande and IceCube telescopes [18] are also shown.

can be looked for (E> 1 PeV). Note that, even though neutrino sources in the Galaxy with a UHE component are not discarded [20], for the more plausible Galactic neutrino sources (e.g. young SNRs) most of the neutrino signal is expected to lie below a few hundred TeV [21, 22].

4. Multimessenger searches

The search of neutrinos in coincidence with other messengers has several advantages. Sources already known to have high-energy emission, e.g. gamma-rays, can be investigated, increasing the chance to observe sites of hadronic acceleration. In addition, the restriction of the search to limited time windows and sky directions highly reduces the atmospheric neutrino background and therefore increases the sensitivity to possible signals, so that a handful of events can be enough to claim a signal. In the case of neutrino events coincident with gravitational waves, the same astrophysical phenomena are expected to produce both types of signals. We give below a couple of examples of the multimessenger program, which is too broad to be fully reported here.

A selection of flares from blazars observed by the LAT detector of the Fermi satellite during 2008 was carried out and the data taken by ANTARES in the same period was investigated for neutrino coincidences with the flaring period of the blazars [23]. The selected blazars are shown in Table 1 together with the number of events required to claim a 5σ signal. Only one event –during a flare of 3C279– was detected. The post-trial p-value of such a coincidence is 10%, compatible with a background fluctuation. The 90% C.L. limits on the neutrino fluence from these blazars
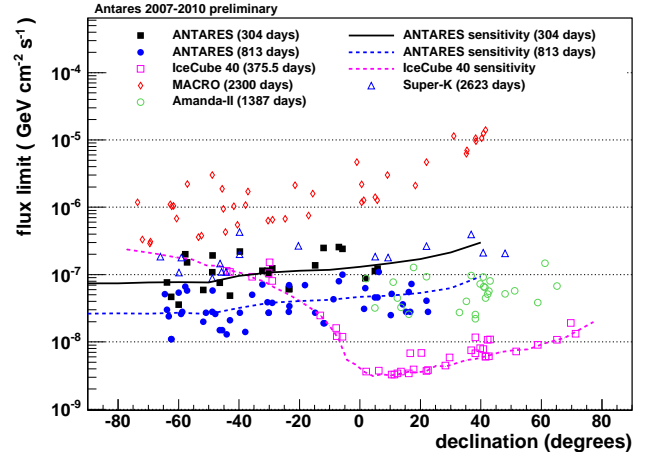
are given in Table 1 for the 100 GeV to 1 PeV region and assuming an E^{-2} spectrum.

Source	N(5σ)	Fluence
PKS0208-512	4.5	2.8
AO0235+164	4.3	18.7
PKS1510-089	3.8	2.8
3C273	2.5	1.1
3C279	5.0	8.2
3C454.3	4.4	23.5
OJ287	3.9	3.4
PKS0454-234	3.3	2.9
WComae	3.8	3.6
PKS2155-304	3.7	1.6

Table 1: List of blazars for which neutrinos were looked for in coincidence with their flares. $N(5\sigma)$ is the average number of events required for a 5σ discovery (50% probability) and *Fluence* is the upper limit (90% C.L.) on the neutrino fluence in GeV·cm^{-2}.

Several models predict the production of high energy neutrinos during gamma-ray bursts. As in the previous analysis, restricting the search to a short time window sizeably reduces the atmospheric background so that only a few events would be enough to claim a discovery. Using the 2007 ANTARES data, a search for neutrinos coming from 40 GRBs events was performed. No neutrino event was found in the corresponding time windows and within the defined search cone around each source. The limits obtained from this lack of signal are shown in Fig. 6, where the 90% C.L. limits on the total fluence of the 40 GRBs are shown as a function of the neutrino energy for three different energy spectra.

