Results from the Antarctic Muon and Neutrino Detector Array

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We show new results from both the older and newer incarnations of AMANDA (AMANDA-B10 and AMANDA-II, respectively). These results demonstrate that AMANDA is a functioning, multipurpose detector with significant physics and astrophysics reach. They include a new higher-statistics measurement of the atmospheric muon neutrino flux and preliminary results from searches for a variety of sources of ultrahigh energy neutrinos: generic point sources, gamma-ray bursters and diffuse sources producing muons in the detector, and diffuse sources producing electromagnetic or hadronic showers in or near the detector.
1. INTRODUCTION

Ultrahigh energy (UHE) neutrinos with energies in the TeV range and higher may be produced by a variety of sources. Particle physics exotica like WIMPs and topological defects are expected to produce neutrinos in their annihilation or decay \[1\], and models of astrophysical phenomena such as gamma-ray bursts, active galactic nuclei, supernovae and microquasars \[2\] also predict UHE neutrino fluxes.

AMANDA is sensitive to UHE neutrinos produced by these sources and can provide some of the most stringent tests to date of UHE neutrino production models. More generally, AMANDA and other similar neutrino telescopes \[3\] open a heretofore unexplored window on the universe in a region of the energy spectrum bounded between roughly $10^{12}$ eV and $10^{20}$ eV. In the somewhat narrower energy range between roughly $10^{14}$ eV and $10^{19}$ eV, photons are absorbed by intervening matter and starlight, and cosmic-ray protons are insufficiently energetic to reach us without experiencing unknown amounts of curvature in intervening magnetic fields, leaving neutrinos as the only known particles that can serve as astronomical messengers. Neutrino telescopes are also sensitive to supernova neutrino bursts at neutrino energies of roughly $10^7$ eV.

2. THE AMANDA DETECTOR

The AMANDA-B10 high energy neutrino detector consists of 302 optical modules (OMs) on 10 strings. Each OM comprises a photomultiplier tube (PMT) with passive electronics housed in a glass pressure vessel. The OMs are deployed within a cylindrical volume about 120 m in diameter and 500 m in height at depths between roughly 1500 and 2000 m below the surface of the South Pole ice cap. In this region the optical properties of the ice are well suited for reconstructing the Cherenkov light pattern emitted by relativistic charged particles \[4\]. This light is used to reconstruct individual events. An electrical cable provides high voltage to the PMTs and transmits their signal pulses to the surface electronics. A light diffuser ball connected via fiber optic cable to a laser on the surface is used for calibration purposes. Copious down-going cosmic ray muons are also used for calibration purposes.

In January 2000, AMANDA-B10 was enlarged to a total of 19 strings with 667 OMs to form AMANDA-II. This new detector is 200 m in diameter and approximately the same height and depth as AMANDA-B10. Figure 1 shows a schematic diagram of AMANDA. Design and con-
struction has begun on IceCube, a kilometer-scale device with 4800 OMs on 80 strings [3].

3. ATMOSPHERIC NEUTRINOS AND OTHER PHYSICS WITH AMANDA-B10

AMANDA was shown to be a functioning neutrino telescope by virtue of its ability to reconstruct upward-going muons induced by atmospheric muon neutrinos [6, 7]. A fraction of the atmospheric muon neutrinos produced in the northern hemisphere travel through the earth, interact with the underlying earth or the ice near AMANDA, and produce a muon which can be detected and reconstructed. Using data collected by AMANDA-B10 in 1997, we reconstructed roughly 300 upward-going muons which, as shown in fig. 2, are in agreement with the predicted angular distribution.

AMANDA-B10 data has also been used to set competitive limits on WIMPs [8], monopoles [9], extremely energetic neutrinos [10], UHE $\nu_\mu$ point sources [11] and diffuse fluxes [12].

The detector is also sensitive to bursts of low energy neutrinos from supernovae [13].

