IceCube - a Telescope to Map the Neutrino Sky

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IceCube is a neutrino telescope under construction at the South Pole. When finished it will encompass a cubic kilometer of ice residing 1500 m below the surface of the Antarctic ice sheet. It is designed to discover and map the sources of high-energy neutrinos in the northern hemisphere. By February 2007, shortly after the Conference in Cocoyoc, there were 22 strings (of the 70+ envisioned), each with 60 photomultiplier tubes, working in the deep ice. The performance of the IceCube array with up to nine strings and some results from IceCube’s predecessor, AMANDA (the Antarctic Muon and Neutrino Detector Array), are described here.

Keywords: Neutrinos; Cerenkov detectors; cosmic rays.

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1. Introduction

The use of neutrinos to study distant objects or regions may rightly be called neutrino astronomy [2,3]. Neutrino detectors that measure the track of the charged particle produced in a neutrino-induced collision are telescopes because the neutrino’s direction points back to its origin, and the charged particle carries information about the neutrino’s direction. At high energies, the neutrino and charged particle are collinear to the order of a degree or better. The Sun and Supernova 1987a are the two heavenly objects observed in “neutrino light” so far. It is thus with justification that neutrinos appear in the Physics and Astronomy Classification system under the section Astronomical Observations, which also includes the electromagnetic spectrum from radio to gamma rays. Neutrino detectors can also provide valuable information even when directional information may be very poor or absent. Neutrinos from radioactivity in the Earth’s crust have recently been detected [4], providing another example of neutrinos as messengers, bringing us information from the distant or the inaccessible.

Neutrino telescopes can be placed in two physical categories - compact and densely instrumented, or extended - depending on whether they are designed to detect low-energy or high-energy neutrinos. In the low-energy case, a large number of phototubes can be arranged to view the same volume and determine the location, direction, and energy of an event that occurs within that volume. High-energy neutrinos produce muons with ranges on the kilometer scale, which requires distributing the phototubes over a large volume in order to do tracking, as well as to have a larger instrumented volume to detect the lower fluxes that accompany higher energy. Detection of a muon neutrino consists of observing a muon that is “upward going,” that is, the muon arrives from a direction that lies below the horizon. Only a neutrino can penetrate the correspondingly long distance in the Earth. It may then undergo a collision that produces a muon traveling in the same direction, which then passes through the instrumented volume and can be tracked via the associated Cerenkov radiation in the optical spectrum. The natural occurrence on Earth of large bodies of water and ice, which can provide both detector medium and overhead shielding, enables the construction of high-energy, water-Cerenkov neutrino detectors. They have been sited (or are under construction or planned) in deep fresh water (Baikal, NT200+), in ice (AMANDA, IceCube), and in the oceans; first in the Pacific (DUMAND, until it was cancelled) and now in the Mediterranean sea (ANTARES, NESTOR, NEMO, KM3Net) [5,6].

Low-energy detectors were developed and began operating much earlier than their high-energy counterparts because of a number of factors. Foremost was the availability of intense sources of low-energy neutrinos to detect - from reactors, accelerators, the Sun, and cosmic-ray interactions in the atmosphere. Another reason was the search for proton decay, which employed compact water Cherenkov detectors. For this reason, the low-energy “neutrino spectrum” up to tens of MeV or, in the case of accelerators, up to tens of GeV, is relatively well-explored. Atmospheric neutrinos (produced in the Earth’s atmosphere by the interaction of cosmic rays) define a middle ground in energy that is also relatively well measured, at least at its lower end. But the high-energy neutrino spectrum beginning at a few TeV and extending upward to the highest cosmic-ray energies yet detected ($\sim 10^{20}$ eV) is still...
unexplored. There are sound theoretical reasons to believe that this region of energy, when explored or mapped, will exhibit features and sources [2,7]. In fact, NOT observing some of them could in principle create a “Cosmic Neutrino Problem” analogous to the “Solar Neutrino Problem” that arose when not enough solar neutrinos were observed.

In the following we will describe IceCube, a kilometer-scale neutrino telescope under construction at the South Pole [8]. To begin we review the experience with AMANDA [9], the predecessor of IceCube. AMANDA has been operating for ten years and has provided much of the technical and scientific motivation for IceCube.

