Search for Astrophysical Point Sources of High Energy Neutrinos with Complete Data from the AMANDA-II Neutrino Telescope

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We present a search for astrophysical point sources of high energy neutrinos using 3.8 years of data recorded by the AMANDA-II neutrino telescope during 2000-2006. Applying muon track reconstruction and quality criteria, we select 6595 candidate events, mostly from atmospheric neutrinos. Our search reveals no indications of a neutrino point source. We place the most stringent limits to date on E^{-2} neutrino fluxes from points in the Northern Hemisphere, with an average upper limit of 5.2×10^{-11} TeV cm^{-2} s^{-1} for equal $\nu_\mu + \nu_\tau$ fluxes over the energy range from 1.7 TeV to 2 PeV.

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Detecting extraterrestrial sources of high energy (>TeV) neutrinos is a longstanding goal of astrophysics. Neutrinos are neither deflected by magnetic fields nor significantly attenuated by matter and radiation en route to Earth, thus neutrino astronomy offers a clear image of the high energy universe. Particularly, neutrinos offer an opportunity to probe the sources of high energy cosmic rays, which remain unknown. Potential cosmic ray sources include galactic microquasars and supernova remnants as well as extragalactic phenomena such as active galactic nuclei and gamma ray bursts. These objects are thought to accelerate protons and nuclei in shock fronts via the Fermi mechanism, resulting in power law energy spectra E^α, with $\alpha \sim -2$. A fraction of the energized particles interact with local matter and radiation producing pions. The neutral pions decay into high energy photons, and charged pions ultimately produce neutrinos with a flavor ratio ν_e:ν_μ:ν_τ = 1:2:0, mixing to approximately 1:1:1 at Earth due to vacuum oscillations. Observations of TeV gamma rays [1–3] hint at possible cosmic ray source locations but currently cannot separate neutral pion decay spectra from purely electromagnetic inverse Compton emission. The Auger collaboration reports a correlation of arrival directions of the highest energy cosmic rays with active galactic nuclei [4]; however, a similar correlation is not observed by HiRes [5]. Identification of a high energy neutrino point source would provide an unambiguous signature of energetic hadrons and cosmic ray acceleration. Neutrino flux predictions exist for many potential sources [6–10]; however, no high energy neutrino point source has yet been identified [11, 12].

The search for high energy neutrino point sources is a major mission of the Antarctic Muon And Neutrino Detector Array (AMANDA). High energy leptons are produced in the Earth by the charged-current interaction of neutrinos. In transparent matter, a cone of Čerenkov photons propagates from the lepton track according to the optical properties of the medium. AMANDA-II is an instrumentation of the glacier at the geographic South Pole with 677 optical modules designed to detect optical Čerenkov radiation. The modules are arranged in 19 vertical strings frozen 1500 m - 2000 m below the ice surface. Approximately 540 modules in the core of the array showing stable performance are used in this search. Each module contains a 20 cm PMT inside and optically coupled to a glass high-pressure sphere. The PMT signals are propagated to the surface, and, when the trigger threshold of 24 hit PMTs within 2.5 μs is satisfied, the signal leading edge times are recorded. The leading edge times along with known detector geometry and optical properties of South Pole ice [13] allow reconstruction of tracks passing through the detector [14]. High energy electrons produce short electromagnetic cascades with little directional information and consequently are not useful for point source searches; however, muons produced in the ice and bedrock propagate up to tens of kilometers to the detector and are reconstructed with $1.5^\circ - 2.5^\circ$ accuracy depending on energy and zenith angle. Tau leptons decay rapidly and produce tracks too short for reconstruction below ~PeV energies. Tau decay, however, contributes high energy muons with a branching ratio of 17.7% [15], and these muons can be reconstructed. We thus search for upward propagating muons produced in the Earth by ν_μ ($\bar{\nu}_\mu$) and ν_τ ($\bar{\nu}_\tau$) fluxes following an E^{-2} energy spectrum. While downward fluxes of neutrino induced muons also trigger the detector, such events are difficult to distinguish from downward muons produced by cosmic ray air showers. Located at the geographic South Pole, AMANDA-II is thus most sensitive to neutrino fluxes from the northern sky. Air showers also produce neutrinos, and this atmospheric neutrino flux [16, 17] is the main background for our search.

