Search for Point Sources of High Energy Neutrinos with AMANDA

Addendum to the IceCube Proposal

The AMANDA Collaboration

March 27, 2000

This addendum describes the search for astronomical point sources of high-energy neutrinos using the AMANDA detector. It updates the results presented in the proceedings to the TAUP99 conference. The complete data set from 1997 (approximately 138 live days) was analyzed. No point source candidates were identified. For sources with $E^{-2}$ spectra, the detector exceeds 10,000 m$^2$ in average muon effective area between declinations of 50 and 90 degrees. Preliminary flux limits for declinations larger than +45 degrees are competitive with the best limits in the Southern sky. Many of the plots in this report are best viewed in color. The postscript version of this file can be downloaded from http://www.ps.uci.edu/~amanda.

1. INTRODUCTION

The search for astrophysical sources of high energy ($E_\nu > 1$ TeV) neutrinos is one of the central missions of the AMANDA detector. In this report, we describe the status of a general search for continuous emission in the northern sky, restricted to declination greater than +10 degrees. The data was collected between April and October of 1997. Due to construction, the array was not powered until after February. Operations ceased between late October, 1997 and February, 1998, due to additional construction of the AMANDA array. Furthermore, limitations in the data acquisition and archiving system during that first year of operation reduced the maximum lifetime to approximately 140 days.

Most theoretical models of potential astrophysical sources predict that the neutrino energy spectrum is very hard, approximately $E^{-2}$. Therefore, the most probable energy of the detected neutrino is well above 1 TeV (typically 10-30 TeV for hard spectra). The analysis procedure utilizes two essential characteristics of the signal to simplify the analysis relative to atmospheric neutrino measurements. First, the sources are assumed to be point sources in the sky, so only events within a selected angular region are considered. Secondly, we use the topological characteristics of spectrally hard neutrino signal to reject poorly reconstructed atmospheric muons, which have softer spectra. We have utilized a variable initially designed to estimate energy to help discriminate between signal and several classes of background topologies.

The search for point sources differs from the atmospheric neutrino search in several ways. First, by concentrating on harder spectra, the effective area of the detector can be increased by relaxing the background rejection criteria. Unlike many neutrino detectors, the effective sensitivity of AMANDA varies dramatically as a function of the background rejection requirements, which are less demanding for point sources compared to diffuse sources. The point source analysis tolerates a larger background contamination in the final data sample, so the analysis procedure optimizes on signal to noise rather than signal purity.

The relaxed rejection requirements eliminate fewer background events, which simplifies the task of background simulation. Fewer statistics need to be generated to achieve the requisite statistical precision. The comparison between data
and background Monte Carlo only needs to be carried to relatively modest levels.

Point searches require an assessment of the angular resolution and absolute pointing accuracy. Sources are revealed by a statistically-significant clustering of events within a selected angular bin. The optimal bin size and shape depend on the two-dimensional point-spread function, estimated by computer simulation and confirmed by the analysis of events which simultaneously trigger both the AMANDA detector and SPASE air shower array.

2. ANALYSIS PROCEDURE

Downgoing atmospheric muons dominate the event sample at the trigger level. They must be rejected while retaining good efficiency for upgoing neutrino- induced muons. Computer programs determined the effective area for the detection of background muons from the atmosphere. Similar programs were used for neutrino-induced muons. The accuracy of the simulation programs was evaluated by comparing the results to experimental data at various steps along the analysis chain. Alternatively, atmospheric neutrinos provide a guaranteed signal that can be used to calibrate (or normalize) the signal efficiency estimated by the simulation program. The atmospheric neutrino addendum shows agreement between the measured and expected event rates at the factor of 2 level. The discrepancy can be explained by uncertainties in the atmospheric flux and known inadequacies of the simulation programs. The detection of atmospheric neutrinos provides an important confirmation of the sensitivity of the detector to neutrino-induced muons, although the angular-dependent evaluation of sensitivity has large error due to the limited statistics of the atmospheric neutrino sample between the horizon and declination of $+45$ degrees. The mean energy of the muons from atmospheric neutrinos tends to be small, near the energy threshold of the detector. The accuracy of the simulation of detector response should improve for signal well above threshold, so the factor 2 discrepancy for atmospheric neutrinos may be a conservative overestimate of the uncertainty for the search for point sources.