4. ATMOSPHERIC NEUTRINOS WITH AMANDA-II

A preliminary analysis of atmospheric neutrino data taken with AMANDA-II demonstrates the substantially increased power of the enlarged detector. Compared to the analysis using AMANDA-B10 data, fewer selection criteria are required to extract a larger and qualitatively cleaner sample of atmospheric neutrino-induced muons. Figure 3 shows the excellent shape agreement between data and simulation achieved with a preliminary set of selection criteria applied. With more sophisticated selection criteria we expect to see roughly twice the number of events shown in the figure (corresponding to 2-3 times more events in AMANDA-II relative to AMANDA-B10 for equivalent live-times) and we also anticipate improved angular response close to the horizon.

5. SEARCH FOR CASCADES WITH AMANDA-B10 and -II

We have performed a full-reconstruction search for the Cherenkov light patterns resulting from electromagnetic or hadronic showers (cascades) induced by a diffuse flux of high-energy extraterrestrial neutrinos. Data collected by AMANDA-B10 in 1997 was used. Demonstrating $\nu$-induced cascade sensitivity is an important step for neutrino astronomy because the cascade channel probes all neutrino flavors, whereas the muon channel is primarily sensitive to $\nu_\mu$. Compared to muons, cascades provide more accurate energy
Data  events 527
Atmos  events 519

Figure 3. Number of upward-going muon events in AMANDA-II data from the year 2000 as a function of zenith angle, using a preliminary set of selection criteria. There are a total of 527 events in the data (solid line), and 519 events predicted by the atmospheric neutrino Monte Carlo (dashed line). Simulations indicate that these events have an energy range given roughly by

100 \text{GeV} \lesssim E_\nu \lesssim 1 \text{TeV}.

With more sophisticated selection criteria we expect improved response near the horizon.

measurement and better separation from background, but they suffer from worse angular resolution and reduced effective volume. In addition, it is straightforward to calibrate the cascade response of neutrino telescopes such as AMANDA through use of, for example, in-situ light sources. As with muons, cascades become increasingly easier to identify and reconstruct as detector volumes get larger.

The electron neutrino produces cascades via the charged current interaction and all neutrino flavors produce cascades via the neutral current interaction. Cascade-like events are also produced in charged current \(\nu_\tau\) interactions.

After application of simple selection criteria to reduce the data sample size while preserving any potential signal events, cascade vertex position, time of production, energy and direction are reconstructed using several maximum likelihood functions that take into account the Cherenkov emission, absorption and scattering of light [14, 15, 16, 17]. This full-reconstruction approach is less susceptible to spurious backgrounds than other techniques.

In the absence of a tagged source of high energy neutrino-induced cascades, we rely on in-situ light sources, catastrophic energy losses by down-going cosmic ray muons, and Monte Carlo simulations to understand the response of the detector. The successful reconstruction of pulsed laser data and the reconstruction of isolated catastrophic muon energy losses, described in [17], demonstrate that the detector is sensitive to high energy cascades. The 90\% C.L. limit on the diffuse flux of \(\nu_e + \nu_\mu + \nu_\tau + \overline{\nu}_e + \overline{\nu}_\mu + \overline{\nu}_\tau\) for neutrino energies between 5 TeV and 300 TeV, assuming a neutrino flux ratio of 1:1:1 at the detector, is:

\[
E^2 \frac{d\Phi}{dE} < 9.8 \times 10^{-6} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}.
\]

(1)

The 90\% C.L. limit on the diffuse flux of \(\nu_e + \overline{\nu}_e\) for neutrino energies between 5 TeV and 300 TeV is:

\[
E^2 \frac{d\Phi}{dE} < 6.5 \times 10^{-6} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}.
\]

(2)

The latter limit is independent of the assumed neutrino flux ratio. (Note that since the limit in Eq. 1 is on the sum of the fluxes of all neutrino flavors, and the limit in Eq. 2 is on an individual flavor, the former limit should be divided by a factor of three to compare it properly to the latter.)

Our results together with other limits on the flux of diffuse neutrinos are shown in fig. 4. Since recent results from other low energy neutrino experiments [18, 19, 20, 21] indicate that high-energy extragalactic neutrinos will have a neutrino flavor flux ratio of 1:1:1 upon detection, in
this figure we scale limits derived under different assumptions accordingly. For example, to do a side-by-side comparison of a limit on the flux of $\nu_e + \nu_\mu + \nu_\tau + \overline{\nu}_e + \overline{\nu}_\mu + \overline{\nu}_\tau$, derived under the assumption of a ratio of 1:1:1, to a limit on just the flux of $\nu_\mu + \overline{\nu}_\mu$, the latter must be degraded by a factor of three. (N.B.: We assume that $\nu_e:\nu_\mu::1:1$, and we take into account the different cross sections for $\nu$ and $\overline{\nu}$.)