2. AMANDA and Present Results

AMANDA consists of 19 strings of photomultiplier tubes (contained in pressure spheres and called optical modules, or OMs) deployed over the period 1997 - 2000 [9]. The 677 OMs are located at depths from 1250 m to 2250 m with most of them between 1500 m and 2000 m. With typically 50 m between strings, the OMs define an instrumented volume of about 0.02 km$^3$. A number of different technologies to get the signals from the phototubes to the surface were developed and tried in AMANDA, with the result that the detector is somewhat heterogeneous, thus complicating data analysis. In 2001 the AMANDA Collaboration published results on the detection of atmospheric neutrinos [10], which effectively demonstrated the feasibility of a neutrino telescope at the South Pole. From inception until the present, AMANDA has detected more than 4000 neutrinos, all of which, subsequent analysis has shown, are consistent with being generated by the collision of cosmic rays with nuclei in the atmosphere of the northern hemisphere [11].

The scientific scope of high-energy neutrino astronomy can be illustrated by describing the topics that AMANDA (and Baikal) have addressed and the results to date.

2.1. Searches for point sources of neutrinos

There are a number of potential point sources of high-energy neutrinos in and beyond our galaxy [2]. These are objects that are known from their emissions in the electromagnetic spectrum to radiate large amounts of energy. Some of these are steady state, others are one-time explosions.

2.1.1. Steady state sources

Active Galactic Nuclei are the energetic cores of galaxies, powered by massive black holes that accrete matter and produce jets of radiation emerging along the axis of rotation. The strong magnetic fields associated with this rotation, and the acceleration of protons and nuclei to relativistic energies in the jets provide an environment in which the accelerated nuclei can collide with residual gas and, in a mechanism akin to a “beam dump” at an accelerator, produce pions, muons, and hence neutrinos. The remnants of supernova explosions also contain strong, moving magnetic fields and therefore are able to accelerate nuclei, which then produce neutrinos by hadronic collisions. Both these classes of objects are also considered potential sources for a portion of the cosmic-ray energy spectrum [2].

Table I gives the upper limits of neutrino fluxes from different classes of AGNs in the northern hemisphere based on AMANDA data from 2000-2004 [12]. These are obtained by “stacking” the sources. That is, regions of the sky where different objects appear are summed in order to be more sensitive to the presence of a signal [13]. More general searches for point sources anywhere in the sky have produced a limit of $E^2\Phi < 10^{-10}$ GeV cm$^{-2}$s$^{-1}$ [14].

2.1.2. Time dependent sources

The cosmos is a violent place - in terms of cosmic volume and cosmic history, explosions happen everywhere, all the time. Supernovae were discovered until recently with only the naked eye. Many more have been and are being discovered with search techniques enabled by modern CCD technology in the focal planes of optical telescopes. With the advent of x- and gamma-ray detectors in space, another class of explosion, the Gamma Ray Burster (GRB), was observed at the rate of a few per day. A huge amount of energy emitted in a very short time by these objects (possibly as high as 10$^{52}$ erg over tens of seconds) has resulted in their being considered as the source of the UHE (Ultra High-energy) cosmic rays, those with energies above the “ankle” in the CR spectrum, i.e., above about 10$^{15}$ eV [15]. Waxman and Bahcall have calculated a limit on the neutrino flux expected from the collisions and excitations of these high-energy cosmic rays in the region they are produced [15].

