Recent Results from the Antares Deep-sea Neutrino Telescope

AART HEIJBOER\textsuperscript{1}, ANTARES COLLABORATION
\textsuperscript{1}Nikhef, Amsterdam
aart.heijboer@nikhef.nl

Abstract:
The Antares observatory is currently the largest neutrino telescope in the Northern Hemisphere. Located at a depth of 2.5 km in the Mediterranean Sea, it aims to detect high energy neutrinos that are expected from cosmic ray acceleration sites. The status of the experiment will be discussed, including a broad target-of-opportunity program. The latest results will be presented, including searches for a diffuse high-energy cosmic neutrino flux, neutrinos from Gamma Ray Bursts, and for (galactic) point-like sources.

Keywords: Antares, neutrino

1 The Antares Neutrino Detector

Cosmic Rays are thought to originate in Galactic and extra-Galactic sources that accelerate protons and other nuclei up to high energies. Identification of the responsible objects could be achieved by detecting the distinct signatures of these cosmic accelerators, which are high energy neutrinos and gamma rays produced through hadronic interactions with ambient gas or photoproduction on intense photon fields near the source. While gamma rays can be produced also by directly accelerated electrons, the detection of high-energy neutrinos from these objects would provide unambiguous and unique information on the sites of the cosmic accelerators and hadronic nature of the accelerated particles.

The ANTARES Collaboration has constructed a neutrino telescope [1] at a depth of about 2475 meters deep, offshore Toulon, France. Neutrinos are detected by Photomultiplier tubes (PMTs), housed in pressure resistant glass spheres, which are regularly arranged on 12 detection lines. Each line accommodates up to 25 triplets of PMTs, located between 100 and 350 m above the sea bed. The lines are connected to the shore via a central junction box and a single, 40 km electro-optical cable, which provides both power and an optical data link. On shore, a computer farm runs a set of trigger algorithms to identify events containing Cherenkov light from high energy muons within the data stream, which otherwise consists mostly of signals from radioactive decay and bioluminescence. The selected events are stored for offline reconstruction. In 2007, the first 5 detector lines became operational, followed, in May 2008, by the completion of the full 12-line detector.

The reconstruction of muon tracks is based on the arrival time of the Cherenkov photons on the PMTs. For high energy neutrinos, the angular resolution is determined by the timing accuracy, which is limited by the transit time spread of the PMTs (1.3ns). Time calibration is performed by a number of independent systems, including LED and laser beacons [2] located throughout the detector. The relative inter-line timing has been calibrated using the time residuals measured in a large number of down-going reconstructed muon events, in addition to the optical beacon systems. The positions of the PMTs vary with time because of the sea currents. Using an acoustic positioning system, combined with information from internal compasses and tiltmeters, the positions of the PMTs are determined every 2 minutes with an accuracy of $\sim 10$ cm.

Most of the analyses described here use a muon track reconstruction algorithm (based on [3]) that consists of multiple fitting steps. The final step is based on a full likelihood description of the arrival times of the detected Cherenkov photons, which also accounts for background light. The achieved angular resolution is, by necessity, determined from simulations. However, several aspects of the simulations were confronted with data in order to constrain the possible systematic effects in the timing resolution that would result in a deteriorated angular resolution. The angular resolution (i.e. the median angle between the neutrino and the reconstructed muon) was found to be $0.4 \pm 0.1$ (sys) degrees for the detector with all 12 lines operational. Studies of the detector and the optical water properties [4] are ongoing and may help to further improve and constrain the angular resolution in the near future. Moreover, a study to observe the shadow of the moon using down-going muons...
might in the future provide additional information on the (absolute) pointing accuracy [19].

In the following, a selection of results recently obtained by the Antares experiment will be summarized; many of them are discussed in more detail in dedicated contributions to this conference.

2 Searches for high energy cosmic sources

Searches for cosmic neutrinos and their sources comprise a main goal of the Antares experiment. Various searches for high energy cosmic neutrinos have been performed using the first years of data.

