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Results from the AMANDA neutrino telescope

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We review recent results from AMANDA on the search for cosmic point sources of neutrinos, both in the diffuse and point-like channels. Assuming a E^{-2} spectral shape of the neutrino energy at the source, we derive limits on the diffuse ν_μ flux as well as in the all-flavour diffuse flux from the cascade search. We report limits on selected point sources as well as on GRB searches. We present results on primary cosmic CR composition in the range ~ 100 TeV–PeV obtained with the help of the SPASE air shower array run in coincidence with AMANDA.

1. INTRODUCTION

High energy neutrino astronomy is a natural extension to traditional cosmic ray physics. They share the interest on the same objects as potential accelerators of the cosmic rays observed at Earth. Candidate cosmic accelerators include supernova remnants, the accretion disk and jets of Active Galactic Nuclei (AGN), or the violent processes behind Gamma Ray Bursts (GRB). Neutrinos are expected to be produced in these violent environments through proton-proton or proton-photon collisions and subsequent decay of the created pions. Although these objects 'work' at different energies, it is believed that in the most violent environments protons can be accelerated to energies of the order of \gtrsim PeV and, according to most models, one should therefore expect neutrinos to be produced at TeV energies and above.

While the original direction of the protons can be randomized by intergalactic magnetic fields and photons are easily absorbed in the infrared background, neutrinos have the advantage of traveling cosmic distances unabsorbed and undeflected. This turns into a disadvantage when trying to detect them, requiring large detector volumes to collect a decent rate. At extremely high energies, $\mathcal{O}10^{20}$ eV, where protons would point to their sources, they are also absorbed by the CMB. At such energies the detection of cosmic rays suffers from the GZK suppression, rendering the size of the visible Universe to ~ 10 Mpc. A similar effect occurs for UHE gamma rays.

The AMANDA detector has been built to explore the high energy universe in neutrinos, using the advantages of neutrinos as cosmic messengers.

2. THE AMANDA DETECTOR

The AMANDA detector consists of an array of optical modules (OM) buried deep in the ice at the South Pole. The OMs consist of a Hamamatsu 8-inch photomultiplier tube housed in a glass sphere. They are connected to the surface electronics by a copper cable which supplies

the high voltage to the photomultiplier tube and transmits the signal to the surface. Some of the modules were connected also through a fiber optic cable in order to test the technique.

Due to the complexity of the construction and the constraints set by the site, the detector was built in stages between 1996 and 2000. In this paper we will mention results from the 10-string detector, AMANDA-B10, and from the full AMANDA array, AMANDA-II. AMANDA-B10 consisted of 302 OMs in 10 strings arranged in two concentric circles, the outer one with a diameter of 100 m. and was operational during 1997. The AMANDA-II detector was completed in 2000 and it consists of an additional circle of 9 strings, increasing the total number of OMs to 677 and the detector diameter to 200 m. The typical OM vertical separation is 10 m. and the inter-string separation about 50 m. The instrumented height is 500 m, between 1500 m and 2000 m under the ice surface.

With the help of calibration devices deployed with some strings and a YAG laser at the surface, we have mapped the optical properties of the ice at the depths of the detector [1]. The antarctic ice is very transparent in the window of Cherenkov wavelengths, with an absorption length of ~ 110 m at 400 nm. The scattering length is quite independent of wavelength, but it reflects the impurities of the ice with depth. It is about 20 m at 400 nm with variations of more than a factor of two for specific depths.

Muons produced in charged-current ν_μ -nucleon interactions near the array are detected by the Cherenkov photons they emit. Electromagnetic and hadronic cascades that result from neutral current interactions of all three flavors or from charged-current ν_e and ν_τ are also detected through the Cherenkov light of the produced secondaries. AMANDA is therefore an all-flavor neutrino detector. This is important in the context of neutrino oscillations since neutrinos are expected to be produced at the source with the ratio $\nu_e:\nu_\mu:\nu_\tau=1:2:0$ (typical from pion decay), but are expected at the Earth with a ratio 1:1:1.

Events are reconstructed by minimizing the log-likelihood that the timing of the produced light pattern is compatible with a track or cascade hypothesis [2]. The current angular resolution for muon tracks lies between 1.5° and 2° , while the cascade angular resolution is $\approx 30^\circ$. This just reflects the longer lever arm for reconstruction of muon tracks, while cascades produce more spherically-shaped light patterns. For this same reason, the energy resolution (correlated to the total light detected) is better for cascades, $\sigma(\log E) \approx 15\%$ than for muon tracks, $\sigma(\log E) \approx 40\%$.