<table>
<thead>
<tr>
<th>AGN class</th>
<th>$N_{\text{src}}$</th>
<th>$n_{\text{obs}}$</th>
<th>$n_0$</th>
<th>$\mu_{90}$</th>
<th>$\Phi_{\nu_e}^0$</th>
<th>$\Phi_{\mu}^0$</th>
<th>$\Phi_{\nu_e}/N_{\text{src}}$</th>
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</thead>
<tbody>
<tr>
<td>GeV blazars</td>
<td>8</td>
<td>17</td>
<td>25.7</td>
<td>2.7</td>
<td>2.7</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>unidentified GeV sources</td>
<td>22</td>
<td>75</td>
<td>77.5</td>
<td>14.1</td>
<td>16.5</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>IR blazars</td>
<td>11</td>
<td>40</td>
<td>43.0</td>
<td>9.3</td>
<td>10.6</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>keV blazars (HEAO-A)</td>
<td>3</td>
<td>9</td>
<td>14.0</td>
<td>2.7</td>
<td>3.6</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>keV blazars (ROSAT)</td>
<td>8</td>
<td>31</td>
<td>33.4</td>
<td>8.3</td>
<td>9.7</td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>TeV blazars</td>
<td>5</td>
<td>19</td>
<td>23.6</td>
<td>4.7</td>
<td>5.5</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>GPS and CSS</td>
<td>8</td>
<td>24</td>
<td>29.5</td>
<td>5.0</td>
<td>5.9</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>FR-I galaxies</td>
<td>1</td>
<td>3</td>
<td>3.1</td>
<td>4.3</td>
<td>4.1</td>
<td>4.11</td>
<td></td>
</tr>
<tr>
<td>FR-I without M87</td>
<td>17</td>
<td>40</td>
<td>57.2</td>
<td>2.7</td>
<td>2.9</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>FR-II galaxies</td>
<td>17</td>
<td>77</td>
<td>68.5</td>
<td>25.5</td>
<td>30.4</td>
<td>1.79</td>
<td></td>
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<tr>
<td>radio-weak quasars</td>
<td>11</td>
<td>35</td>
<td>41.6</td>
<td>5.6</td>
<td>6.7</td>
<td>0.61</td>
<td></td>
</tr>
</tbody>
</table>

TABLE I. Results of the stacking analysis for each AGN class: number of sources ($N_{\text{src}}$), number of expected background events ($n_{\text{obs}}$) and number of observed events ($n_0$). $\chi$ is the cumulative event upper limit and $\Phi_{\nu_e}^0$ is the upper limit to the cumulative muon flux, in units of $10^{-11}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$, for a spectral index $\gamma = 2$. The last column gives the limits divided by the number of sources ($\Phi_{\nu_e}/N_{\text{src}}$). These limits do not include the contribution of tau neutrinos.
Given the time and coordinates of a GRB as determined by, e.g., the SWIFT satellite or the BATSE detector, it is possible to search for neutrinos coming from that direction in an appropriate time interval. By placing a cut on direction and time the background is lowered significantly. A number of searches in AMANDA data have been made for possible neutrino events coincident in time and direction with observed Gamma Ray Bursts. In one search, 408 GRBs were considered [16]. The limits placed from this analysis are within a factor of four of the Waxman-Bahcall limit. Other limits obtained through searches for neutrinos from specific GRB events can be compared with neutrino fluxes predicted by calculations made for that specific event, based on all the information known about that event [17].

2.1.3. WIMP search

Another potential point source of neutrinos is the annihilation of WIMPs, Weakly Interacting Massive Particles, that have lost energy through collisions with nuclei and have migrated under the influence of gravity to the cores of the Sun and/or the Earth. The energies of the neutrinos depend on the mass of the WIMPS and, for a wide range of plausible WIMP masses, are above the threshold for detection with AMANDA. The neutrinos originating from WIMP annihilation in the core of the Earth can be observed all year, since the Earth’s center is always below the horizon. In the case of a detector at the South Pole, neutrinos from the Sun can be detected for the six months when the sun is below the horizon. The azimuthal symmetry of this geometry helps in the determination of the background. Searches for WIMPs from the Sun and Earth have been published for a portion of the AMANDA data [refs. 18, 19 for the Earth, and ref. 20 for the Sun]. In neither case has an excess above background been observed, although interesting limits have been obtained. These indirect searches are complementary to direct ones that search for the (quite low) recoil energy of a nucleus that has undergone a collision with a WIMP. At the present the direct searches are more sensitive than the indirect searches in terms of the parameter space for minimal supersymmetric models that they can exclude.

