Search for extraterrestrial point sources of high energy neutrinos with AMANDA-II using data collected in 2000-2002


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The results of a search for point sources of high energy neutrinos in the northern hemisphere using data collected by AMANDA-II in the years 2000, 2001 and 2002 are presented. In particular, a comparison with the single-year result previously published shows that the sensitivity was improved by a factor of 2.2. The muon neutrino flux upper limits on selected candidate sources, corresponding to an $E^{-2}$ neutrino energy spectrum, are included. Sky grids were used to search for possible excesses above the background of cosmic ray induced atmospheric neutrinos. This search reveals no statistically significant excess for the three years considered.

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The detection of high energy cosmic rays raises fundamental questions about their generation and the mechanisms responsible for such energies. The origin of cosmic rays above the “knee” (10$^{15}$ eV) still remains uncertain. Nevertheless there is evidence that below such energies they are generated through acceleration mechanisms in expanding supernova remnant shocks $\mathbb{H}$ and in microquasars $\mathbb{H}$, although we cannot exclude the possibility of extragalactic sources at these energies. The interaction of accelerated protons with ambient matter or radiation leads to pion production and, consequently,
to neutrinos and gamma rays following a power-law energy spectrum. High energy gamma rays are affected by absorption during propagation and may also be produced by inverse Compton scattering of shock-accelerated electrons. Therefore detection of gamma rays alone is insufficient evidence for hadronic acceleration. Neutrinos can provide a link to increased understanding of high energy cosmic rays, although most predictions of high energy extraterrestrial neutrino fluxes conservatively require kilometer-scale detectors.

AMANDA-II operates at the geographic south pole. It is composed of 677 optical modules (OMs) – photomultiplier tubes encased in glass pressure vessels – spaced along 19 vertical cables (strings) arranged in concentric circles. The instrument spans a geometrical volume of clear glacial ice between depths of 1500 and 2000 m, with a diameter of 200 m. The AMANDA-II neutrino telescope has been in operation since 2000. In this letter, we follow up on a previously published search for high-energy neutrino point sources from the data sample collected in 2000, using data from the three years, 2000 to 2002. The sensitivity for the detection of point sources has significantly improved in AMANDA, compared to 1997 and 1999 results, due to both detector performance and analyses technique improvements.

A high-energy muon neutrino interacting with the ice or bedrock in the vicinity of the detector produces a high-energy muon propagating a few kilometers when above 1 TeV. At these energies the mean angular offset between the muon track and incident neutrino is less than 0.8°. The muon track is reconstructed using the detection of Cherenkov light emitted as it propagates through the array of OMs, and the likelihood of arrival time of detected photons at each OM location. The resulting zenith-dependent median pointing resolution varies between 1.5° and 2.5°.

Muons are also produced by the interactions of cosmic rays in Earth’s atmosphere. These atmospheric muons dominate the AMANDA-II trigger rate so the search for neutrino-induced muon tracks is only conducted in the northern hemisphere, using Earth as an atmospheric muon filter. A second source of background is represented by atmospheric muon tracks reconstructed as up-going. These events can be rejected using track quality criteria. The most important source of background is the residual up-going flux of neutrinos produced in the atmosphere by the impact of cosmic rays. These atmospheric neutrinos also serve as a verification of the detection principle and demonstrates AMANDA’s capability as a neutrino detector. The search for possible extraterrestrial neutrinos begins with a dataset dominated by the well-understood atmospheric neutrinos. This analysis selects a three-year sample of events with median energy of ~1.3 TeV and extending up to ~100 TeV. Extraterrestrial neutrinos are believed to be distinguished by a harder energy spectrum, taken as proportional to $E^{-2}$ in this analysis.

The exposure of the present analysis is three times higher than that of the previous analysis. A different search strategy is used, which includes an explicit high energy event selection to reduce the expected lower energy atmospheric neutrino background.

## I. DATA ANALYSIS

The data used for this analysis were collected between the months of February and November in the years 2000, 2001 and 2002 (see Table I).

<table>
<thead>
<tr>
<th>year</th>
<th>livetime (days)</th>
<th>triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>197</td>
<td>$1.34 \times 10^{9}$</td>
</tr>
<tr>
<td>2001</td>
<td>194</td>
<td>$2.04 \times 10^{9}$</td>
</tr>
<tr>
<td>2002</td>
<td>216</td>
<td>$2.17 \times 10^{9}$</td>
</tr>
</tbody>
</table>

**TABLE I:** The experimental livetime and number of triggered events for each year used in this analysis. The triggered events may vary in different years mostly due to different cleaning procedures, which are mainly affected by the number of stable OMs during the specific year.

