High Energy Neutrino Astronomy: First Light

Francis Halzen

Department of Physics, University of Wisconsin, Madison, WI 53706

We review:

1. The compelling case for doing neutrino astronomy,
2. Why we anticipate that we need kilometer-scale observatories to do the science,
3. The recent successful commissioning of the Lake Baikal and South Pole neutrino detectors.

1. THE CASE FOR NEUTRINO ASTRONOMY

Of all high-energy particles, only neutrinos can directly convey astronomical information from the edge of the universe—and from deep inside the most cataclysmic high-energy processes. Copiously produced in high-energy collisions, travelling at the velocity of light, and not deflected by magnetic fields, neutrinos meet the basic requirements for astronomy. Their unique advantage arises from a fundamental property: they are affected only by the weakest of nature's forces (but for gravity) and are therefore essentially unabsorbed as they travel cosmological distances between their origin and us.

Many of the outstanding mysteries of astrophysics may be hidden from our sight at all wavelengths of the electromagnetic spectrum because of absorption by matter and radiation between us and the source. For example, the hot dense regions that form the central engines of stars and galaxies are opaque to photons. In other cases, such as supernova remnants, gamma ray bursters, and active galaxies, all of which may involve compact objects or black holes at their cores, the precise origin of the high-energy photons emerging from their surface regions is uncertain. Therefore, data obtained through a variety of observational windows—and especially through direct observations with neutrinos—may be of cardinal importance.

While the many questions a high-energy neutrino telescope can address naturally begin with astronomy, fascinating issues in particle physics and other branches of science are accessible as well. Neutrino telescopes will search for the annihilation products of halo cold dark matter particles (WIMPS and supersymmetric particles) and for topological defects that are the remnants of early Universe phase transitions. Using neutrino beams with a baseline of the size of the Hubble radius they will test relativity, and study neutrino oscillations with unprecedented precision.

The sun is an intense source of electron neutrinos (ν_e), albeit of relatively low energy. Solar neutrino astronomy began with first experiments in the mid-1960s; today there are five complementary neutrino detectors viewing the nuclear reactions in the core of the sun and, at the same time, studying the fundamental properties of neutrinos. The sun remained the only astronomical object studied with neutrinos until neutrinos from Supernova 1987A were observed. These are still the only two sources marking the astronomical neutrino spectrum.

With high-energy neutrino astrophysics, we are poised to open a new window into space and back in time to the highest-energy processes in the universe. The potential scientific payoff of neutrino astronomy arises from the great penetrating power of neutrinos, which allows them to emerge from dense inner regions of energetic sources. It necessarily follows that the expected interaction rates are small, even with a kilometer-scale detector. History has shown, however, that the opening of each new astronomical window has led to unexpected discoveries. Thus, for example, there could be hidden particle accelerators from which only the neutrinos escape. Yet the science these instruments may do which we cannot anticipate, may well fuel the quest for astronomical knowledge in the next century. Unexpected discovery has followed the inauguration of most new astronomical instruments. Large reflecting telescopes on mountaintops led to the discovery of distant galaxies and an expanding universe; radio telescopes found the cosmic microwave background; X-ray and gamma-ray satellites have uncovered a bestiary of awesome cosmological objects. Even the first modest solar-neutrino observatory revealed a paradox about the nature of fundamental interactions which is yet to be fully explained. No one can predict all that a high-energy neutrino observatory will find in the sky—except that it is very likely to amaze us.

Whereas the science is compelling, the real challenge is to develop a reliable, expandable and affordable detector technology. Suggestions to use a large volume of water for high-energy neutrino astronomy were made as early as the 1960s [1]. In the case of the muon neutrino, for instance, the neutrino (ν_μ) interacts with a hydrogen or oxygen nucleus in the water and produces a muon travelling in nearly the same direction as the neutrino. The blue Čerenkov light emitted along the muon's ~kilometer-long trajectory is detected by strings of photomultiplier tubes deployed deep below the surface. With the first observation of neutrinos in the Lake Baikal and the (under-ice) South Pole neutrino telescopes, there is optimism that the technological challenges to build neutrino telescopes have been met. We will return to the experimental status of the field at the end of this talk.