2.1 Search for a diffuse neutrino flux

A search for a diffuse cosmic neutrino flux has been conducted using 334 live-days of data collected in 2008 and 2009 [5]. Such a flux results in an excess of high energy events over the irreducible background of atmospheric neutrinos. A measure of the energy is provided by an observable $R$, which measures the number of PMTs that detect multiple photons separated in time. The distribution of the $R$ variable agrees well with the background-only simulations and shows no evidence for a contribution from a cosmic diffuse $E^{-2}$ flux, which would result in an excess of high-$R$ events. Consequently, a 90% C.L. limit on such a flux is obtained in the energy range $20 \text{ TeV} - 2.5 \text{ PeV}$. The limit is shown in figure 1 together with previously published limits from other experiments.

2.2 Point source search

Cosmic point-like source of neutrinos have been searched for using 813 live-days of data from 2007 up to and including 2010 [17]. An earlier version of the analysis is described in [18]. Event selection criteria have been applied which optimize both the sensitivity and the discovery potential. Events are required to be reconstructed as upward-going and to have a good reconstruction quality, quantified by a variable based on the reduced log-likelihood of the track fit, and an angular error estimate better than $1^\circ$.

The resulting event sample consists of 3058 neutrino candidates, of which $\sim 84(16)\%$ is expected to be atmospheric neutrinos (muons misreconstructed as upward-going). To search for point sources, the analysis uses an unbinned maximum likelihood method, which exploits the knowledge on the angular resolution$^1$ of $0.5^\circ$ and the rate of background events as a function of the declination.

Two different versions of the search were conducted: in the 'full-sky' search, the full visible sky is searched for point sources. In the 'candidate search', neutrinos are searched for only in the direction of 24 a-priori selected candidate source-locations, corresponding to known gamma ray objects of interest. Neither search yields a significant excess of events over the background: the post-trial $p$-values are 2.5% (for a cluster of events at $\alpha, \delta = (-46.5^\circ, -65.0^\circ)$ for the full sky search and 41% for the most signal-like source in the candidate source list (HESS J1023-575).

Limits have been extracted on the intensity$^2$ of an assumed $E^{-2}$ neutrino flux from the candidate sources. They are shown in Figure 2. The limit computation is based on a large number of generated pseudo experiments in which systematic uncertainties on the angular resolution and acceptance are taken into account.

These limits are more stringent than those from previous experiments in the Northern hemisphere (also indicated in the figure) and competitive with those set by the IceCube observatory [8] for declinations $< -30^\circ$. The various experiments are sensitive in different energy ranges, even though they all set limits on $E^{-2}$ spectra. For this spectrum, ANTARES detects most events at energies in a broad range around 10 TeV, which is a relevant energy range for several galactic source candidates.

An independent point source analysis was performed using a different search method based on the 'EM-algorithm' [9]. This cross-check yielded similar results as the likelihood based analysis described above.

The sample of neutrino candidates from the previous search [18] has been used for additional studies, which are also reported on at this conference:

1. Since part of the data in this analysis was taken by a 5-line detector, the resolution is slightly worse than the 0.4° mentioned earlier for the full detector.
2. The limits are on $\phi$, which is defined by the following expression for the neutrino flux: $dN/dE = \phi \times (E/\text{GeV})^{-2} \text{ GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$. 

---

Vol. 4, 227
3 Multi-messenger Astronomy

Several analyses are performed in ANTARES, which focus on coincident measurement of neutrinos with a variety of external measurements. A selection is described below.

3.1 Neutrinos from flaring blazars

In addition to the time-integrated searches described above, a time-dependent point source search has been conducted to look for neutrinos in correlation to the variable gamma-ray emission from blazars measured by the LAT instrument on-board the Fermi satellite. By restricting the search to the ‘high state’ (typically 1-20 days) of the gamma emission, the background is reduced compared to the time-integrated point source search. An analysis using 60 days of live time collected during 2008 is presented in [11]; no significant excess above the expected background was observed.