From a large pool of geometric and quality variables, a set of analysis variables was selected that exhibited the greatest differences between signal and atmospheric background distributions. The signal distributions were generated by Monte Carlo, but the background distribution were obtained for data (since it is dominated by background through all levels of this analysis) and Monte Carlo. The experimental data, while more ambiguous than the MC sample, was used for detailed studies at large rejection due to the greater statistics. The optimization of analysis procedure was defined prior to the manipulation of the data. Variables were selected that rejected the largest fraction of background events while retaining good efficiency for upgoing signal. This analysis sequentially applied the cuts on the seven selection variables. The cut values were chosen to retain 95% of the signal.

Each of the seven variables were compared at several stages of the analysis. Nearly one billion experimental triggers were reduced to manageable quantities by a series of filtering steps. Most events are readily identified as downward traveling by computationally simple routines. After two filtering stages, the event sample is reduced by a factor of 1000. At this point, the seven selection variables are applied in sequential order to reduce the data sample to the final 1269 events. One example of the comparison is shown in figures 1 and 2. The comparison is performed after the filtering stages, but prior to the application of additional selection criteria. Therefore these tests possess high statistical precision.

The distribution of direct hits reveals an excess of counts in the experimental data when compared to Monte Carlo expectation. Even though the MC does not replicate the experimental data, it implies that fewer signal events should be removed than expected from Monte Carlo. In any case, the application of this variable should not adversely affect the results of this analysis.

As the previous plots showed, detailed comparisons of data and background MC show good agreement for many, but not all, crucial parameters. In all cases of disagreement, the background efficiencies estimated by MC are less than ob-
Figure 1. (left) Signal Monte Carlo and experimental data distributions for the number of direct hits in a -15 to 25ns time window. The upper left plot shows the distributions of signal and data. They are normalized to contain the same number of events. The upper right plot shows the integrated sum of the distributions, indicating the fraction of the data and signal retained after the cut is applied. The value of the cut is shown by the solid vertical line. The bottom plot shows the calculated signal to noise as a function of cos(zenith) (cos(zenith)=-1 for vertical up-going tracks and cos(zenith)=0 for horizontal tracks). The solid line traces the signal to noise after all selection criteria are applied. The dashed line: all cuts excluding the plotted variable.

Figure 2. (right) Comparison of the experimental data with the background Monte Carlo for the number of direct hits in a -15 to 25ns time window. The distributions are scaled to their passing efficiencies from the trigger level.

dependence has been addressed only recently in detector simulation studies. It is expected that agreement between experimental data and background simulations will improve as depth dependent effects are included. Several improvements in the simulation code have addressed deficiencies in the description of the hardware response. We have improved the the afterpulse and amplitude response of individual Optical Modules in the latest simulation programs. It is probable that the current procedures to remove cross-talk induced hits are not sufficient. These effects are not yet simulated. The AMANDA collaboration has embarked on a detailed study of crosstalk that remains in the data sample after moderately strong cuts are imposed on the data. The analysis procedure maximized the Signal/√Background, assuming a source energy spectrum \( \propto E^{-2} \). After optimizing the procedure, the sensitivity was

There are several likely sources of the observed disagreements. While the optical properties of deep Antarctic ice are temporally stable, they vary with depth due to the influence of episodic geologic events, such as Ice Ages. The depth
evaluated for power law spectra with indices between -2.0 and -3.0.

3. RESULTS

Simulation programs determine the space angle resolution, which is needed to address the question of appropriate bin size. The upper panel of figure 3 shows that the median resolution is 3.3 degrees, and the lower panel indicates that this value does not depend on declination (zenith angle). The distribution of the differences in both zenith and azimuth angle shows evidence for second gaussian component, implying at least two classes of events. The nature of the poorly fit events is still under investigation but visual inspection suggests that these events are predominantly cascade-like in their topologies. Obviously, the next iteration of the point source analysis must address this background.