The experimental sample used in this analysis corresponds to a total of 607 days of livetime and contains almost 5.6 billion triggers. Starting from 2002, a first level filter is performed at the South Pole during data taking. The reduced amount of data is transferred via satellite to the northern hemisphere for analysis. After the application of an iterative maximum-likelihood reconstruction algorithm and the selection of tracks that are likely to be upgoing, about 0.45 million events with reconstructed declination $\delta > -10^\circ$ remain. Since AMANDA-II is located at the south pole, $\delta = 0^\circ$ corresponds to horizontal and $\delta = 90^\circ$ to vertical up-going directions. These events, containing mostly mis-reconstructed atmospheric muons and a contribution of atmospheric neutrinos, were used as an experimental background for selection optimization.

To avoid biasing the event selection the data were scrambled by randomizing the reconstructed right ascension ($\alpha$) of each event. The optimization procedure makes use of three observables: the number of hit OMs for each event (nch), the reconstructed track length in the array and the likelihood ratio between the muon track reconstruction and a muon reconstruction constrained by using an atmospheric muon prior. A full simulation chain, including neutrino absorption in the Earth, neutral current regeneration, muon propagation and detector response for the given data taking periods, is used to simulate point sources of muon neutrinos and anti-neutrinos. Events are simulated at the center of each $5^\circ$ band of declination ($\delta$), according to an $E^{-2}$ energy spectrum. The final cuts on these observables and the optimum size of each circular search bin were independently determined for each declination band in order to have the strongest constraint on the signal hypothesis.
This corresponds to the best sensitivity, i.e. the average flux upper limit obtained in an ensemble of identical experiments assuming no signal \(^\text{[16]}\). The true directional information was then restored for the calculation of the limits.

The upper limits of this analysis were calculated using the background \(n_b\) measured using the events off-source in the corresponding declination band, and the expected number of events, \(n_s\), from a simulated point source of known flux \(\Phi(E)\): \(\Phi_{\text{limit}}(E) = \Phi(E) \times \frac{n_b}{n_s}\). Here \(n_{\text{obs}}\) is the number of observed events in the given source bin, and \(\mu_{90}\) is the upper limit on the number of events following the unified ordering prescription of Feldman and Cousins \(^\text{[17]}\). The three years were analyzed both separately and as combined data samples.

FIG. 1: Sensitivities on the integrated flux above \(E_{\nu} = 10\,\text{GeV}\) as a function of declination and for an \(E^{-2}\) energy spectrum. The sensitivities for the year 2000, 2001 and 2002 are compatible with each other, and shown along with the one for 2000-01 and for the 2000-02 three-year sample.

TABLE II: The number of observed events with \(\delta > 5^\circ\) after cut optimization, for each year and the combined three-year sample. The numbers relative to reference \(^\text{[9]}\) are compatible with a normalization factor of \(\sim 0.86\), for the atmospheric neutrino simulation, as quoted in the above reference. The numbers \(n_p\) of the predicted atmospheric and signal neutrino events (with signal energy spectrum of \(\Phi_{\text{sig}} = 10^{-6} \times E^{-2} \,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,\text{GeV}^{-1}\)) are also shown.

Table: | Year     | \(n_{\text{obs}}\) | \(n_p(\nu_\mu^{\text{true}})\) | \(n_p(\nu_\mu^{\text{true}})\) |
<table>
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<tr>
<th></th>
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<tbody>
<tr>
<td>2000</td>
<td>601</td>
<td>60</td>
<td>133</td>
</tr>
<tr>
<td>2001</td>
<td>306</td>
<td>290</td>
<td>111</td>
</tr>
<tr>
<td>2002</td>
<td>429</td>
<td>364</td>
<td>115</td>
</tr>
<tr>
<td>646</td>
<td>635</td>
<td>297</td>
<td>121</td>
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The final three-year sample consists of 646 upward (\(\delta > 5^\circ\)) reconstructed muons (see Table II). The predicted number of atmospheric neutrinos is 635. In the year 2000 alone, the number of selected events is 306, compared with the 601 (699 for \(\delta > 0^\circ\)) in reference \(^\text{[9]}\). The difference between the two samples is due to the different choice of observables used for the selection optimization. In particular the use of the \(nch\) observable, which is correlated to the energy released by the muon in the array and, ultimately, to the neutrino energy selects \(\sim 26%\) higher median energies than those in \(^\text{[8]}\) (from \(\sim 700\,\text{GeV}\) to \(\sim 1\,\text{TeV}\) for a single year). This selection is obtained at the price of removing a significant fraction of atmospheric neutrino events: for instance only 221 events in \(^\text{[8]}\) would survive the new selection, 94% of which (i.e. 207) are also found in the new sample from the year 2000.