3. PHYSICS TOPICS AND RESULTS

AMANDA can be used for different physics topics, ranging from astrophysics to particle physics. Due to the focus of this conference we will restrict here to those topics more closely related to high energy astrophysics, rather than to particle searches. We will present recently obtained results on searches for a diffuse neutrino flux using different signal channels and energy ranges, results from the search for point sources and results from cosmic ray composition studies using downward-going muons. A recent summary that includes results of other AMANDA topics can be found in [3]

3.1. General analysis strategies

The analyses summarized in the next section are all based in the following simulations. For the background atmospheric muon flux we have used the CORSIKA [4] air shower generator with the QGSJET hadronic interaction model. The average winter atmosphere at the South Pole has been used. For the neutrino signal we have used two AMANDA-grown generators, `nusim` and a newly developed generator which treats all-flavor generation in a more consistent manner, `ANIS` [5]. Both can be weighted to any desired spectrum, so we produced events following an E^{-1} spectrum, that was later re-weighted to an atmospheric spectrum, an E^{-2} or to the spectra predicted by the specific models probed.

The muons were propagated through the ice including stochastic energy losses using the program MMC [6].

A detailed simulation of the detector response is performed for both signal and background events, including individual OM response to light, trigger simulation and pulse recording. A specific ice model needs to be used at this stage to determine the pulse timing. After the detector simulation, data and simulated events are written in the same format and the same reconstruction and event selection procedure is done on both sets.

The main sources of systematic uncertainties in the analyses mentioned below are the muon propagation and the ice model parameters in the detector simulation. For most of the analyses presented in this summary, the systematic uncertainties amount to $\sim 25\%$. In the case of the search for UHE events, one should include the uncertainty of the neutrino-nucleon cross sections at these energies, which are just model-dependent extrapolations of accelerator measurements at lower energies [7]. There is an additional uncertainty, common to all analyses which use the atmospheric neutrino simulations as background estimation, in the absolute normalization of the atmospheric neutrino flux, only known to within $\sim 25\%$ at energies $\gtrsim 100$ GeV, which is just a translation of the uncertainties in the primary cosmic ray flux.

We emphasize that AMANDA presents all its limits following the ordering scheme described in [8] and including all systematic uncertainties in the calculation of the limit according to the method derived in [9]. We should also mention here that AMANDA follows the policy of performing all analysis in a 'blind' manner to guarantee statistical purity of the results. Cuts are optimized on a subsample of the data set, which is then not used to obtain the final result, or on a time-scrambled data set, which is just unscrambled after cut values have been optimized and frozen.

3.2. Diffuse search

Even if individual sources turned out to be too weak to produce an unambiguous neutrino signal from their direction in a detector of the size of AMANDA, the summed neutrino output from all

sources could produce a detectable diffuse 'glow'.

We have performed such search with data collected during 130 days of live-time in 1997 with the AMANDA-B10 detector [10]. An analysis with data taken during 2000 is under way. This analysis is designed to retain high-energy events, since the expected energy spectrum from shock acceleration in cosmic sources ($\propto E_\nu^{-2}$) is harder than that of atmospheric neutrinos, $\propto E_\nu^{-3.7}$. The energy of the muon is correlated to the total light detected by the array, higher energy muons producing more light from catastrophic energy losses along the track. We have used the hit-channel multiplicity as the main variable to separate the expected signal-like events from the atmospheric neutrino background, and optimized to cut in such variable for best sensitivity. After applying all the quality cuts to the data and simulated atmospheric neutrino background, we obtain 3 data events while we expect 3.1 atmospheric neutrinos. Including the systematic uncertainties this leads to a 90% CL flux limit on an E_ν^{-2} spectrum in the region 3 TeV to 6 PeV of $E_\nu^2 \Phi(E_\nu) = 8.4 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, which is shown in figure 1 as the full line labeled 'AMANDA-B10 $E^{-2} \nu_\mu$ '.

Given specific models of neutrino production, the cut optimization can be done to maximize sensitivity to probe any chosen model. We have done this for a sample of predictions resulting in that three of the models in the market are excluded at 90% CL ([11–13]). Figure 1 shows the prediction and the AMANDA limit on one of them, from reference [11]. This is an important result since brings AMANDA to the level of sensitivity to predictions of current neutrino production models in AGN and allows the detector to probe concrete physics predictions.

