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Exploring the Universe with Very High Energy Neutrinos

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Abstract

With the discovery of a high-energy neutrino flux in the 0.1 PeV to PeV range from beyond the Earth's atmosphere with the IceCube detector, neutrino astronomy has achieved a major breakthrough in the exploration of the high-energy universe. One of the main goals is the identification and investigation of the still mysterious sources of the cosmic rays which are observed at Earth with energies up to several 10^5 PeV. In addition to being smoking-gun evidence for the presence of cosmic rays in a specific object, neutrinos escape even dense environments and can reach us from distant places in the universe, thereby providing us with a unique tool to explore cosmic accelerators. This article summarizes our knowledge about the observed astrophysical neutrino flux and current status of the search for individual cosmic neutrino sources. At the end, it gives an overview of plans for future neutrino telescope projects.

Keywords: high-energy neutrinos, neutrino astronomy, neutrino telescopes, ANTARES, BAIKAL, IceCube, KM3NeT, cosmic neutrino flux, point-like neutrino sources, gamma-ray bursts

1. Introduction

The discovery of cosmic rays by Victor Hess in 1912 marked the beginning of astroparticle physics which has enabled us to explore the Universe at the highest energies reaching up to several 10^5 PeV. But even more than 100 years later, the central question regarding the sources that can accelerate particles to energies far beyond what is achievable with man-made accelerators is mostly unanswered. First of all, cosmic rays cannot directly reveal their sources except maybe at the very highest energies as the charged particles are deflected in the galactic and intergalactic magnetic fields and hence do not point back to their origin. High-energy gamma-ray photons, which are produced in the interaction of cosmic rays with matter or photon fields, on the other hand, can also be generated via up-scattering of low-energy photons by accelerated electrons (inverse Compton scattering). Though the gamma-ray spectra of at least two supernova remnants seem to originate from pion decay and hence from acceleration of protons or heavier nuclei [1], a clear picture whether supernova remnants are indeed the main sources of the Galactic cosmic rays is still missing. Furthermore, the origin of ultra-high energy cosmic rays (UHECRs) above $\gtrsim 3 \times 10^{18}$ eV remains a complete mystery. With their unique properties, neutrinos will help in solving these and other important astrophysical questions, as their observation from an object or region would unambiguously identify it as a source of high-energy protons or heavier nuclei. This has been one of the main drivers for the development and construction of neutrino telescopes over the past decades. At the same time, the fact that until recently the high-energy neutrino sky has been total terra incognita implies a high potential for unexpected discoveries.

The low interaction cross section that renders neutrinos very valuable for the exploration of the high-energy universe, however, also makes them very hard to detect. In particular, over the past years it has become clear that huge detectors of at least km^3 size are necessary to eventually open this exciting new window to the universe (see e.g. [2, 3]).

[1]http://icecube.wisc.edu

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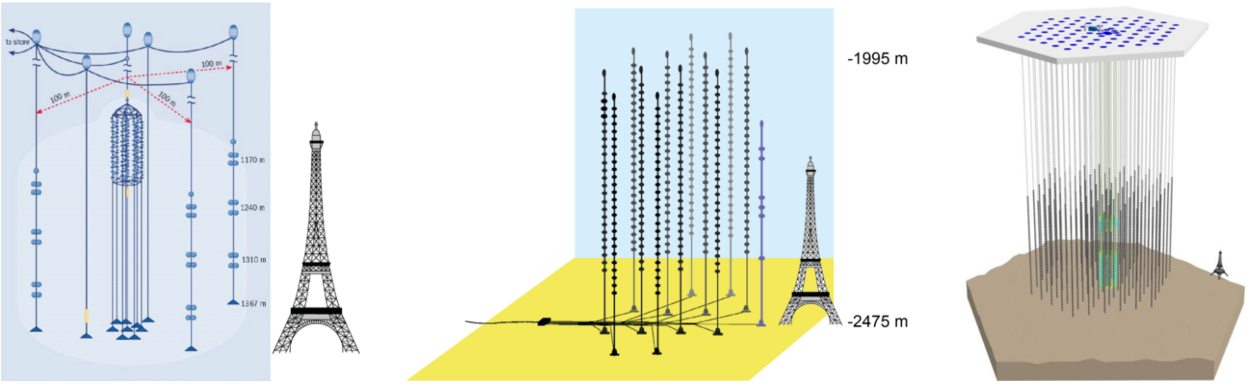