The Baikal collaboration has also performed a search for neutrinos associated to 303 GRBs alerts provided by
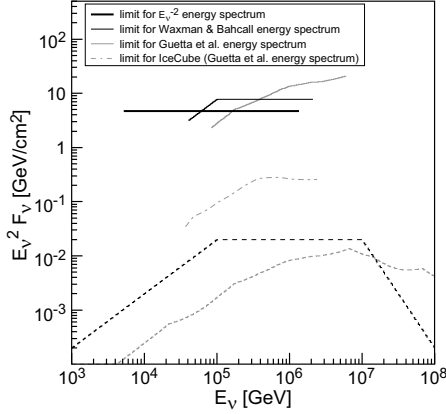
Figure 6: 90% C.L. limits on the total muon neutrino fluence from the selected 40 GRBs as a function of the neutrino energy for three different energy spectra: E^{-2} (thick solid line), Waxman and Bahcall GRB model [24] and Guetta et al. [25]. The black dashed line is the expected neutrino fluence for 40 GRBs with the Waxman and Bahcall energy spectrum and the grey dashed line is the sum of the 40 expected individual GRB fluences according to Guetta et al. The total prompt emission duration of the 40 GRBs is 2114 s. The grey dash–dotted line is the 90% C.L. limit set by IceCube using 117 GRBs [26].

the BATSE detector from 1998 to 2000 [27]. From the absence of neutrino events in coincidence with the GRBs a 90% C.L. limit on the neutrino flux of $E^{-2}\Phi_\nu < 1.1 \times 10^{-6}$ GeV cm^{-2} s^{-1} was set for a Waxman and Bahcall–type energy spectrum [24].

5. Indirect search for dark matter

If dark matter is made up of weakly interacting massive particles (WIMPs), some of these will slow down by elastic scattering and end up gravitationally trapped in heavy astrophysical objects such as the centre of the Galaxy, the Sun or the Earth. They will then self-annihilate and high energy neutrinos will be emitted in the decay chain of their products.

ANTARES is analysing the data taken during 2007 and 2008, a total live time of around 300 days, looking for high energy neutrinos coming from the Sun. The analysis is based on the optimization of the cuts based on the re-construction quality of the muon tracks and the size of the half-cone angle around the Sun direction to select neutrino candidates. The sensitivity, i.e. the expected average 90% C.L. upper limit, for the muon flux coming from the Sun is shown in Fig. 7 for the CMSSM framework. As expected the more stringent limits will come from the hard channels, i.e those that produce W^+W^- or $\tau^+\tau^-$ in the annihilation process.

Using the data recorded during the period 1998–2002, a total of 1007 live days, the Baikal collaboration was able to set a 90% C.L. upper limit of $\Phi < 3\times10^3$ km^{-2} yr^{-1} on an excess in the muon flux coming from the Sun for neutralino masses larger than 100 GeV [32]. Similarly using a total
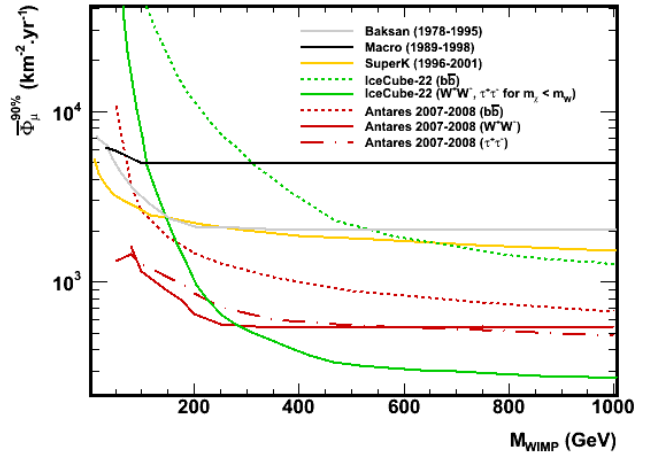

Figure 7: ANTARES 90% sensitivity on the muon flux as a function of the WIMP mass using the 2007-2008 data. Also shown are the 90% C.L. limits on the same flux set by different experiments: with Baksan [28], Macro [29], SuperKamiokande [30], and IceCube-22 [31] for the $b\bar{b}$ and W^+W^- channels).

of 1038 live days, the corresponding 90 % C.L. upper limit for a flux coming from the Earth's core was found to be $\Phi < 1.2 \times 10^3$ km^{-2} yr^{-1} for neutralino masses greater than 100 GeV.

