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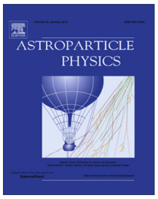

Neutrino astronomy: An update

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ABSTRACT

Detecting neutrinos associated with the still enigmatic sources of cosmic rays has reached a new watershed with the completion of IceCube, the first detector with sensitivity to the anticipated fluxes. In this review, we will briefly revisit the rationale for constructing kilometer-scale neutrino detectors and summarize the status of the field.

1. Introduction

Soon after the 1956 observation of the neutrino [1], the idea emerged that it represented the ideal astronomical messenger [2–4]. Neutrinos reach us from the edge of the Universe without absorption and with no deflection by magnetic fields. Neutrinos have the potential to escape unscathed from the inner neighborhood of black holes and from, the subject of this update, the accelerators where cosmic rays are born. Their weak interactions also make cosmic neutrinos very difficult to detect. Immense particle detectors are required to collect cosmic neutrinos in statistically significant numbers [5]. Already by the 1970s, it had been understood that a kilometer-scale detector was needed to observe the "cosmogenic" neutrinos [6] produced in the interactions of cosmic rays with background microwave photons [7].

Today's estimates of the sensitivity for observing potential cosmic accelerators such as Galactic supernova remnants, active galactic nuclei (AGN), and gamma-ray bursts (GRB) unfortunately point to the same exigent requirement [8]. Building a neutrino telescope has been a daunting technical challenge.

Given the detector's required size, early efforts concentrated on transforming large volumes of natural water into Cherenkov detectors that catch the light emitted by the secondary particles produced when neutrinos interact with nuclei in or near the detector [3]. After a two-decade-long effort, building the Deep Underwater Muon and Neutrino Detector (DUMAND) in the sea off the main island of Hawaii unfortunately failed [9]. However, DUMAND pioneered many of the detector technologies in use today and inspired the deployment of a smaller instrument in Lake Baikal [10] as well as efforts to commission neutrino telescopes in the Mediterranean [11–13]. These have paved the way toward the planned construction of KM3NeT [14]. The development of early, very high-energy neutrino detectors has been recently reviewed by Spiering [15].

The first telescope on the scale envisaged by the DUMAND collaboration was realized instead by transforming a large volume of deep, transparent, natural Antarctic ice into a particle detector, the Antarctic Muon and Neutrino Detector Array (AMANDA). In operation from 2000 to 2009, it represented the proof of concept for the kilometer-scale neutrino observatory, IceCube [16,17].

Neutrino astronomy has already achieved spectacular successes: neutrino detectors have "seen" the Sun and detected a supernova in the Large Magellanic Cloud in 1987. Both observations were of tremendous importance; the former showed that neutrinos have a tiny mass, opening the first crack in the Standard Model of particle physics, and the latter confirmed the basic nuclear physics of the death of stars. Fig. 1 illustrates the cosmic neutrino energy spectrum covering an enormous range, from the neutrinos produced in association with the 2.725 K microwave photon background to 10^{20} eV [18]. The figure is a mixture of observations and theoretical predictions. At low energy, the neutrino sky is dominated by neutrinos produced in the Big Bang. At MeV energy, neutrinos are produced by the Sun and by supernova explosions; the flux from the 1987 event is shown. At higher energies, the neutrino sky is dominated by neutrinos produced by cosmic ray interactions in the atmosphere, measured up to energies of 100 TeV by the AMANDA experiment [19]. Atmospheric neutrinos are a key to our story, because they are the dominant background for extraterrestrial searches. The flux of atmospheric neutrinos falls dramatically with increasing energy; events above 100 TeV are rare, leaving a clear field of view of the sky for extraterrestrial sources.

The highest energy neutrinos in Fig. 1 are the decay products of pions produced by the interactions of cosmic rays with microwave photons [20]. Above a threshold of $\sim 4 \times 10^{19}$ eV, cosmic rays interact with the microwave background introducing an absorption feature in the cosmic-ray flux, the Greisen–Zatsepin–Kuzmin (GZK) cutoff. As a consequence, the mean free path of extragalactic

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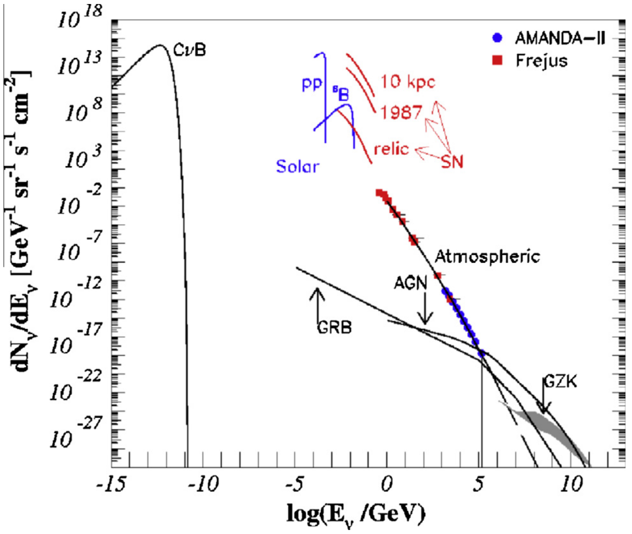

Fig. 1. The cosmic-neutrino spectrum. Sources are the big bang (CνB), the Sun, supernovae (SN), atmospheric neutrinos, gamma-ray bursts (GRB), active galactic nuclei (AGN), and cosmogenic (GZK) neutrinos. The data points are from a detector at the Fréjus underground laboratory [21] (red) and from AMANDA [19] (blue).

cosmic rays propagating in the microwave background is limited to less than 100 Mps. Therefore, the secondary neutrinos are the only probe of the still enigmatic sources at further distances. The calculation of the neutrino flux associated with the observed flux of extragalactic cosmic rays is straightforward, and yields on the order of one event per year in a kilometer-scale detector. The flux, labeled GZK in Fig. 1, shares the high-energy neutrino sky with neutrinos anticipated from gamma-ray bursts and active galactic nuclei [8].

