A search for point sources of high energy neutrinos with the AMANDA neutrino telescope

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Abstract

This paper describes a search for astrophysical point sources of high energy neutrinos using AMANDA-B10 data from 1997. The current status of elimination of backgrounds is shown, including both downgoing cosmic-ray muons penetrating the ice sheet and upgoing atmospheric neutrino events. We expect to present limits on the flux of astrophysical neutrino sources in the Northern sky at the conference.

Motivation

The origin of ultra high-energy ($> 10^{12}\ eV$) cosmic rays is an enduring mystery in astrophysics. Detection of extraterrestrial neutrinos would be a potential window into how these particles are produced. Unlike photons or protons, neutrinos can reach us essentially without attenuation in flux from even the largest red-shifts, with no bending from magnetic fields.

EGRET's detection of γ-rays from more than 40 active galactic nuclei (Fichtel et al., 1994) and the Whipple group's observation of Markarian 421 above $0.5\ TeV$ (Punch et al., 1992) have motivated searches for even higher energy sources. The search for ultra high-energy extraterrestrial neutrinos is an independent way to investigate active compact objects like pulsars and active galactic nuclei (AGN). Evidence for neutrino emission will unambiguously demonstrate that charged pions are produced and hence UHE protons and nuclei are accelerated.

In this report we describe a search for astronomical point sources of ultra high-energy neutrinos using the AMANDA detector, and status of present sensitivity. We expect to present limits at the conference.

1 Data

The AMANDA-B10 detector are described in detail elsewhere (Hill, 1999). The detector consists of 302 optical modules spaced along 10 strings of cable, located at depths of 1500 to $2000m$ in the ice below the South Pole. The data used in this search were collected between March and October of 1997. A total of 5×10^8 events triggered the detector during this time. These data were reduced by $\sim 90\%$ using a fast filtering routine (Dahlberg, 1998) to select upward-going muons, leaving 4.5×10^7 events that were reconstructed and analyzed. Downward-going muon events are totally dominated by penetrating cosmic rays generated in the atmosphere, and were not considered. Thus, the data are only sensitive to neutrino sources in the Northern sky.

The filtered data were reconstructed by fitting the Cherenkov light cone generated by a relativistic muon to the observed arrival times of the light (Wiebusch et al., 1998). The hit probability as a function of time were calculated using a new function that produces improved angular resolution and efficiency (called a "U-Pandel" function). After reconstruction, selection criteria were applied to suppress background events.

Data presented in this paper were selected using the same quality criteria ("Level 3") described in other analyses (Karle et al., 1999). These cuts improve angular resolution, and reduce background from misreconstructed downgoing muons to minor levels. However, the cuts also greatly reduce the acceptance of upgoing events away from vertical.

The primary selection criterion is the quality of the reconstruction fit, as measured by the number of phototube hits which are consistent with approximately un-scattered Cherenkov light emitted by the muon. Secondary criteria are topological variables which ensure that the events represent extensive tracks.

† See talk of F. Halzen (HE 6.3.01) for the full list.

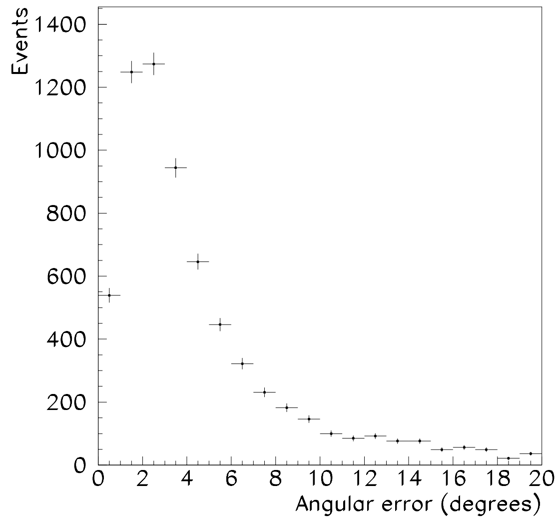

Figure 1: Space angle error (ψ) of neutrino events from a source with an E^{-2} energy spectrum, as expected from Monte Carlo.

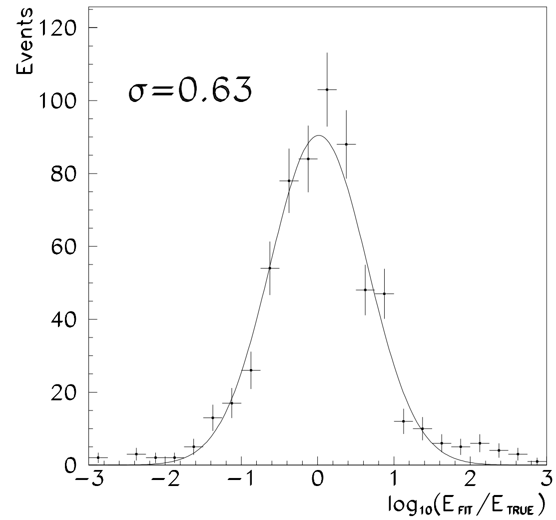

Figure 2: Ratio of estimated to true energy of neutrino events from a source with an E^{-2} energy spectrum, as expected from Monte Carlo.