As shown in Table II the number of events in the final sample \((n_{\text{obs}})\) does not sum up with experimental exposure. Since the signal hypothesis predicts a higher event intensity at high energy than the atmospheric neutrino background, a longer exposure allows a stronger constraint on a given model by requiring a stronger energy cut (the median energy increases from \(\sim 1\,\text{TeV}\) for a single year to \(\sim 1.3\,\text{TeV}\) for the three-year sample), which...
rejests more background events and results in stricter limits. Consequently the three-year sample contains ∼40% fewer observed events than the sum of single years, but only ∼17% of the high energy neutrino signal events are lost.

The detector performance is assessed by the neutrino effective area $A_{\nu}^{\text{eff}}(E_{\nu}, \delta)$, which contains the neutrino interaction probability, muon propagation, detector response and the analysis selection. It is defined by the relation between the differential neutrino flux $\Phi_{\nu}(E_{\nu})$ and the predicted number of neutrino events $n_{\nu}(E_{\nu})$, through the equation

$$n_{\nu}(E_{\nu}) = T_{\text{live}} \cdot \int_{\Omega} \int_{E_{\nu}^{\text{min}}}^{E_{\nu}^{\text{max}}} A_{\nu}^{\text{eff}}(E_{\nu}, \delta) \frac{d\Phi_{\nu}}{d\Omega dE_{\nu}} d\Omega dE_{\nu} \tag{1}$$

Figure 2 shows the muon neutrino effective area as a function of neutrino energy at different declinations. The effect of neutrino absorption in the Earth is responsible for the effective area decrease at high energies and declinations.

The binning search for excesses in the $5^\circ < \delta < 85^\circ$ region was performed on the three-year event sample. The search grid contains 290 rectangular bins with declination-dependent width ranging from 5.6$^\circ$ to 8.8$^\circ$, based on the optimized search bin diameter. The grid is shifted 4 times in $\delta$ and $\alpha$ to fully cover boundaries between the bins of the original configuration. A higher number of grid shifts showed no improvement in the average maximum statistical significances on simulated Poisson-fluctuated signal with intensities comparable to the background. The probability distribution for background fluctuations in the ensemble of bins was evaluated by using 20,000 experimental samples with scrambled $\alpha$ and calculating the highest value of the maximum statistical fluctuation significance over the entire sky.

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The bin with the most statistically significant excess from the three-year experimental sample is at about $\alpha = 22h$ and $\delta = 21^\circ$, with 10 observed events in the search bin on a background of 2.38 events, estimated from the corresponding declination band. The observed excess has a statistical significance of $1.9 \times 10^{-3} \, (3.73 \, \sigma)$. The chance probability of such an excess, in the ensemble of bins, is 28%.

Table III shows the 90% CL upper limits on candidate sources. Results from the present analysis are reported for a comparison with the limits from \cite{9}. Limits are for the assumed $E_{\nu}^{-\alpha}$ spectral shape, integrated above $E_{\nu} = 10$ GeV, and in units of $10^{-8} \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} (\Phi_{\nu}^{\text{lim}})$.

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FIG. 3: 2000-02 upper limits (90% CL) on the neutrino flux integrated above 10 GeV in equatorial coordinates for \( \delta > 5^\circ \). Limits (scale on right axis) are given in units of \( 10^{-8} \text{cm}^{-2} \text{s}^{-1} \) for the assumed \( E^{-2} \) spectrum. Systematic uncertainties are not included. The cross symbols represent the observed events.

in equatorial coordinates. The limits are calculated by scanning the sky and counting the events within the optimized search bins at the given declination. The highest upper limit in the Figure corresponds to the previously discussed statistically significant bin. Other high limit spots visible in the figure have statistical significances smaller than 3.4 \( \sigma \).

We analyzed the 2000-02 data sample collected by the AMANDA-II detector to search for point sources of high energy neutrinos. We performed both a non-targeted binned search and a targeted search focussing on known objects that are potential high energy neutrino emitters (as in reference [9]). We found no evidence of a significant flux excess above the background. A km-scale experiment, such as IceCube [22], will be able to increase the detection sensitivity by at least a factor of 30 in the same time scale.

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