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Recent results from the ANTARES neutrino telescope

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ABSTRACT

The ANTARES neutrino telescope is currently the largest operating water Cherenkov detector and the largest neutrino detector in the Northern Hemisphere. Its main scientific target is the detection of high-energy (TeV and beyond) neutrinos from cosmic accelerators, as predicted by hadronic interaction models, and the measurement of the diffuse neutrino flux. Its location allows for surveying a large part of the Galactic Plane, including the Galactic Centre.

In addition to the standalone searches for point-like and diffuse high-energy neutrino signals, ANTARES has developed a range of multi-messenger strategies to exploit the close connection between neutrinos and other cosmic messengers such as gamma-rays, charged cosmic rays and gravitational waves. This contribution provides an overview of the recently conducted analyses, including a search for neutrinos from the Fermi bubbles region, searches for optical counterparts with the TAToO program, and searches for neutrinos in correlation with gamma-ray bursts, blazars, and microquasars. Further topics of investigation, covering e.g. the search for neutrinos from dark matter annihilation, searches for exotic particles and the measurement of neutrino oscillations, are also reviewed.

1. Introduction

Neutrinos have long been proposed as an alternative to cosmic rays and photons to explore the high-energy sky, as they can emerge from dense media and travel across cosmological distances without being deflected by magnetic fields nor absorbed by ambient matter and radiation. High-energy ($>$ TeV) neutrinos are expected to be emitted in a wide range of astrophysical objects. Along with gamma-rays, they originate from the decay of π's and K's produced in the interactions of accelerated protons and nuclei with matter and radiation in the vicinity of the source. Candidate neutrino emitters therefore include most known or putative cosmic ray accelerators, ranging from galactic sources such as supernovae remnants or microquasars to the most powerful extragalactic emitters such as Active Galactic Nuclei (AGNs) and Gamma-Ray Bursts (GRBs) (see [1] for a review on the subject). Apart from tracing the existence of hadronic processes inside astrophysical sources, the observation of cosmic neutrinos could also reveal new types of sources, yet unobserved in photons or cosmic rays. Due to oscillations, the expected flavor ratio at Earth for cosmic neutrinos is $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$.

Neutrino astronomy is challenged both by the weakness of neutrino interactions and by the feebleness of the expected fluxes of cosmic neutrinos. Neutrino telescopes therefore require the instrumentation of large volumes of transparent medium (water or ice) with arrays of photosensors, in order to detect the Cherenkov light emitted by the charged leptons produced when a neutrino interacts with material in or around the detector. Muons are the most straightforward detection channel, but showers induced by electron- and tau-neutrino can also be detected. The timing, position and amplitude of the light pulses (or hits) recorded by the photosensors allow the reconstruction of the muon trajectory, providing the arrival direction of the parent neutrino and an estimation of its energy. Such detectors are installed at great depths and optimized to detect up-going muons produced by neutrinos which have traversed the Earth, in order to limit the background from down-going atmospheric muons. As a consequence, one single neutrino telescope can efficiently monitor only half of the sky in the TeV–PeV range. The ANTARES detector, located in the Mediterranean Sea, is well suited for the observation of Galactic sources; its layout and performances are described in Section 2.

Atmospheric neutrinos produced in cosmic-ray-induced air showers can also traverse the Earth and interact close to the detector, providing an irreducible source of background with energy spectrum $\propto E_\nu^{-3.7}$. Diffuse fluxes of neutrinos from astrophysical origin, which are expected to be harder (typically $\propto E_\nu^{-\alpha}$ with $\alpha =$ 1–2), can then be identified as an excess of events above a certain energy. Another approach consists in looking for

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localized excesses of events, either blindly over the full sky, or in the direction of a priori selected candidate source locations that correspond e.g. to known gamma-ray emitters. Such searches are well suited to look for steady, point-like sources, in particular in the Galaxy. Finally, multimessenger searches develop specific strategies to look for neutrinos with timing and/or directional correlations with other cosmic messengers such as photons, charged cosmic rays or gravitational waves. The outcome of such searches performed with the ANTARES detector is described in Sections 3 (diffuse fluxes), 4 (neutrino sources) and 5 (multimessenger searches).

Beyond its astrophysics goals, the science reach of a neutrino telescope such as ANTARES also includes an extended particle physics program, ranging from the study of neutrino oscillations and the indirect search for dark matter (in the GeV–TeV energy range) to the search for exotic particles (at the upper end of the energy spectrum). These topics are discussed in Section 6. Recent reviews on the techniques and challenges of neutrino astronomy can be found e.g. in [2,3].