It should be noted that most searches of diffuse fluxes shown in fig. 4 are based on the observation of up-going neutrino-induced muons. Only Baikal and AMANDA have presented limits from analyses that search for neutrino-induced cascades and only the AMANDA analysis uses full cascade event reconstruction.

Data acquired by AMANDA-II is currently under study and, as with the analysis of atmospheric neutrinos, preliminary results from that work clearly demonstrate the enhanced power of the larger AMANDA-II detector. Angular acceptance improves to nearly $4\pi$, backgrounds are much easier to reject, and energy acceptance improves by a factor of three to $E_\nu \sim 1$ PeV. In accordance with our blind analysis procedures, we presently use just 20% of the AMANDA-II data from the year 2000, and obtain a preliminary limit which is lower than that described above by roughly a factor of 2–3. For a UHE neutrino flux at the current best limit [27], we would expect to detect about eight UHE-neutrino-induced cascade events in the full 2000 dataset, on an expected background of less than one event. This analysis is described in more detail in a contributed poster at this conference [29].

6. SEARCH FOR UHE $\nu_\mu$ FROM POINT SOURCES WITH AMANDA-II

We have conducted a general search for continuous emission of muon neutrinos from a spatially localized direction in the northern sky. Backgrounds are reduced by requiring a statistically significant enhancement in the number of reconstructed upward-going muons in a small bin in solid angle. Furthermore, the background for a particular bin can be calculated from the data by averaging over the data external to that bin in

Figure 4. The limits on the cascade-producing neutrino flux, summed over the three active flavors, presented in this work and in other experiments, with multiplicative factors applied as indicated to permit comparison of limits derived with different assumed neutrino fluxes at the detector: Baikal ($\nu_e$) [22] (at the $W^\pm$ resonance); Baikal NT96 ($\nu_\mu + \overline{\nu}_\mu + \nu_e$) [23]; Frejus ($\nu_\mu + \overline{\nu}_\mu$) [24]; MACRO ($\nu_\mu + \overline{\nu}_\mu$) [25]; Baikal NT96+NT200 ($\nu_\mu + \overline{\nu}_\tau$) [23, 26]; AMANDA B-10 ($\nu_\mu + \overline{\nu}_\mu$) [27]. Also shown are the predicted horizontal and vertical $\nu_e$ and $\nu_\mu$ atmospheric fluxes [28].
the same declination band. In contrast to other searches, this search is more tolerant of the presence of background, so the signal is optimized on $S/\sqrt{B}$, where $S$ represents the signal and $B$ the background, rather than on $S/B$, which emphasizes signal purity.

Data acquired by AMANDA-B10 in 1997 has been analyzed and the results presented in [11]. With AMANDA-II data taken in 2000, we gain improved sensitivity to events near the horizon since the detector has double the number of PMTs and a larger lever arm in the horizontal dimension. Assuming a customary $E^{-2}$ power law spectrum at the source, and a flux of $10^{-8}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$, we predict approximately two signal and one background events in a $6^\circ \times 6^\circ$ angular bin. Preliminary sensitivities to various point sources are given in Table 1. In order to achieve blindness in this analysis the right ascension of each event (i.e., its azimuthal angle) has been scrambled (at the South Pole this effectively scrambles the event time), and they will only be unscrambled once all selection criterion have been set.

7. SEARCH FOR $\nu_\mu$ FROM DIFFUSE SOURCES WITH AMANDA-II

The search for diffuse sources of UHE $\nu_\mu$-induced muons is similar to the analysis used to detect atmospheric $\nu_\mu$-induced muons, as both analyses require a sample of events with low contamination from misreconstructed downward-going atmospheric muons. Since high-energy muons will deposit more energy in the detector volume than low-energy muons, the diffuse analysis further requires that events have a high channel density, $\rho_{ch} > 3$, where the channel density is defined as the number of hit channels per 10 m tracklength. The background in the signal region is estimated by extrapolating from lower-energy data satisfying $\rho_{ch} < 3$.