2. The first kilometer-scale neutrino detector: IceCube

A series of first-generation experiments [22,23] have demonstrated that high-energy neutrinos with ~10 GeV energy and above can be detected using large volumes of highly transparent ice or water instrumented with a lattice of photomultiplier tubes. Such instruments detect neutrinos by observing Cherenkov radiation from secondary particles produced in neutrino interactions inside the detector. Construction of the first second-generation detector, IceCube, at the geographic South Pole was completed in December 2010 [24]; see Fig. 2.

IceCube consists of 80 strings, each instrumented with 60 ten-inch photomultipliers spaced 17 m apart over a total length of one kilometer. The deepest modules are located at a depth of 2.45 km so that the instrument is shielded from the large background of cosmic rays at the surface by approximately 1.5 km of ice. Strings are arranged at apexes of equilateral triangles that are 125 m on a side. The instrumented detector volume is a cubic kilometer of dark and highly transparent [25] Antarctic ice. The ice is sterile with the radioactive background dominated by the instrumentation deployed in this natural ice.

Each optical sensor consists of a glass sphere containing the photomultiplier and the electronics board that digitizes the signals locally using an onboard computer. The digitized signals are given a global time stamp with residuals accurate to less than 3 ns and are subsequently transmitted to the surface. Processors at the surface continuously collect the time-stamped signals from the optical modules, each of which functions independently. The digital messages are sent to a string processor and a global event builder. They are subsequently sorted into the Cherenkov patterns emitted by secondary muon tracks, or electron and tau showers, that reveal the direction of the parent neutrino; see [26].

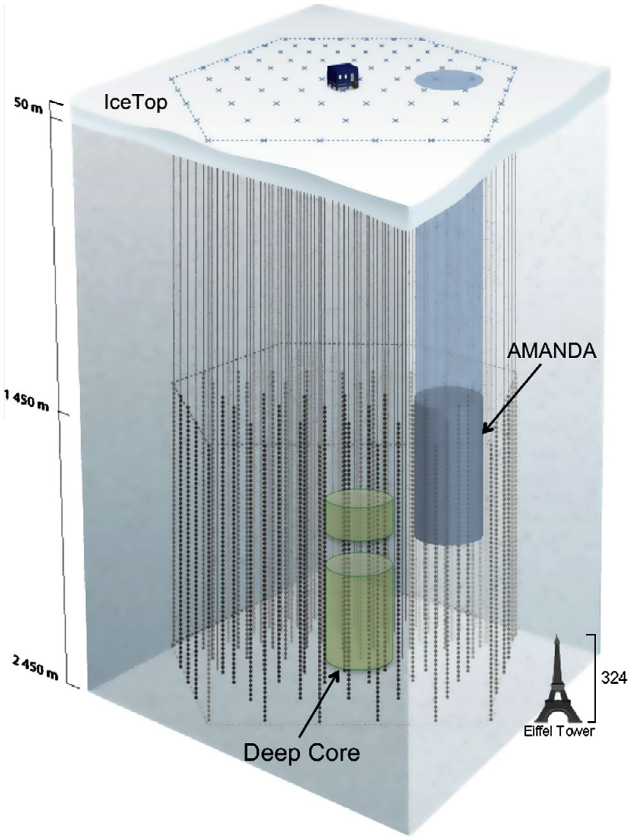

Fig. 2. Schematic of the IceCube detector.

Based on data taken during construction, the actual effective area of the completed IceCube detector is larger by a factor 2 (3) at PeV (EeV) energy over what had been expected [17], mostly because of improvements to the data acquisition system. The neutrino-collecting area is expected to increase further with improved calibration and development of optimized software tools for the detector, which has been operating stably in its final configuration since May 2011. Already reaching an angular resolution of better than 0.5° for muon tracks triggered, this resolution can be reduced off-line to $\leqslant 0.2°$ for individual events. The absolute pointing has been determined by measuring the shadowing of cosmic-ray muons by the moon to 0.1° at FWHM.

IceCube detects 10^{11} muons per year at a trigger rate of 2700 Hz. Among these it filters 10^5 neutrinos, one every 6 min, above a threshold of ~100 GeV. The DeepCore infill array identifies a sample, roughly equal in number depending on the quality cuts, with energies as low as 10 GeV; see Fig. 2. These muons and neutrinos are overwhelmingly of atmospheric origin and are the decay products of pions and kaons produced by collisions of cosmic-ray particles with nitrogen and oxygen nuclei in the atmosphere. With larger detectors, the separation of cosmic-ray muons from secondary muons of neutrino origin becomes relatively straightforward even though their ratio is at the level of 10^6: 1. Muons tracks are reconstructed by likelihood methods and their energy deposition in the detector is determined in real time. High-purity neutrino samples of upgoing muon tracks of neutrino origin are separated from downgoing cosmic-ray muons by quality cuts; for instance, on the likelihood of the fit, on the number of photons that arrive at DOMs at the Cherenkov time (i.e., without a significant time delay resulting from scattering), on the length of the track, on the