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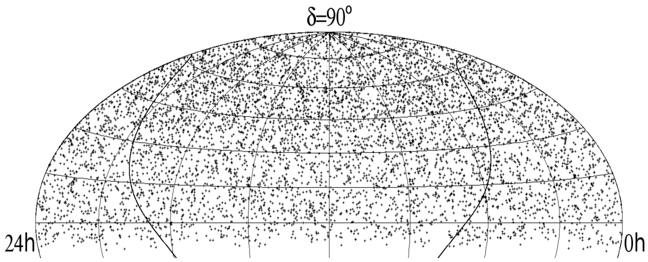

FIG. 1: Equatorial sky map of 6595 events recorded by AMANDA-II from 2000-2006.

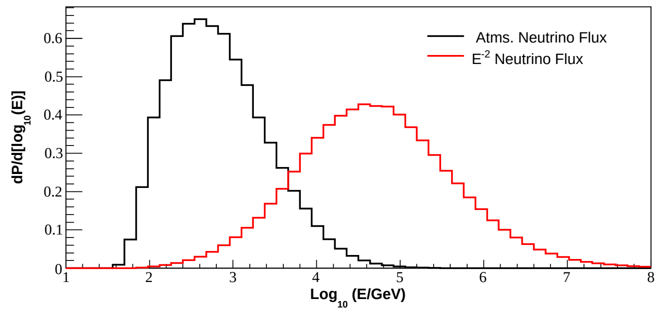

FIG. 2: Energy distribution of simulated E^{-2} and atmospheric [16] neutrino events passing selection criteria.

Here we present the results of a search for astrophysical point sources of high energy neutrinos using 3.8 years of data recorded by the AMANDA-II neutrino telescope during 2000-2006. We report flux limits for a catalog of 26 selected source candidates along with results of a general search for neutrino sources over the Northern Hemisphere sky. Additionally, we report results from a search for correlations of neutrino emission with six high energy gamma ray sources in the galactic plane identified by Milagro. Finally, we discuss the results of a search for angular correlations among the highest energy events we record. In all cases, we observe no indications of an astrophysical neutrino point source.

AMANDA-II records $O(10^9)$ events per year from downward propagating muons produced by cosmic ray air showers, $O(10^3)$ events per year from atmospheric neutrinos, and at most ∼20 quality events per year from astrophysical E^{-2} neutrino fluxes given current limits [18]. 3.8 years of AMANDA-II livetime from stable periods during 2000-2006 are used in this search. Events first pass through fast pattern matching algorithms, and cuts on returned zenith angles reduce downward muons by more than a factor of 100 [11]. A more computationally expensive maximum likelihood, leading edge time based reconstruction is applied to the remaining events. This reconstruction is possible since the expected time distribution of photons arriving at the modules in ice is well understood for a given track hypothesis [14]. The reconstruction is repeated several times to find the globally best fit track, and events reconstructed above 80° zenith are discarded.

After the cut, $O(10^6)$ misreconstructed downward muon events per year remain, which still outnumber atmospheric neutrinos by a factor of 1000. The vast majority of these events are removed by topological quality cuts. This topological selection includes cuts on the smoothness of hits along the track and the track length, a cut on the event angular resolution estimated by the behavior of the likelihood near the best-fit position [19], and a cut based on the likelihood difference between the best fit and a Bayesian likelihood fit with a zenith prior following the zenith distribution of downward muons. Additionally, a support vector machine [20] trained on the above parameters is used for declinations -10° $< \delta <$ 1.5° to improve event selection. 6595 events remain following the cuts, shown in figure 1. A simulation of atmospheric neutrino fluxes [16, 17] generated by ANIS [21], with resultant muons propagated to the detector with MMC [22], agrees well with data. Similarly, ν_μ and ν_τ events with an E^{-2} energy spectrum are produced and used to calculate flux limits. The contribution of misreconstructed downward muons is less than 5% for $\delta > 5°$, but becomes more significant near the equator and dominates events in the southern sky.