Figure 1 shows the angular resolution expected from Monte Carlo with the Level 3 cuts, assuming neutrinos from a point source with an E^{-2} energy spectrum (Protheroe, 1996). Angular resolution is shown by the distribution of space angle difference (ψ) between the true and reconstructed track. This is total angle difference including both zenith and azimuthal angular differences. The median angular resolution for the Level 3 cuts is $\sigma_\psi = 3.4°$. The angular resolution of the detector varies only slightly as a function of zenith angle ($\pm 5\%$).

Results from optimization of selection criteria for this search will be presented at the conference. A key addition will be selection on an estimate of muon energy currently under development. This selection is necessary to reduce background due to atmospheric neutrino events, which have an energy spectrum of $E^{-3.8}$ compared to the E^{-2} spectrum expected for a point source. The energy criteria should also help select well-reconstructed events.

The muon energy is estimated using the distance of each optical module from the fitted muon track. i.e. An optical module close to the track that did not fire indicates a low-energy muon, while an optical module far from the track that did fire indicates a high energy muon. The likelihood from all modules are combined and fitted for a best guess energy.

Figure 2 presents a preliminary energy resolution of Monte Carlo events, shown as log of the ratio of true to reconstructed energy. This estimate was made using only binary information of whether or not each module was hit. Information from amplitude and time-width of the pulses is currently being added into the energy estimate. By combining information from the binary hit information with the pulse information, a more sensitive measurement can be made.

Absolute energy scale and angular scale will be calibrated by using coincident events between AMANDA and a surface array (SPASE-2). The SPASE-2 coincident events and Monte Carlo can be used to verify that there is no systematic trend for average zenith angle mismatch as well as the overall efficiency of the detector.

2 Analysis Technique

In this analysis we survey the data as a function of the equatorial coordinates right ascension (α) and declination (δ). At the South Pole, α corresponds exactly to zenith angle, while δ corresponds to azimuthal angle with a random phase shift. Our sensitivity thus varies with zenith, while azimuthal variation is averaged

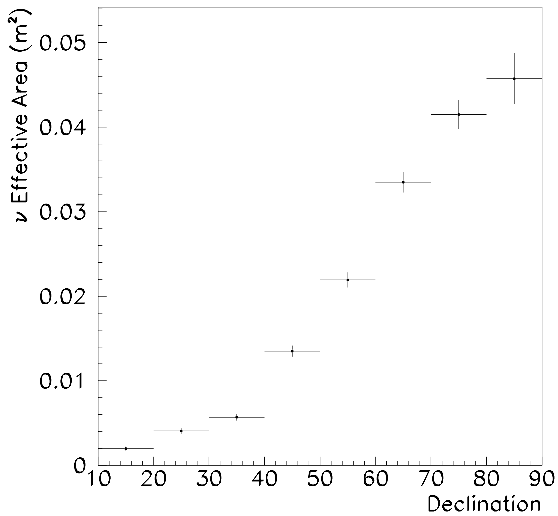

Figure 3: Neutrino effective area ($E_\nu > 1\ TeV$) as a function of declination (δ) for a source with an E^{-2} energy spectrum and $E_\nu > 1\ TeV$, using "Level 3" cuts (which are not optimized for this search). The error bars represent Monte Carlo statistical errors only.

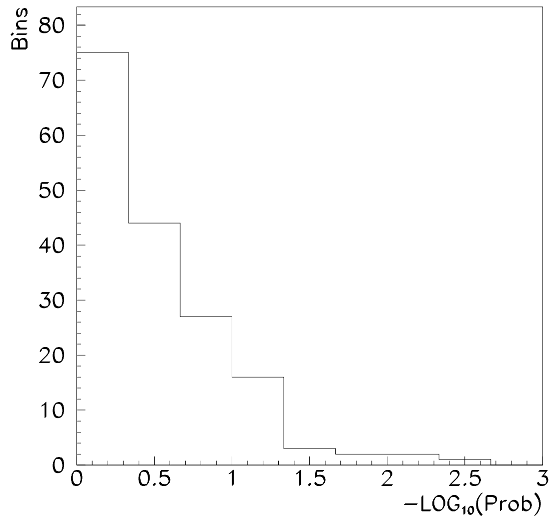

Figure 4: Distribution of significance for the 172 data bins in declination and right ascension. Significance is shown as $-\log_{10}(P)$ where P is the Poisson probability for that bin. i.e. $-\log_{10}(P) = 2$ corresponds to 1% probability.