2. KILOMETER-SCALE DETECTORS

For guidance in estimating expected signals, we make use of the observed energy in high energy cosmic-ray protons and nuclei as well as in known sources of non-thermal, high-energy gamma radiation. Some fraction of cosmic rays will interact in their sources, whatever they may be, to produce pions. These interactions may be hadronic collisions with ambient gas or photoproduction with intense photon fields near the high-energy sources. In either case, the neutral pions decay to photons while charged pions include neutrinos among their decay products with spectra related to the observed γ-ray spectra. Estimates based on this relationship show that a kilometer-scale detector is needed to see the neutrino signals [2].

The observed fluxes of cosmic rays and gamma rays set the scale of neutrino telescopes. If we, for instance, assume that gamma ray bursts are the cosmic accelerators of the highest energy cosmic rays, one can calculate from textbook particle physics how many neutrinos are produced when the particle beam coexists with the observed MeV photons in the original fireball. We thus predict the observation of order 10–100 neutrinos of PeV energy per year in a detector with a kilometer-square effective area. The rate is somewhat smaller when assuming instead that the observed cosmic ray beam originates near supermassive black holes at the center of active galaxies. Interaction of the cosmic rays with the abundant UV light in the galaxy is the source of the observed neutrinos. For detailed reviews, see reference [3].

TeV γ-rays may be produced by radiative processes from accelerated electrons, whereas neutrinos must be produced by hadronic processes. Therefore, high-energy neutrino astronomy has the potential to discriminate between hadronic and electromagnetic origin of the intriguing TeV emission from objects such as supernova remnants, gamma-ray burst sources and active galactic nuclei. With this capability, neutrino telescopes may resolve unambiguously one of the oldest puzzles in science: the origin of cosmic rays. TeV photon fluxes determine, independently from the cosmic ray flux, the scale of the neutrino telescope. If one assumes that the observed TeV gamma rays emitted by blazars and supernova remnants are the decay products of neutral pions, one can estimate the accompanying flux of neutrinos in a largely model-independent way. One anticipates neutrino rates of order a few events per year from the Crab and the observed Markarian sources to, possibly, a few hundred from Sgr A[4]. The conclusion is, once more, that a kilometer-scale instrument is required to confirm or rule out the hadronic origin of the highest energy photons.

3. NEUTRINO ASTRONOMY: FIRST LIGHT IN LAKE BAIKAL AND AT SOUTH POLE

The first generation of neutrino telescopes, launched by the bold decision of the DUMAND collaboration to construct such an instrument[5], are designed to reach a large telescope area and detection volume for a neutrino threshold of order 10 GeV. This relatively low threshold permits calibration of the novel instrument on the known flux of atmospheric neutrinos. The architecture is optimized for reconstructing the Čerenkov light front radiated by an up-going, neutrino-induced muon. Only up-going muons made by neutrinos reaching us through the Earth can be successfully detected. The Earth is used as a filter to screen the fatal background of cosmic ray muons. This makes neutrino detection possible over the lower hemisphere of the detector. Up-going muons must be identified in a background of down-going, cosmic ray muons which are more than 10^6 times more frequent for a depth of 1∼2 kilometers. The method is sketched in Fig. 1.

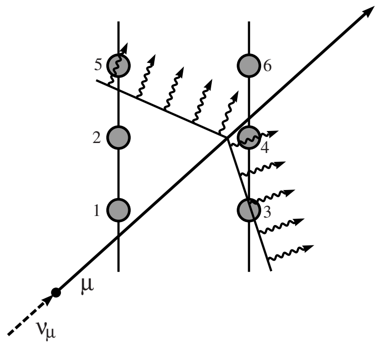

Figure 1. The arrival times of the Čerenkov photons in 6 optical sensors determine the direction of the muon track.