3.3. Diffuse cascade search

Another search for a diffuse neutrino glow can be done in the cascade channel, being sensitive to all neutrino flavors. The cascade analysis is sensitive to the whole sky since down-going neutrinos can also interact nearby the detector producing a detectable cascade. A previous analysis with data taken in 1997 with the AMANDA-B10 detector has been published in [14]. Here we describe the

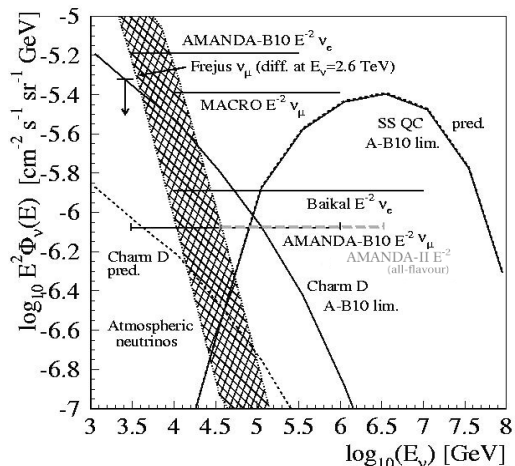


Figure 1. 90% CL limits on the neutrino flux from the diffuse search and from the all-flavor cascade search (dashed line in lighter shade) assuming a E^{-2} spectrum. We have end-marked both lines to emphasize the different energy coverage of both analyses. Shown in the figure is also the limit obtained for an specific AGN model ([11]) which is disfavored and the AMANDA-B10 limit on neutrinos from charm production in the atmosphere. Limits from other experiments are shown for comparison.

more recent analysis performed with data taken with AMANDA-II during 197 days of live-time in 2000 [15].

Given the energy range we are looking at (50 TeV to \sim PeV), the contamination from atmospheric muons is reduced to negligible levels, as well as the atmospheric neutrino background. We have simulated signal events for the three flavors for an assumed spectrum of E_ν^{-2} and from all directions. After all cuts are applied, 1 experimental event remains, while $0.90_{-0.43}^{+0.69}$ events are expected from atmospheric muons and $0.06_{-0.04}^{+0.09}$

from atmospheric neutrinos. This leads to a 90% CL limit on the diffuse flux of neutrinos from all flavors in the region 50 TeV to 5 PeV of $E_\nu^2 \Phi(E) = 8.6 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. As for the diffuse ν_μ search mentioned in section 3.2, the cascade analysis can be optimized for given model predictions. Figure 1 shows the E_ν^{-2} limit compared to several models and to the result of the diffuse search in the muon channel. Note that the published cascade limit with AMANDA-B10 data in [14] was $E_\nu^2 \Phi(E) = 8.9 \times 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. Since the live-times of both analyses are just about 50% different, the improvement of an order of magnitude is mainly due to the increased sensitivity of AMANDA-II due to its larger size.

3.4. UHE neutrino search

Above a few PeV, the increasing neutrino cross section with energy makes the Earth opaque. Above such energies the events should concentrate near the horizon, where the path length is still not enough for complete absorption. We have performed a search for events in the range 1 PeV–3 EeV near the horizon using data from 130 days of live-time in 1997. A new analysis with data from 2000 is underway. At these energies the atmospheric neutrino background is negligible, and the main source of background arises from mis-reconstructed atmospheric muon bundles. A somewhat different event selection techniques were developed for this analysis. A neural network based event selection was used, where in addition of the hit channel multiplicity and reconstruction quality variables, the number of hit channels with exactly one hit proved to be a good discriminant variable. The upper energy range available to this analysis is limited by detector saturation effects: muons or cascades from neutrinos in the EeV energy range emit enough light to illuminate the whole detector, and at about a few EeV, the event energy reconstruction based on the detected light becomes unreliable.

Assuming an E^{-2} spectral shape on the neutrino energy, and not having detected any excess over the expected background, we have set a pre-

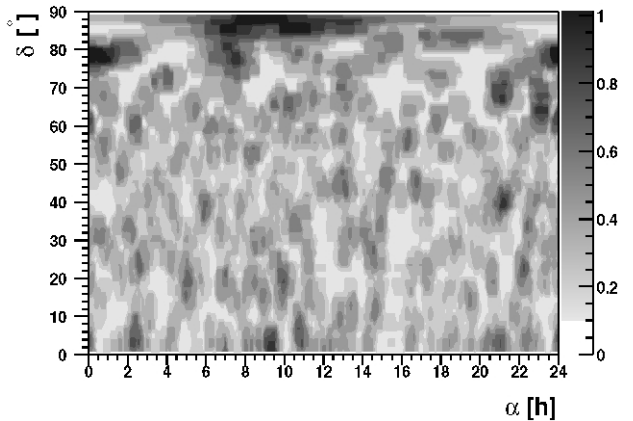


Figure 2. 90% CL limits in equatorial coordinates in units of $10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ for an assumed E_ν^{-2} spectrum, integrated above 10 GeV. Systematic uncertainties are not included in this plot.