3.2 Neutrinos from GRBs

Various models predict high energy neutrinos to be emitted by Gamma Ray Burst events. Restricting the neutrino search to the duration (i.e. T$_{90}$) of the GRB virtually eliminates all background events. Hence, the detection of only a few events could already constitute a discovery. Two such searches [12] have been performed. The first uses the muon-neutrino channel, exploiting the good angular resolution of the detector to demand directional correlation in addition to the time. This search has so far been performed using 37 GRBs and ANTARES data from 2007 (5 detector lines). No neutrino events were found in the a-priori-defined search cone and limits on the neutrino flux were obtained; see figure 3.

The second search is ongoing and searches for ‘shower’ events, which are the result of a localized energy deposition in the detector. These events can be produced by e.g. electron neutrinos which produce an electromagnetic shower, or by neutral current interactions of all neutrino flavours. A reconstruction algorithm for these events has been developed. The sensitivity of this analysis to GRB neutrinos of all flavours is presented in [12].

3.3 Optical follow-up of ANTARES events.

To search for transient sources of neutrinos with an optical counterpart, a system has been setup to enable fast optical observations in the direction of detected neutrino events. A reconstruction algorithm that does not require full alignment information [10] is run online and alerts are produced for network of small automatic optical telescopes.
Such alerts are produced for very high energy neutrinos or for multiple neutrinos that coincide in time and direction. Since February 2009, ANTARES has sent 37 alert triggers to the TAROT and ROTSE telescope networks, 27 of them have been followed. First results on the analysis of the resulting optical images to search for GRB and core-collapse SNe will be shown at the conference [11].

Another combination of measurements consists of correlating neutrino events with the signals from the gravitational wave detectors LIGO and VIRGO. A joint analysis is being performed that searches for a gravitational wave signal in coincidence with a sample of neutrino candidate events detected by ANTARES in 2007 [13].

4 Searches for Exotic physics

Antares is also searching for signatures of physics beyond the Standard Model. An analysis is performed that looks for neutrinos produced by Dark Matter particles annihilating in the Sun and the Galactic center [15]. Magnetic Monopoles with masses between $10^{10}$ and $10^{14}$ traversing the detector volume would be detected as a very bright track. A search for this signature has been conducted [14] and a limit on the flux of monopoles with $\beta > 0.55$ has been obtained; see Figure 4. This limit is more stringent than those from previous experiments.

Another hypothetical form of matter is formed by Nucleartes: particles composed of strange quark matter. The signature is a slow-moving (e.g. $10^{-3}c$) bright point traversing the detector. The searches are described in [16].

5 Conclusion

The first deep-sea neutrino telescope, ANTARES, has been taking data for four and a half years now. A large number of analysis are being performed, looking for astrophysical signals of neutrinos, either stand-alone or by looking for coincident observations with a variety of other experiments. The geographical position, combined with the good angular resolution allow ANTARES to explore, in particular, Galactic neutrino sources in the relevant energy range. In addition, several analyses are aimed at detecting signals from non-standard model particles.

The successful operation of ANTARES, and analysis of its data, is an important step towards KM3NET [20] a future km3-scale high-energy neutrino observatory and marine sciences infrastructure planned for construction in the Mediterranean Sea.

References

[4] S. Mangano for the ANTARES collaboration, these proceedings
[6] F. Schüssler for the ANTARES collaboration, these proceedings.
[7] J. Petrovic for the ANTARES collaboration, these proceedings
[9] J.P. Gomez for the ANTARES collaboration, these proceedings
[11] D. Dornic for the ANTARES collaboration, these proceedings
[12] C. Reed for the ANTARES collaboration, these proceedings
[13] V. Van Elewyck for the ANTARES collaboration, these proceedings
[14] N. Pimente for the ANTARES collaboration, these proceedings
[15] G. Lambard for the ANTARES collaboration, these proceedings
[16] V. Poppa for the ANTARES collaboration, these proceedings
[17] C. Bogazzi for the ANTARES collaboration, these proceedings
[19] C. Riviere for the ANTARES collaboration, these proceedings
[20] P. Kooijman for the KM3NeT collaboration, these proceedings; also www.km3net.org