The optical requirements of the detector medium are severe. A large absorption length is required because it determines the spacings of the optical sensors and, to a significant extent, the cost of the detector. A long scattering length is needed to preserve the geometry of the Čerenkov pattern. Nature has been kind and offered ice and water as adequate natural Čerenkov media. Their optical properties are, in fact, complementary. Water and ice have similar attenuation length, with the role of scattering and absorption reversed. Optics seems, at present, to drive the evolution of ice and water detectors in predictable directions: towards very large telescope area in ice exploiting the long absorption length, and towards lower threshold and good muon track reconstruction in water exploiting the long scattering length.

DUMAND, the pioneering project located off the coast of Hawaii, demonstrated that muons could be detected by this technique [5], but the planned detector was never realized. A detector composed of 96 photomultiplier tubes located deep in Lake Baikal was the first to demonstrate the detection of neutrino-induced muons in natural water [6]. The Baikal experiment represents a proof of concept for deep ocean projects. These have the advantage of larger depth and optically superior water. Their challenge is to find reliable and affordable solutions to a variety of technological challenges for deploying a deep underwater detector. The European collaborations ANTARES [7] and NESTOR [8] plan to deploy large-area detectors in the Mediterranean Sea within the next few years. The NEMO Collaboration is conducting a site study for a future kilometer-scale detector in the Mediterranean [9].

With data taken with 96 optical modules (OM) only, they have shown that atmospheric muons can be reconstructed with sufficient accuracy to identify atmospheric neutrinos; see Fig. 2. The neutrino events are isolated from the cosmic ray muon background by imposing a restriction on the chi-square of the Čerenkov fit, and by requiring consistency between the reconstructed trajectory and the spatial locations of the OMs reporting signals.

In the following years, *NT-200* will be operated

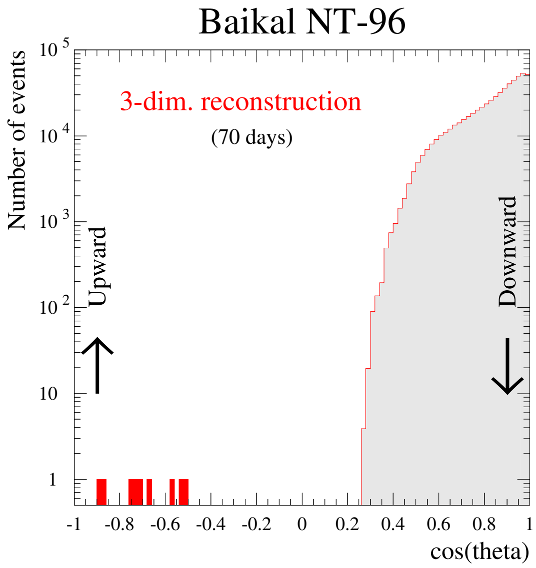

Figure 2. Angular distribution of muon tracks in the Lake Baikal experiment after the cuts described in the text.

as a neutrino telescope with an effective area between $10^3 \sim 5 \times 10^3\,\mathrm{m}^2$, depending on energy. Presumably too small to detect neutrinos from extraterrestrial sources, *NT-200* will serve as the prototype for a larger telescope. For instance, with 2000 OMs, a threshold of $10 \sim 20\,\mathrm{GeV}$ and an effective area of $5 \times 10^4 \sim 10^5\,\mathrm{m}^2$, an expanded Baikal telescope would fill the gap between present underground detectors and planned high threshold detectors of cubic kilometer size. Its key advantage would be low threshold.

The AMANDA collaboration, situated at the U.S. Amundsen-Scott South Pole Station, has strikingly demonstrated the merits of natural ice as a Čerenkov detector medium [10,11]. In 1996, AMANDA was able to observe atmospheric neutrino candidates using only 80 eight-inch photomultiplier tubes [10].