liminary 90% CL limit of $E_\nu^2 \Phi(E_\nu) < 1.5 \times 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ in the range $1 \text{ PeV} < E_\nu < 3 \text{ EeV}$, assuming a ratio $\nu_\mu:\nu_e:\nu_\tau = 1:1:1$ at the Earth. This limit excludes as well the predictions of the model of reference [11], in agreement with the diffuse search mentioned in the previous section, and sensitive to lower neutrino energies.

3.5. Point source search

The main aim of neutrino telescopes is the detection of neutrinos from resolved cosmic accelerators, whether known in the electromagnetic spectrum or not. In this section we summarize the results of a search for an statistically significant excess of events from any spot in the northern sky.

The extended size of AMANDA-II shows a greatly improved sensitivity as a function of zenith angle (see figure 3), down to practically the horizon, as compared with a previous analysis using data from 1997 with the AMANDA-B10 detector [16]. The integrated declination averaged sensitivity above 10 GeV for an assumed E^{-2} spectrum is $2.3 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$. Using data collected during 197 days of live-time in 2000 we

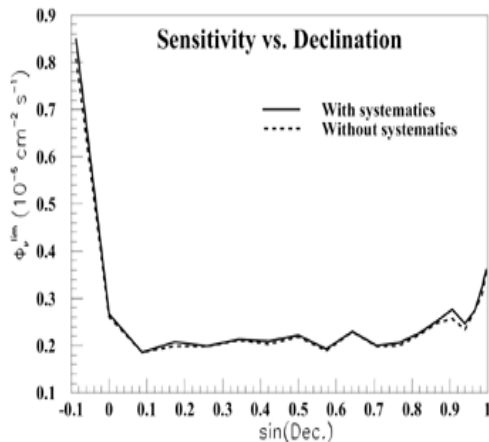


Figure 3. AMANDA-II sensitivity in units of $10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ as a function of declination for an assumed differential E^{-2} spectrum.

have performed a grid search for an event excess in the region $0^\circ < \delta < 85^\circ$ [17]. The size of the search bins has been optimized for each declination band with widths ranging from 6° to 10° . This search benefits from the fact that we can use off-source data as background estimation in each declination band. Figure 2 shows the 90% CL upper limit sky in units of $10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ for an assumed E_ν^{-2} spectrum integrated above $E_\nu = 10 \text{ GeV}$.

We have also performed a search around a number of known blazars, microquasars, SN remnants and other candidates, assuming an E_ν^{-2} spectrum in each case. For this analysis a circular search bin centered at the candidate position has been used. The radius of the bin has been optimized for each candidate. The number of background events is taken from the off-source part of the declination band of the object. The non detection of a signal for any of the candidates has allowed us to set limits on the neutrino flux from each of them. In table 1 we show the limits obtained for

a few selected objects. See [17] for more details.

3.6. GRB search

A special kind of point source search is the search for neutrinos coincident with GRBs. In this case we have the additional handle of the timing of the event, obtained from the detecting satellite. The detector stability at the time of the burst is assessed by monitoring the noise rate within one hour before and after the event. The search for an statistically significant excess of events in AMANDA is done in a time window of ± 5 minutes around the GRB. We have used the GRB sample collected by the BATSE instrument on board of the CGRO satellite. AMANDA and BATSE data taking periods overlapped between 1997 when AMANDA-B10 started taking data, until 2000, when CGRO was decommissioned. We have analyzed a total of 312 BATSE triggered bursts from this period. No excess of events was observed in coincidence with any of the bursts. Assuming a broken power law Waxmann-Bahcall type spectrum [18] with $E_{\text{break}} = 100 \text{ TeV}$, we obtain a 90% CL upper limit on the expected neutrino flux at the Earth of $4.8 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

There is a class of events that did not trigger the BATSE detector but were found by a later off-line analysis on archived data [19]. This class amounts to 26 events during 2000 in the northern hemisphere during the up-time of AMANDA. Since 2000 the only source of GRB detection is the Interplanetary Network, a group of satellites with GRB detectors on board which uses triangulation to spacially locate the burst. We have used their catalogue to add 44 new bursts to the 2000 set. The addition of these bursts to the analysis is not straightforward since there are issues of sensitivity of the different detectors to consider, as well as the dependence of the model being tested on information gathered from the triggered BATSE bursts. Work to obtain a statistically consistent limit with the addition of these new 70 bursts is under way.