2.2. Searches for diffuse sources

A diffuse high-energy neutrino flux is predicted as a consequence of the existence of cosmic rays, which produce neutrinos as a result of their interactions with matter. The energy spectrum of these neutrinos is expected to vary approximately as $E^{-2}$ and, because of neutrino oscillations, the flux is usually assumed to be evenly divided among the three flavors. The flux of atmospheric (electron and muon) neutrinos is also diffuse and represents an irreducible background that must be estimated accurately in order to measure or place limits on a cosmic (i.e., non-atmospheric) diffuse flux. Since the atmospheric flux is softer, falling as $E^{-3.7}$ versus the $E^{-2}$ dependence of a cosmic neutrino flux, the inference of neutrino energy is paramount in conducting such a search. Figure 1 shows this analysis for recent AMANDA data and indicates how an upper limit of $E^2 \Phi > 8.8 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ is set for the flux in the energy range 16 - 2000 TeV [12].

Since the flux is diffuse, searches are not restricted to muon neutrinos, but can also include cascade events induced by electron and tau neutrinos. While these events provide less precise directional information, they have a much lower background and permit better energy resolution. These all-flavor analyses assume that the electron, muon, and tau flavor mixture at the Earth is 1:1:1 from neutrino oscillations. Table II gives current results from these all-flavor searches [12,21].

2.3. Supernovae

The OMs located in the polar ice have very low background counting rates mainly because the ice contains no salt nor any other significant sources of radioactivity. Intrinsic background count rates of less than 1KHz for a single phototube are typical. If there is a supernova in our galaxy, it can be detected as an increase in the background rate during the time the instrumented volume of ice is bombarded by the low-energy neutrinos from the explosion [22]. The lower the intrinsic background rate the greater the sensitivity of the detector to a supernova. AMANDA is a part of the Supernova Early Warning System, or SNEWS network, and the IceCube detector (where background count rates are 300 - 400 Hz) will be as well.

3. IceCube

A neutrino detector with a cubic kilometer of instrumented volume has long been a goal of the neutrino astronomy community. Estimates of neutrino fluxes from a variety of different sources indicate that about one cubic kilometer is needed...
the analog signals from the photomultiplier in situ, whereas in AMANDA this was done on the surface. All communications with the surface electronics are digital. The IceCube Digital Optical Modules or DOMs [Fig. 3] use 10-inch photomultiplier tubes (PMTs) and a DC-to-DC high voltage generator. A low-power custom integrated circuit called the Analog Transient Waveform Digitizer is used to digitize the PMT anode-signal waveform at 300 megasamples/sec. This feature makes it possible to unfold complex waveforms to determine the arrival times of individual photons in a 400 ns time interval, including the first photon, which triggers the waveform digitization [Fig. 4]. A very stable local crystal oscillator running free at 20 MHz is calibrated against a master oscillator on the surface by sending analog signals in both directions in a dedicated time-calibration procedure repeated automatically a few times a second. The time of arrival of a photon can be determined to typically 2 ns rms. When systematic errors are included, the timing accuracy is 3 ns, which is more than sufficient for reconstructing muon tracks. The DOM contains twelve light-emitting diodes, which are used for calibration purposes. Using these it has been possible to study the stability of the timing over a longer period. Figure 5 shows that the timing is stable to better than two nanoseconds over the course of a year [24].

in order to confirm or exclude these estimates in a reasonable period of time, which is the operational lifetime for the detector after completion, or about 10 years.) [2,6]. A km$^3$ is also a reasonable technical goal - it is challenging, but technically feasible based on past experience, at least in ice.

IceCube, if construction continues according to schedule, will be the first neutrino telescope to attain a km$^3$ volume. The 70+ (up to 80) strings are scheduled to be deployed by 2011. During the first season (2005) one string was deployed. The following season eight more were deployed and the third deployment season (December ’06 - January ’07) resulted in 13 strings. The basic performance of the IceCube design was demonstrated by the first string deployed, “String 21” and the first four surface array “IceTop” stations. The equipment deployed the following season exhibited similar performance. This performance, briefly described here, is given in greater detail in refs [8,23,24].