The zenith angle resolution can be independently evaluated using events that coincidentally trigger both the SPASE air shower array and AMANDA. SPASE measures the direction of the air shower with a pointing resolution of approximately 1 degree. The direction of muons within the air shower event is co-aligned with the air shower to very good accuracy. Therefore, the difference between the direction of the air shower and the reconstructed direction in AMANDA is related to the angular resolution of AMANDA. This work was reported in 1999 at the ICRC in Utah (Miller, et al.). There are a sufficient number of coincidence events to track the angular resolution through all stages of the analysis.

The current version of this analysis yields an event sample of 1269 events which are distributed on the sky as shown (Fig. 4):

While visual inspection reveals no obvious clustering, it is apparent that the density of points is greatest near the horizon, a feature also seen in one version of the atmospheric neutrino analysis. The next stage of the development of the simulation programs will properly account for the curvature of the earth’s atmosphere - a necessary ingredient to properly estimate the contamination of background in this event sample.

Guided by the estimate of angular resolution, the sky was divided into 319 non-overlapping angular bins. The sky bins were shifted by half of the bin width to maximize the signal to noise for sources that straddle the boundary. Figure 5 shows that the distribution of counts per sky bin is consistent with random fluctuations, which were determined by randomly redistributing every event within a given declination band. This procedure was iterated to obtain the results indicated by the black dots. Since this procedure includes a potential signal, the conclusions are conservative and will be improved in the future.

The neutrino limits were computed according to

\[
\phi^{\text{isol}}(E_\nu > E_\nu^{\text{min}}) = \frac{\mu(N_0)}{T_{\text{live}} \cdot \epsilon \cdot A^{\text{eff}}} \quad (1)
\]

where \( A^{\text{eff}} \), the neutrino effective area, is related to the muon effective area shown in Figure
The factor $T_{\text{live}} \epsilon$ is the livetime, and $\epsilon$ is the efficiency due to finite angular resolution and also accounts for non-central source placement within an angular bin. The term $\mu(N_b)$ generates the 90% CL assuming all events within a bin are signal. The results of this calculation are shown in Figure 7.

The AMANDA-B10 detector achieves maximum sensitivity for vertical declination, which complements the sky regions scanned by neutrino detectors in the Northern Hemisphere such as MACRO and SuperKamiokande. Figure 8 shows a comparison of the AMANDA sensitivity ($S = A_{\text{eff}} \times \text{livetime}$) with a representative sample of neutrino detectors located in the Northern Hemisphere. With only one year of data (less than half of a year of livetime), AMANDA produces a limit for positive declinations that begins to approach those achieved in the Southern sky (subject to the caveat that systematic errors have not yet been assessed).

A number of potentially interesting sources was investigated. The results are presented in Table 3.

4. DISCUSSION

A search for astrophysical point sources with continuous output revealed no candidates. A set of selection criteria was determined by optimizing the signal to noise for signal with hard energy
Muon Effective Area versus Zenith Angle

Figure 6. The effective area for muon detection as a function of zenith angle for $E_\mu$ between 0.1 TeV and 100 TeV (180 deg is vertically up).

Average neutrino flux limit ($E_\nu > 10$ GeV)

Figure 7. Preliminary neutrino flux limit (90% CL) as a function of declination, averaged over RA.

spectra, yet this analysis retains reasonable sensitivity for softer spectra. A suite of software tools has been written to calculate event rates, flux limits, detector performance, and other quantities of interest. The preliminary $\nu$-flux limits deduced from neutrino-induced high energy muons rely on computer simulations to determine the absolute sensitivity and angular resolution of the array. To improve confidence in the detector simulation programs, the background generators should describe data through the stages of the analysis where background dominates. Systematic differences in the absolute values or shapes in the distributions would complicate the interpretation of the results. Fortunately, inspection of most distributions reveals good agreement between data and simulated background. Those that show less than adequate agreement tend to error in the direction that implies a greater signal efficiency. During the next few months, the detector simulation programs will be extensively investigated to quantify the systematic error, an essential step.

The inferred limits on neutrino flux apply to point sources with continuous emission (or episodic emission averaged over a time interval of approximately 0.6 years) and power law energy spectra with a fixed spectral index. The relatively large energy threshold of the detector only affects the sensitivity for spectra softer than $E^{-2.3}$. The limits for sources at large positive declination are comparable to the best published limits in the Southern sky[5].