Using a 20% subsample of the AMANDA-II data from 2000, we detect 6 events satisfying all selection criteria. Simulations indicate that we would detect 3.0 events from a UHE neutrino flux at the current best limit [11], assuming a customary $E^{-2}$ power law spectrum at the source, and 1.9 events from atmospheric neutrino interactions. (N.B. We use a subsample of the data in order to achieve blindness in this analysis.) The distributions of $\rho_{ch}$ for data, simulated signal and simulated background are shown in fig. 5.

![Figure 5. Distributions of the channel density $\rho_{ch}$ for data, simulated signal and simulated background. The simulated signal assumes a customary $E^{-2}$ power law spectrum at the source and a neutrino flux of $10^{-6}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$. Events are kept if they satisfy $\rho_{ch} > 3$.](attachment:image.png)

The predicted average limit from an ensemble of experiments with no signal, or sensitivity, is roughly $1.3 \times 10^{-6}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$, and the preliminary limit is less than roughly $10^{-6}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$. This is about the same as the limit obtained with the full sample of AMANDA-B10 data from 1997.
Table 1
Preliminary estimated sensitivities of AMANDA-II to various point sources in data taken in the year 2000. The sensitivity is defined as the predicted average limit from an ensemble of experiments with no signal, and is calculated using background levels predicted from off-source data.

| Source  | Declination | $\mu \left( \times 10^{-15} \text{cm}^{-2} \text{s}^{-1} \right)$ | $\nu \left( \times 10^{-8} \text{cm}^{-2} \text{s}^{-1} \right)$ |
|---------|-------------|-------------------------------------------------|-------------------------------------------------|
| SS433   | 5.0         | 11.0                                            | 3.6                                             |
| Crab    | 22.0        | 4.0                                             | 1.9                                             |
| Markarian 501 | 39.8     | 2.5                                             | 1.5                                             |
| Cygnus X-3 | 41.5     | 2.6                                             | 1.6                                             |
| Cass. A | 58.8        | 2.1                                             | 1.5                                             |

8. SEARCH FOR $\nu_\mu$ FROM GRBs WITH AMANDA-B10 and -II

The search for UHE $\nu_\mu$–induced muons from gamma-ray bursts (GRBs) leverages temporal and directional information from satellite-based observations of GRB photons to realize a nearly background-free analysis. Assuming the predicted spectrum $[30]$, we search for muon neutrinos in the energy range of 10 TeV–100 PeV and use off-time data to estimate background and to achieve blindness in the analysis.

The analysis looks for enhancements in the rate of upward-going muons in time windows coinciding with the reported GRB “T90” time window $[31]$, which can range from roughly 2 s to 50 s in width, and in the reported GRB direction. Detector stability over these time scales is therefore an important measure of how effective this analysis can be. Figure 6 shows the count rate per 10 s bin in a time window of roughly ±1 hour around a particular GRB, using events which have passed certain basic selection criteria. The good agreement with a Gaussian distribution shows that the detector did not experience instrumental effects which in principle could mimic a GRB. Plots for all the other GRB in the sample exhibit the same Gaussian behavior. In the AMANDA data spanning the years 1997–2000, we anticipate having a sample of roughly 500 GRBs to search for neutrino emission.

Figure 6. The average event count per 10 s period, demonstrating the high stability of the AMANDA-II data. Some basic event selection criteria have been applied.

9. CONCLUSIONS

The Antarctic Muon and Neutrino Detector Array is a functioning neutrino telescope which has been used to search for a variety of interesting possible sources of ultrahigh energy neutrino flux. Data from AMANDA-B10 have been searched not only for upward-going muons but also for
electromagnetic and hadronic showers using full event reconstruction for the first time. Data from AMANDA-II have been searched in preliminary analyses for $\nu_\mu$-induced muons and $\nu_x$-induced showers, and in all instances the enhanced sensitivity of the enlarged detector is clearly evident. We therefore have confidence that AMANDA-II analyses will yield significantly improved limits over those published using AMANDA-B10 data—or perhaps the analyses will yield the discovery of UHE neutrinos.

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