Figure 1: Schematic views of the BAIKAL (left) [4], ANTARES (middle)[5] and IceCube (right) [6] neutrino detectors. The Eiffel Tower is shown for scale comparison.

2. Neutrino telescopes

The idea for neutrino telescopes was first published in 1960 by Markov [7]. The detection principle is based on the registration of the Cherenkov light induced by charged particles generated in neutrino interactions in an optically transparent medium like ice or water. This light is recorded with a large number of photomultipliers arranged in a three-dimensional array. The direction and energy of the neutrino is reconstructed using the arrival time of the photons (measured with nanosecond precision), the measured light intensity and the position of the photomultipliers.

The technical realization of such a telescope in deep ocean water was pioneered by the DUMAND Collaboration between 1973 and 1995 [8] but terminated after a technical failure of the first deployed string. In the 1980's, the construction of detectors in Lake Baikal [4] and in the ice at the South Pole were proposed. The NT200 in Lake Baikal was completed in 1998, instrumenting a volume of $10^{-4}\,\mathrm{km}^3$ with 192 optical modules on eight strings (Fig. 1, left). Three additional strings at larger distances were added in 2005–2007. The AMANDA detector at the South Pole [9] took data from 1996 until 2009. In its final configuration it consisted of 667 optical modules instrumenting a volume of about $10^{-2}\,\mathrm{km}^3$. Installation of a neutrino telescope in the deep ocean was pursued by the ANTARES, NEMO and NESTOR Collaborations in the Mediterranean Sea. The ANTARES detector (Fig. 1, middle) was eventually built off the coast of southern France near Toulon [5] with construction lasting from 2002 to 2008. It comprises 885 optical modules on 12 strings and instruments a volume of $10^{-2}\,\mathrm{km}^3$. Data taking started early in the construction phase and is ongoing. In 2005, construction of the IceCube detector (Fig. 1, right), the successor of AMANDA, started with the aim to build the first km^3-scale neutrino telescope [10]. In its final configuration, reached in 2010, the detector consists of 5160 optical modules instrumenting one km^3 of clear glacial ice at depths between 1450 m and 2450 m at the geographic South Pole. Physics data taking started in 2006 with 9 installed strings. In contrast to the other detectors, the IceCube Observatory comprises an air shower array at the surface called IceTop [6]. Its main purpose is the investigation of cosmic rays in the energy range between $10^{15}\,\mathrm{eV}$ and $10^{18}\,\mathrm{eV}$ [11]. This article concentrates on results from the IceCube and ANTARES detectors as these are currently the most sensitive detectors in the Southern and Northern hemisphere, respectively.

Two basic event topologies in neutrino telescopes can be distinguished. Charged-current interactions of muon neutrinos produce long track-like patterns due to the resulting muon crossing the detector (muon channel; Fig. 2, top). On the other hand, neutral-current interactions of all neutrino flavors, or charged current interactions of electron neutrinos, induce a more spherical hit pattern originating from the cascade of particles produced at the interaction vertex (cascade channel; Fig. 2, bottom). In case a charged current muon neutrino or tau neutrino interaction with subsequent tau decay into a muon happens inside the detector these two topologies overlap thereby complicating the reconstruction. The direction of elongated muon tracks can be reconstructed with sub-degree precision at high energies, significantly better than that of cascades. At the relevant energies, the neutrino is approximately collinear with the muon and, hence, the muon channel is the prime channel for the search for point-like sources of cosmic neutrinos. On the other hand, cascades deposit all of their energy in-