5. FUTURE

AMANDA-II, completed in January, 2000, surrounds the B10 core with an additional nine strings of optical modules. The composite 19-string array will more than double the number of optical sensors. The neutrino effective area will more than double, especially for nearly horizontal events. The greater sensitivity near the horizon
Figure 8. Preliminary muon flux limit (90% CL) as a function of declination, averaged over RA. We also show limits reported by MACRO[5] and very approximate sensitivity by SuperKamiokande assuming 4 years of livetime.

Figure 9. Resulting angular distribution of events from point source analysis (138.2 live days) and the expected number of atmospheric neutrinos in that sample.

provides the statistics necessary to test the simulation codes over the entire northern hemisphere.

With the completion of AMANDA-II, the collaboration must transition from a hardware-dominated project to an analysis-centered project. Recently, the AMANDA collaboration has re-organized itself to focus a majority of personnel on data analysis and hardware evaluation tasks. We expect that the pace of discovery will accelerate due to these changes.

6. ACKNOWLEDGEMENTS

An expanded set of transparencies on topics briefly covered in this paper can be obtained from www.ps.uci.edu/~amanda/Taup99_talk.pdf

which were presented at a recent conference, Topics in Astrophysics and Underground Physics (TAUP99).

REFERENCES

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4. See contributions in Proc. 26th Inter. Cosmic Ray Conf.(ICRC99), Salt Lake City, UT, (Aug 1999). HE 3.1.06, HE 6.3.07, HE 4.2.06, HE 6.3.01, HE 4.1.15, HE 5.3.05,
HE 4.2.05, HE 6.3.02, HE 4.1.14, HE 4.1.14, HE 3.2.11, HE 4.2.07, HE 5.3.06 at krusty.physics.utah.edu/icrc1999/proceedings.html


Table 1
Muon and neutrino flux limits on selected sources. All limits are determined assuming a 90% CL.

<table>
<thead>
<tr>
<th>Source</th>
<th>Model</th>
<th>bin size</th>
<th>$\Phi^{90%} (cm^{-2} sec^{-1})$</th>
<th>$\Phi^{90%} (cm^{-2} sec^{-1})$</th>
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<tr>
<td>Mrk 501</td>
<td>$\Phi_{\nu} = \Phi_{\nu}^{\text{HEGRA}}$ 0.01 $&lt; E_{\nu} &lt; 10^{3}$ TeV</td>
<td>5.4$^a$</td>
<td>2.35x10$^{-2}$</td>
<td>0.0365x10$^{-8}$</td>
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<td>Mrk 501</td>
<td>$\Phi_{\nu} \propto E_{\nu}^{-0.32}$ (HEGRA) 1 $&lt; E_{\nu} &lt; 10^{3}$ TeV</td>
<td>5.4$^a$</td>
<td>6.12x10$^{-2}$</td>
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<td>Mrk 421</td>
<td>Szabo and Protheroe 1 $&lt; E_{\nu} &lt; 10^{3}$ TeV</td>
<td>5.8$^a$</td>
<td>1.04x10$^{-2}$</td>
<td>1.45x10$^{-9}$</td>
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<td>NGC 4151</td>
<td>Szabo and Protheroe 1 $&lt; E_{\nu} &lt; 10^{3}$ TeV</td>
<td>5.0$^a$</td>
<td>1.18x10$^{-2}$</td>
<td>1.64x10$^{-9}$</td>
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<td>Stecker 1 $&lt; E_{\nu} &lt; 10^{3}$ TeV</td>
<td>5.0$^a$</td>
<td>0.61x10$^{-1}$</td>
<td>0.086x10$^{-8}$</td>
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<td>Cygnus X-3</td>
<td>$E^{-2}$ spectra 1 $&lt; E_{\nu} &lt; 10^{3}$ TeV</td>
<td>5.4$^a$</td>
<td>1.36x10$^{-2}$</td>
<td>1.84x10$^{-9}$</td>
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<td>Hercules X-1</td>
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<td>5.3$^a$</td>
<td>1.14x10$^{-2}$</td>
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<td>Geminga</td>
<td>$E^{-2}$ power spectra 1 $&lt; E_{\nu} &lt; 10^{3}$ TeV</td>
<td>5.8$^a$</td>
<td>1.84x10$^{-2}$</td>
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