6. Search for exotic particles

The existence of monopoles has been put forward in the context of several theories. To date there is no clear evidence of their existence and several limits have been set on the flux of monopoles crossing the Earth.

Relativistic monopoles with masses above 10^7 GeV can cross the Earth and leave a conspicuous signal in neutrino telescopes. Magnetic charges crossing water at a speed larger than their Cherenkov threshold ($\beta > 0.74$ in water) would produce a huge amount of light. For one unit of magnetic charge this radiation would be 8550 times larger than that of a muon. Moreover, even below the threshold, for $\beta > 0.52$, the high energetic ionization electrons (δ-rays) produced by the monopole would also radiate a large amount of light.

The Baikal collaboration used the data taken between April 1998 and February 2003, which includes the NT36, NT96 and NT200 configurations, to perform a search for relativistic monopoles [33]. Events were selected on the basis of a high number of hits and good reconstruction quality as determined by a χ^2 test. Only upgoing tracks (zenith angle greater than $100°$) were kept. A cut on the radial distance depending on the exact detector configuration was also applied. No candidate was found when simulations indicated that around 4 background events were expected. The 90 % C.L. limits on the flux obtained from this negative result are shown in Fig. 8.
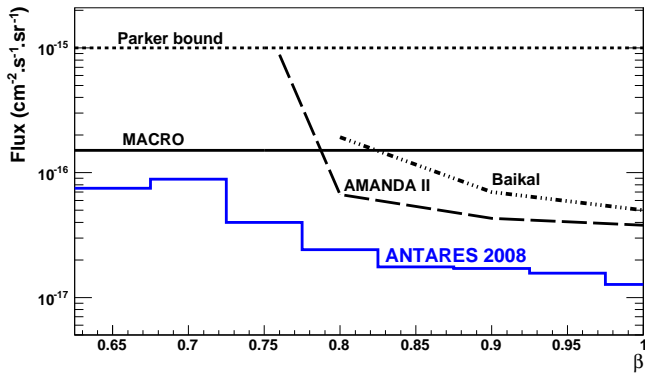
Figure 8: 90% C.L. upper limit on a flux of magnetic monopoles set by the ANTARES [34], Amanda II [35], Baikal [33] and MACRO [36] are also shown.

Using the data taken during 2007 and 2008, ANTARES performed a search for magnetic monopoles based also on the quality of the track and the number of hits as well as on the track reconstructed velocity, β. A special reconstruction was performed in which the β of the particle was a free parameter and the χ^2 values for the hypotheses of β equal or different from one were compared. The selection criteria were optimized for discovery in eight velocity intervals in the region $0.625 \leq \beta \leq 0.995$. Only one candidate was found, compatible with the total expected background. In Fig. 8 the 90% C.L. upper limit on the flux of upgoing monopoles obtained is shown [34]. As can be seen, this limit is more stringent than the previous existing limits [35, 36].

A search for nuclearites, massive aggregates of up, down and strange quarks, has also been performed by ANTARES. Nuclearites would produce in water a thermal shock wave emitting a large amount of radiation at visible wavelengths. No clear indication of nuclearites was observed using the 2007-2008 data sample and a 90% C.L. upper limit of 10^{-16} cm^{-2} sr^{-1} s^{-1} for a flux of nuclearites with masses between 10^{-14} and 10^{-17} GeV was established.

7. Summary

The underwater neutrino telescopes ANTARES and NT-200 not only have shown the technical and scientific feasibility of this sort of devices in sea and lake waters, but have also produced interesting limits in the search of cosmic neutrino sources, dark matter and exotic particles. They are the precursors of much larger telescopes that will be operating in the coming years.

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