With 1997 data, with 302 optical modules instrumenting approximately 6000 tons of ice, AMANDA extracted several hundred atmospheric neutrino events. AMANDA was thus the first neutrino telescope with an effective area in excess of 10,000 square meters for TeV muons. In rate and all characteristics the events are consistent with atmospheric neutrino origin. Their energies are in the $0.1 - 1\,\mathrm{TeV}$ range. The shape of the zenith angle distribution is compared to a simulation of the atmospheric neutrino signal in Fig. 3. The variation of the measured rate with zenith angle is reproduced by the simulation to within the statistical uncertainty. Note that the tall geometry of the detector strongly influences the dependence on zenith angle in favor of more vertical muons.

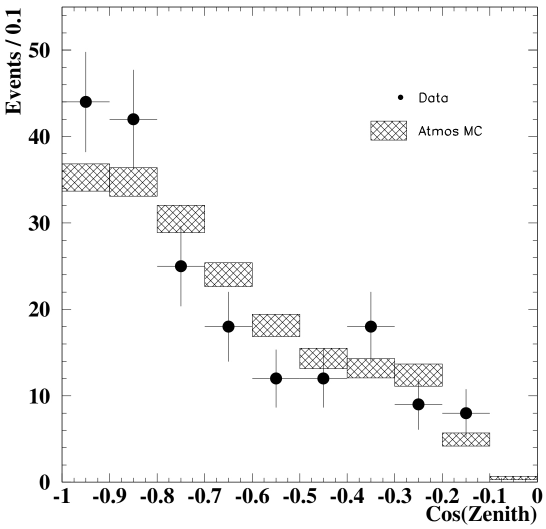

Figure 3. Reconstructed zenith angle distribution. The points mark the data and the shaded boxes a simulation of atmospheric neutrino events, the widths of the boxes indicating the error bars.

The arrival directions of the neutrinos are shown in Fig. 4. A statistical analysis indicates no evidence for point sources in this sample. An estimate of the energies of the up-going muons (based on simulations of the number of reporting optical modules) indicates that all events have energies consistent with an atmospheric neutrino origin. This enables AMANDA to reach a level of sensitivity to a diffuse flux of high energy extra-terrestrial neutrinos of order $dN/dE_\nu = 10^{-6} E_\nu^{-2}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}$, assuming an E^{-2} spectrum[12]. At this level they would exclude a variety of theoretical models which assume the hadronic origin of TeV photons from active galaxies and blazars[13]. Searches for neutrinos from gamma-ray bursts, for magnetic monopoles, and for a cold dark matter signal from the center of the Earth are also in progress and, with only 138 days of data, yield limits comparable to or better than those from smaller underground neutrino detectors that have operated for a much longer period.

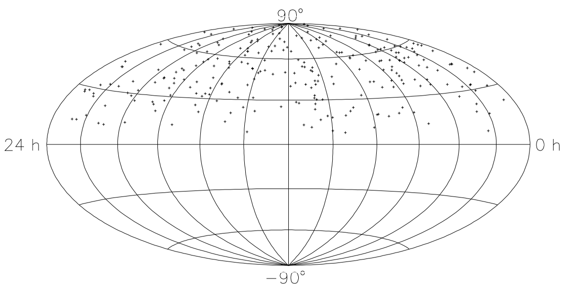

Figure 4. Distribution in declination and right ascension of the up-going events on the sky.

In January 2000, AMANDA-II was completed. It consists of 19 string with a total of 677 OMs arranged in concentric circles, with the ten strings from AMANDA forming the central core of the new detector. AMANDA has met the key challenge of neutrino astronomy: it has developed a reliable, expandable, and affordable technology for deploying a kilometer-scale neutrino detector named IceCube.

IceCube and the detectors to be located in the Mediterranean Sea will be complementary in several respects. First and foremost, they will cover different portions of the sky. (From its location at the South Pole, IceCube observes the northern sky.) Because of the different properties of Antarctic ice and ocean water—ice scatters light more but absorbs it less—IceCube should have better energy resolution and a larger effective area for neutrino detection, while the deep sea detectors should have somewhat higher pointing resolution. Finally, one of the key challenges in neutrino astronomy has been the ability to deploy and maintain optical modules far below the surface; here, too, ice and ocean are essentially different.

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