2. The ANTARES detector

The ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental Research) detector is the first undersea neutrino telescope and the only one currently operating [4]. Its deployment at a depth of 2475 m in the Mediterranean Sea, about 40 km off the French coast near Toulon (Var), was completed in May 2008. It consists of an array of 12 lines anchored to the sea bed and connected to a junction box which distributes the electrical power and transmits the data to shore through an electro-optical cable (see Fig. 1). The detector lines are 450 m high, with an inter-line spacing ranging from 60 m to 75 m. Each line supports 25 storeys made of triplets of 10-in. photomultipliers (PMTs) enclosed in 17-in. pressure-proof glass spheres. The detector comprises a total of 885 optical modules (OMs), corresponding to an instrumented volume of about 0.02 km^3. Acoustic devices and inclinometers regularly spread along the lines allow us to accurately monitor the position and orientation of the OMs [5], and time calibration is performed by means of an in situ array of laser and LED beacons [6].

The PMTs are orientated at 45° downwards in order to maximize the sensitivity to Cherenkov light from upcoming muons. The time and charge of all PMT signals (or “hits”) that pass a predefined threshold (typically 0.3 photoelectron) are digitized and sent to shore, where they are processed on the fly by a PC farm. The data flow to the shore amounts to about 1–10 Gb/s; it is dominated by random hits ($\sim$ 60–150 kHz per PMT) due to the background light produced by the radioactive decay of ^{40}K and by bioluminescence. Online filtering algorithms run on the PCs to select the physics events among the raw data and write them to disk to be analyzed offline. Such events are then reconstructed using the hits time and position information, typically by means of a modified maximum likelihood method [7]. The median angular resolution achieved for muon tracks is $\lesssim 0.5°$, allowing good performance in the searches for neutrino point sources, as reported in Section 4.

The detector records a baseline rate of ~ 10 Hz of muons. Those associated with upgoing (atmospheric) neutrinos can be identified by imposing both quality cuts on the track fit parameters, and a directional cut on the reconstructed zenith angle ($\theta > 90°$). Within these conditions, the detector instantaneous sky coverage is 2π sr, and its integrated visibility covers about $\frac{3}{4}$ of the sky. Its location in the Northern Hemisphere allows for surveying a large part of the Galactic Plane, including the Galactic Centre, thus complementing the sky coverage of the IceCube detector installed at the South Pole [8].

The main junction box of ANTARES also supports an additional instrumented line which provides measurements of environmental parameters such as sea current and temperature, and hosts part of the AMADEUS prototype array for ultra-high energy neutrino acoustic detection [9]. Since April 2013, this line hosts a prototype OM, housing 31 3-in. PMTs, designed for the next-generation deep-sea neutrino telescope, KM3NeT [10]. A secondary junction

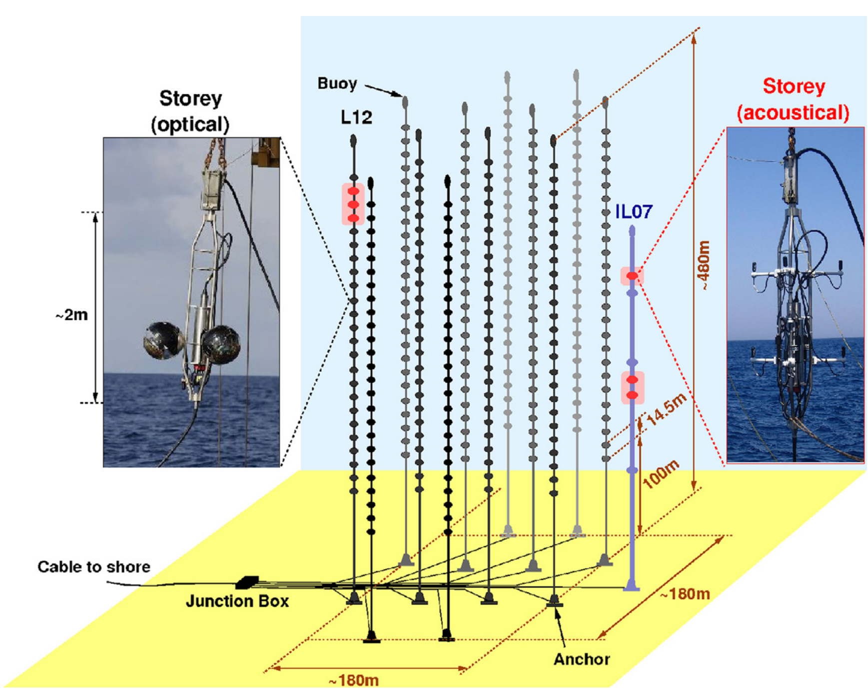

Fig. 1. The ANTARES detector configuration, showing the 12 lines hosting standard storeys with optical modules (in black), as well as the instrumented line (IL07). The red storeys on L12 and IL07 correspond to the AMADEUS acoustic detection modules. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)