This background, mostly atmospheric neutrinos, is difficult to further reduce. We apply our search to these 6595 events, looking for both spatial excesses and excesses of high energy events. Events from point sources cluster around the source location with a median spread of ∼1.5°−2.5° depending on energy and zenith angle, while atmospheric neutrinos are distributed evenly in right ascension. Additionally, neutrinos from E^{-2} point sources should typically be more energetic than atmospheric neutrinos, which follow a steeper ∼E$^{-3.7}$ energy spectrum, shown in figure 2. The amount of light deposited in the detector depends strongly on muon energy above 1 TeV, and thus the number of hit modules provides a rough measure of event energy. We apply an unbinned maximum likelihood search method [23], using an angular resolution estimated for each event [19] and using the number of hit channels as an energy estimator. This unbinned method improves sensitivity to E^{-2} neutrino fluxes by more than 30% relative to a method based on angular bins used previously [24].

We first apply the search to a predefined list of 26 potential sources. For each source, we compute significance by comparing the value of the unbinned search test statistic [23] to the distribution of test statistic values obtained from data randomized in right ascension. Flux upper limits are computed from the test statistic using Feldman-Cousins unified ordering [25]. Systematic uncertainty is incorporated into the limit calculation using the method of Hill [26]. We estimate the systematic uncertainty in our flux limits to be 16%, with significant contributions from the absolute sensitivity of optical modules (9%), neutrino cross section (8%), and event reconstruction (10%). Limits on ν_μ + ν_τ fluxes at 90% confidence level and pre-trials significances are shown in table I. Limits on ν_μ fluxes alone correspond to half these values. The source of highest significance is Geminga with P=0.0086. The chance probability of obtaining P=0.0086 for at least one of 26 sources is 20% and not significant.

We then apply the search to the northern sky on a

Candidate	$\delta(^\circ)$	$\alpha(h)$	Φ_{90}	p	$\Psi(^\circ)$	N
3C 273	2.05	12.49	8.71	0.086	2.1	3
SS 433	4.98	19.19	3.21	0.64	2.2	1
GRS 1915+105	10.95	19.25	7.76	0.11	2.3	8
M87	12.39	12.51	4.49	0.43	2.3	3
PKS 0528+134	13.53	5.52	3.26	0.64	2.3	0
3C 454.3	16.15	22.90	2.58	0.73	2.3	5
Geminga	17.77	6.57	12.77	0.0086	2.3	2
Crab Nebula	22.01	5.58	9.27	0.10	2.3	7
GRO J0422+32	32.91	4.36	2.75	0.76	2.2	3
Cyg X-1	35.20	19.97	4.00	0.57	2.1	3
MGRO J2019+37	36.83	20.32	9.67	0.077	2.1	7
4C 38.41	38.14	16.59	2.20	0.85	2.1	4
Mrk 421	38.21	11.07	2.54	0.82	2.1	3
Mrk 501	39.76	16.90	7.28	0.22	2.0	6
Cyg A	40.73	19.99	9.24	0.095	2.0	3
Cyg X-3	40.96	20.54	6.59	0.29	2.0	8
Cyg OB2	41.32	20.55	6.39	0.30	2.0	8
NGC 1275	41.51	3.33	4.50	0.47	2.0	4
BL Lac	42.28	22.05	5.13	0.38	2.0	2
H 1426+428	42.68	14.48	5.68	0.36	2.0	3
3C66A	43.04	2.38	8.06	0.18	2.0	6
XTE J1118+480	48.04	11.30	5.17	0.50	1.8	3
1ES 2344+514	51.71	23.78	5.74	0.44	1.7	2
Cas A	58.82	23.39	3.83	0.67	1.6	2
LS I +61 303	61.23	2.68	14.74	0.034	1.5	5
1ES 1959+650	65.15	20.0	6.76	0.44	1.5	5