The configuration of IceCube and AMANDA is shown in Fig. 2. Each IceCube string hosts 60 optical modules at depths from 1450 m to 2450 meters below the surface. The modules are spaced 17 m apart in the vertical direction while the strings are spaced 125 m apart horizontally. The location and relative size of the AMANDA strings are indicated in Fig. 2. These strings are operated as a part of the IceCube observatory, which includes the surface air shower array, IceTop, the deep IceCube array, and the AMANDA strings.

The optical module in IceCube digitizes and time-stamps the analog signals from the photomultiplier in situ, whereas in AMANDA this was done on the surface. All communications with the surface electronics are digital. The IceCube Digital Optical Modules or DOMs [Fig. 3] use 10-inch photomultiplier tubes (PMTs) and a DC-to-DC high voltage generator. A low-power custom integrated circuit called the Analog Transient Waveform Digitizer is used to digitize the PMT anode-signal waveform at 300 megasamples/sec. This feature makes it possible to unfold complex waveforms to determine the arrival times of individual photons in a 400 ns time interval, including the first photon, which triggers the waveform digitization [Fig. 4]. A very stable local crystal oscillator running free at 20 MHz is calibrated against a master oscillator on the surface by sending analog signals in both directions in a dedicated time-calibration procedure repeated automatically a few times a second. The time of arrival of a photon can be determined to typically 2 ns rms. When systematic errors are included, the timing accuracy is 3 ns, which is more than sufficient for reconstructing muon tracks. The DOM contains twelve light-emitting diodes, which are used for calibration purposes. Using these it has been possible to study the stability of the timing over a longer period. Figure 5 shows that the timing is stable to better than two nanoseconds over the course of a year [24].
Reliability is a major concern because, once deployed, the strings are frozen in the ice and cannot be accessed nor retrieved. Components are selected for reliability and a DOM undergoes extensive testing at several stages before it is deployed. Experience so far with the nine strings and critical examination of the few failures (of individual DOMs) suggests that the goals for reliability are being met.

The ice itself is a critical component of the detector and its properties must be studied in detail in order to both understand its characteristics and make the most accurate possible track reconstructions. The ice absorbs light (average absorption length is 110 m at a wavelength of 400 nm) and scatters light (the scattering length varies from 6 to 30 m depending on depth and location of dust layers). The calibration devices employed by AMANDA and IceCube have made it possible to learn much about the optical properties of the ice. Figure 6 shows a) the scattering, and b) absorption lengths deduced as a function of depth and wavelength [25]. The ice contains layers of dust, deposited by, e.g., volcanic events occurring over past thousands of years. These have been measured to very high accuracy by a “dust logger” attached at the bottom.
with only the first string deployed. Figure 7 shows a candidate event in which seven of the nine strings participated. The locations of the DOMs are indicated by small black dots, while the size of a colored circle reflects how many photons that DOM recorded, and the color indicates time (red early, blue late). The arrow shows the reconstructed upward-going muon track.

4. Summary and outlook

The performance of IceCube has been examined using the first nine IceCube strings of 60 DOMs each and 16 IceTop surface stations. 98% of all DOMs are functioning well and the system meets or exceeds the design requirements. The resolution of the time calibration system is typically 2 ns. An analysis of cosmic-ray muon events indicates that the overall accuracy relative to the master clock, including any systematic time offsets among DOMs is 3 ns or less. Coincidences between IceCube and IceTop, and between IceCube and AMANDA have been observed. As a result of this excellent performance, at most very minor changes in the hardware are foreseen for subsequent years. In future austral summers the number of strings deployed per season is expected to increase to 14 or more until a minimum of 70 (or maximum of 80) strings are deployed by 2011. The search for neutrino events with IceCube will begin following the commissioning of this (06-07)season’s thirteen deployed strings. The number of modules in IceCube is now twice the number in AMANDA.

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1. http://icecube.wisc.edu
5. See Proc. XXII International Conference on Neutrino Physics and Astrophysics; “Neutrino 2006” Santa Fe, New Mexico, (June, 2006)
23. R. Stokstad for the IceCube Collaboration, in Proc. 11th Workshop on Electronics for LHC and Future Experiments, Heidelberg, (Germany, September, 2005).