Table 1

90% CL upper limits on the muon-neutrino flux from several selected candidate sources in units of $10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$ assuming a E^{-2} spectrum and integrated above 10 GeV.

source	Dec. [$^{\circ}$]	RA [h]	n_{obs}	n_b	Φ_{ν}^{lim}
SS433	5.0	19.2	0	2.38	0.7
M87	12.4	12.51	0	0.95	1.0
Cassiopeia A	58.8	23.39	0	1.01	1.2
Cygnus X1	35.2	19.97	2	1.34	2.5
Cygnus X3	41.0	20.54	3	1.69	3.5
Markarian501	39.8	16.90	1	1.57	1.8
Markarian421 (fm)	38.2	11.07	3	1.50	3.5
Crab	22.0	5.58	2	1.76	2.4

3.7. Cosmic-ray composition at the knee

The South Pole Air Shower Array (SPASE) [21] located at the surface of the ice about 360 m from the vertical of the AMANDA center, and provides a unique tool for studying the composition of cosmic rays at energies above 10^{15} eV by running it in coincidence with AMANDA. SPASE is used to reconstruct the position direction and electron content of air showers, while AMANDA can measure the muon component. Track reconstruction in AMANDA for coincident events benefits from the knowledge of the shower core location at the surface, reducing the number of degrees of freedom of the fit and giving an angular resolution of less than half a degree.

The muon energy at the detector depth is estimated from a fit of the expected light intensity of a muon bundle as a function of lateral distance to a given OM. This quantity correlates with the total number of electrons in the shower measured by SPASE. By means of CORSIKA simulations these two observables can be related to the energy and mass of the primary. The resolution achieved in the determination of the primary energy is energy dependent itself, and it is about 10% in $\log(E)$ in the range 1 PeV to 10 PeV. Figure 4 shows the result of plotting the energy of the primary versus its mass, comparing the results of AMANDA using data from 1998, with other existing experiments. The error bars for all experiments are statistical only. In the

case of AMANDA, systematic uncertainties arise from the choice of the shower generation model and muon propagation in the ice. The estimated systematic uncertainties for this analysis are at the level of 30%.

The AMANDA results are compatible with an increase of the primary mass in the range 1 PeV to 6 PeV, and in agreement with HEGRA, KASCADE, EAS-TOP/MACRO and Chacaltaya for example, but in disagreement with BLANCA and DICE, which seem to indicate a lighter primary component at such energies. Details of this analysis can be found in [20]

3.8. Summary and Outlook

AMANDA has reached the sensitivity to probe specific physics models predicting neutrino production in AGN and blazars, having disfavoured a few of them at 90%CL with the results of the diffuse, cascade and UHE analyses. We have also vastly improved our limits on known point source candidates from previous analyses by using the extended AMANDA-II detector, operational since 2000.

Using events in coincidence with the surface scintillator array SPASE allowed us to study the composition of air showers at energies between 400 TeV and 6 PeV. The results indicate a mass dependence with energy that is compatible with an increase of primary mass in such energy range.

We have recently finished a common processing of

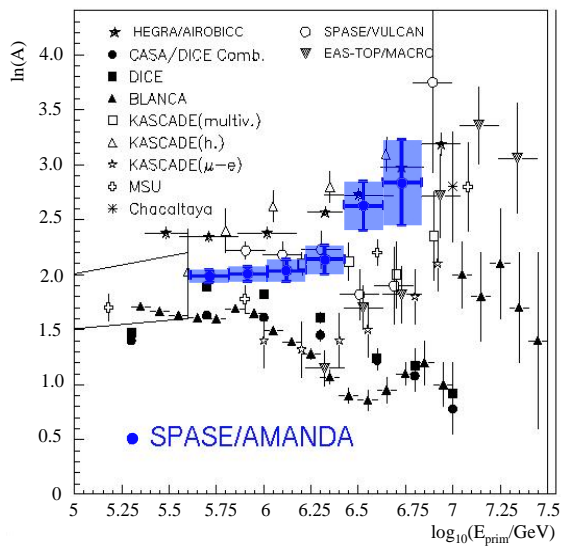


Figure 4. SPASE/AMANDA composition results as a function of primary energy, compared with other experiments.

four calendar years of data, from 2000 to 2003 and results of different analyses from this extended data set will be available soon. Since the beginning of 2004 AMANDA-II is fully equipped with a new fully digital read out that improves single photoelectron detection and will therefore improve energy resolution for the UHE analysis.

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