out. The sensitivity is estimated using a Monte Carlo calculation which takes into account fluctuations in muon range and the screening effect of the Earth of high energy neutrinos (Hill, 1997). The Monte Carlo simulates sources with an E^{-2} energy spectrum of ν_μ, starting from a minimum energy (E_ν^0) of $1\ TeV$. Throwing against the cross-section ($\sigma_{\nu\mu}$), this generates events over a large volume which have probability (P_{ev}) of passing the specified cuts. The sensitivity can be expressed as a neutrino effective area ($A^\nu_{eff}(E_\nu)$, as follows:

$$A^\nu_{eff}(E_\nu(E_\nu) = \sigma_{\nu\mu}(E_\nu)\ n\ V\ P_{ev} \tag{1}$$

where n is the density of ice (in moles times Avogadro's number) and V is the generation volume.

Figure 3 shows the effective area of the detector (A^ν_{eff} in m^2) in response to neutrinos for the Level 3 cuts as a function of declination of the incoming neutrino. Note that for these cuts, the effective area decreases sharply for tracks away from vertical. The absolute error in Optimization of the cuts for this search (including use of the energy estimate) will allow increased acceptance for sources away from vertical.

The 90% confidence limit of neutrino flux (ϕ_ν) then depends on the number of data events (N_0) and expected background events (N_b) in the bin, the mean neutrino effective area ($< A^\nu_{eff} >$) for detecting a signal event from the source, and the efficiency ϵ of source events falling in that bin.

The efficiency ϵ is a function of the angular resolution (σ_ψ) and the size and shape of the bin. When checking a source at a known location, the signal-to-noise rate is optimized for a Gaussian error by choosing an circular region of $1.6\ \sigma$ centered on the source, giving an efficiency of $\epsilon \approx 0.85$. The expected number of events (N_e) is then:

$$N_e = \epsilon \left[\int_{E_\nu^0}^{\infty} \frac{d\phi_\nu}{dE_\nu} A^\nu_{eff}(E_\nu) dE_\nu \right] t_{live} \tag{2}$$

where t_{live} is the live-time of the data, in this case 81 days or $6.9 \times 10^6\ sec$. This is converted to a limit on neutrino flux by finding the upper limit of expected events (μ_2) based on N_0 and N_b.

$$\phi_\nu(E_\nu > 1\ TeV, E^{-2}) = \frac{\mu_2(N_0, N_b)}{\epsilon\ A^\nu_{eff}\ t_{live}} \quad (90\%\ CL) \tag{3}$$

For a hypothetical source at ($\delta = 65°$), the neutrino flux limit would be $5.8\mu_2 \times 10^{-6}\ m^{-2} sec^{-1}$ for ($E_\nu > 1\ TeV$).

3 Sky Survey Technique

For the full sky survey, we divide up the sky into bins of approximately equal solid angle (Ω). Bins at the equator subtend exactly 10° in δ and 10° in α. Away from the equator, the bins are still 10° in δ, while the number of bins in α is the nearest integer to providing equal solid angle ($.0298 < \Omega < .0318$ steradians). This results in 416 bins for the whole sky, or 172 bins over our observable region of $\delta > 10^\circ$.

Figure 4 shows the distribution of significance using Level 3 cuts for each of the 172 bins in δ and α. The significance is calculated using the Poisson probability (P) of each bin, taking the mean of that bin to be the average of the other bins at the same declination. Plotted is the negative $\log_{10}$ of the Poisson probability (P) of each bin. i.e. $-\log_{10}(P) = 2$ corresponds to 1% probability. There are three bins with $\log_{10}(P) > 2$ (corresponding to 1% likelihood), which is consistent with random fluctuation of 172 entries. The current data show no evidence for point sources.

Note that the sensitivity of the search may be significantly decreased if a potential source is on the edge of a bin, since the signal is then split. This is checked for by re-binning the data with an offset of 5° in δ and recalculated bins in α.

4 Results

At present, 4.5×10^7 events that passed the filter have been reconstructed and analyzed. These represent 80 days of live time, or roughly half the statistics for 1997. The results are consistent with downgoing muon background and atmospheric neutrinos. Limits will be presented based on these data at the conference.

The efficiency of the filter is currently being improved as the complete 1997 data set is being re-analyzed. The energy resolution is being optimized by combining hit information with the amplitude and pulse width information. The absolute energy scale will then be calibrated by using coincident events with SPASE-2. Finally, the changes in the energy resolution and filtering will allow a re-optimization of the cuts to maximize the signal to noise.

Acknowledgments

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