TABLE I: Flux upper limits for 26 neutrino source candidates: Source declination, right ascension, 90% confidence level upper limits for $\nu_\mu + \nu_\tau$ fluxes with E^{-2} spectra ($E^2 \times \Phi < \Phi_{90} \times 10^{-11}$ TeV cm^{-2} s^{-1}) over the energy range 1.7 TeV to 2 PeV, pre-trials significance, median angular point spread, and number of events inside a cone centered on the source location with radius equal to median point spread.

0.25°x0.25° grid. At each point, we similarly compute a flux limit and significance. We find a maximum significance of 3.38σ at δ=54°, α=11.4h, shown in figure 3. The chance probability of observing a 3.38σ maximum significance is determined by performing the search on sky maps randomized in right ascension and is found to be 95% and not significant. Sensitivity and flux limits are summarized in figure 4.

In the northern sky, the galactic TeV gamma ray sources observed by Milagro [28] are some of the strongest candidates for detection with neutrino telescopes [10]. Our ability to detect a small signal from this class of objects is improved by combing observations from several source locations, with an expected improvement $\sim \sqrt{N}$ by combining N sources. We consider six of eight sources with pre-trials significance $>5\sigma$, including four sources near Cygnus and two sources near the equator. We exclude the two sources with pulsar-wind nebula counterparts near Geminga and the Crab Nebula, which are considered weaker candidates for significant hadron acceleration [10]. We adapt a method developed by HiRes [29] to perform our maximum likelihood search simultaneously for all six source locations, and we observe a small excess with a chance probability of 20%. The limit obtained on the average flux per source is 9.7×10^{-12} TeV cm^{-2} s^{-1}, shown in figure 5 along with source flux predictions [10].

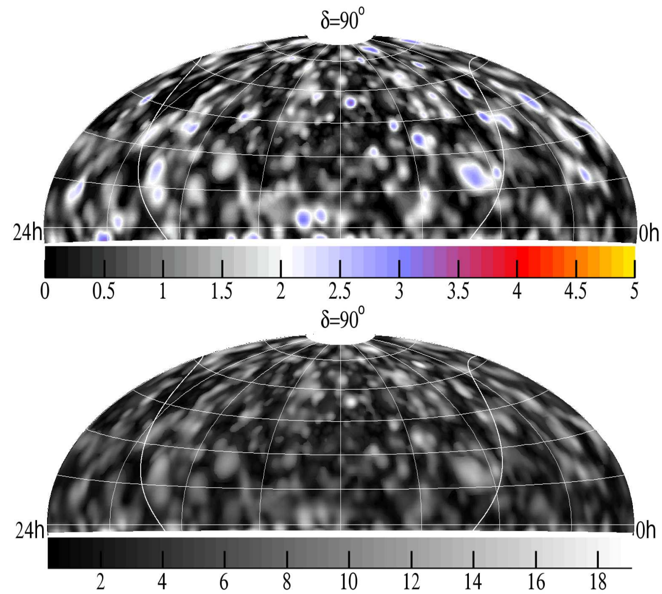

FIG. 3: Sky map of pre-trials significances (σ) obtained in the full-sky search (top), and sky map of $\nu_\mu + \nu_\tau$ flux upper limits for an E^{-2} energy spectrum (10^{-11} TeV cm^{-2} s^{-1}) over the energy range 1.7 TeV to 2 PeV (bottom).

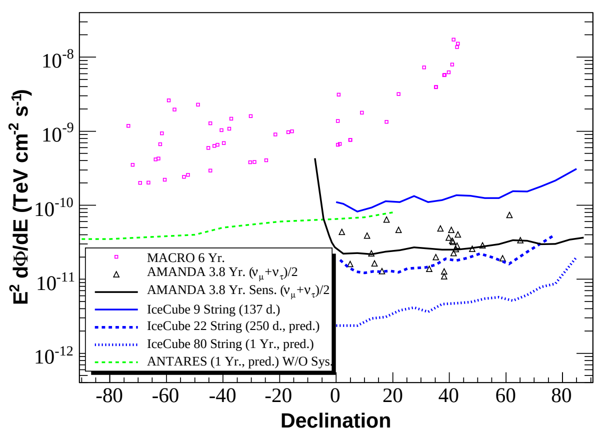

FIG. 4: E^{-2} flux limits for this work and MACRO [12], E^{-2} sensitivity for this work and the IceCube 9-string analysis [24], and predicted sensitivity for ANTARES [27] and IceCube. Our $\nu_\mu + \nu_\tau$ limits are divided by 2 for comparison with limits on only ν_μ.

Finally, we search for groups of neutrino sources and extended regions of neutrino emission by scanning for correlations of events at all angular distances up to 8°. We perform the search over a range of energy thresholds, using the number of modules hit as an energy parameter. For each threshold in angular distance and number of modules hit, we count the number of event pairs in the data and compare with the distribution of pairs from data randomized in right ascension to compute significance, shown in figure 6. The highest obtained significance is 1.6σ with a threshold of 146 modules hit and

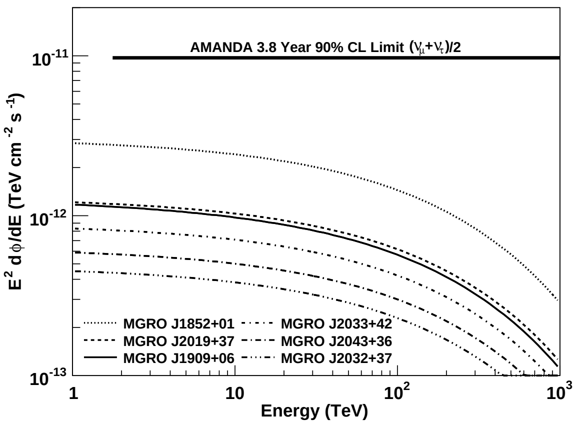

FIG. 5: Average flux limit per source for 6 Milagro sources and comparison to predicted ν_μ fluxes [10].

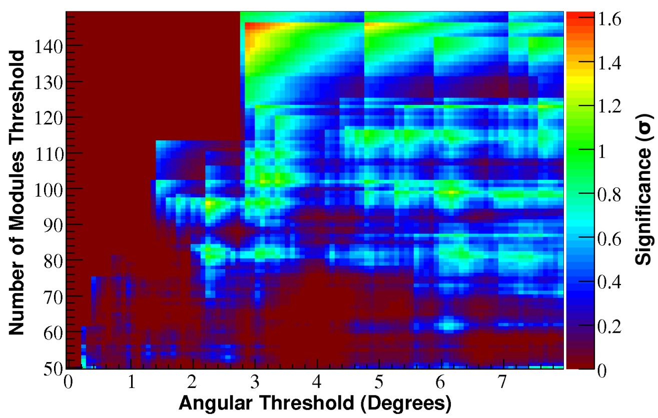

FIG. 6: Significance of the observed number of event pairs with respect to thresholds on angular separation and number of modules hit.

2.8° angular separation, where we observe 2 event pairs. The probability of observing a maximum significance of 1.6σ by random chance is 99%.

We analyze 3.8 years of data taken with AMANDA-II and find no evidence of high energy neutrino point sources. This search places the most sensitive limits to date on astrophysical point source fluxes. IceCube [30], a next-generation neutrino telescope at the South Pole, is scheduled for completion in 2011 with 80 strings and $\sim$km^3 detector volume. Data taken by the first 22 strings of IceCube during 2007-2008 are expected to improve this sensitivity by a factor of 2. Currently 40 strings are operating, and continued construction should achieve an angular resolution of better than 0.7° and an order of magnitude improvement over the current sensitivity within a few years.

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