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Neutrino Point Source Search Strategies for AMANDA-II and Results from 2005

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Abstract: Current point source searches mostly utilize only direction and time of the reconstructed event; furthermore, they reduce available information by grouping events into sky bins. In this analysis we use a search based on maximum likelihood techniques, utilizing both event angular resolution and energy, to enhance our ability to detect point sources. Especially, use of energy information allows us to fit the spectral index of a hypothetical source simultaneously with flux. This method improves both sensitivity and discovery potential of the AMANDA-II array by greater than 30%. The method can naturally be applied to IceCube and allows superposition of data from detectors with different sensitivity and angular resolution, such as the IceCube array which changes and improves with each season of construction.

Introduction

Pinpointing the origin of high energy cosmic rays is one of the most important goals of neutrino astrophysics. Observation of a high energy neutrino source would provide clear indication of hadronic processes associated with cosmic rays. Neutrinos are neither deflected by magnetic fields nor significantly attenuated on transit to Earth, making them excellent astronomical messengers in the $>$TeV universe.

The Antarctic Muon And Neutrino Detector Array (AMANDA), a subdetector of the IceCube Observatory, is composed of 19 strings with 677 total optical modules located 1500 m – 2000 m below the ice surface at the Geographic South Pole. Muons produced by charged-current ν_μ and $\bar{\nu}_\mu$ interactions produce tracks of Čerenkov light and are reconstructed with 1.5^o–2.5^o median angular resolution [2]. The large background of muons from cosmic ray interactions in the atmosphere precludes ν_μ and $\bar{\nu}_\mu$ searches in half of the sky, but for $\delta > 0$ cosmic ray muons are attenuated by Earth leaving a relatively pure atmospheric neutrino background.

Detection of an extraterrestrial high energy neutrino source has so far eluded the neutrino telescope community. To probe lower fluxes, either larger neutrino telescopes must be built, more sophisticated point source analysis techniques [8] [5] must be developed to better utilize data from existing experiments, or both [1].

Method

An unbinned maximum likelihood search method is used in contrast to previous AMANDA point source analyses [2]. The past binned search method makes use of a single statistic, namely "How many events are within bin radius 'b'" and a background estimation to make a statement about the existence of a source at any particular position in the sky. It is reasonable to think the use of additional information must enhance ability to search for point sources. Additional information includes:

- Events outside the search bin
- The distribution of events within the search bin
- Event energy estimation.

The energy distribution of a hypothetical E^{-2} source is drastically different from that of the atmospheric neutrino background. If high energy events are observed, such events are not very compatible with atmospheric neutrino background and enhance discovery potential. Conversely, if high energy events are not observed, the method is able to reject the signal hypothesis with higher confidence. In AMANDA, the number of optical modules, or channels, hit by at least one photon during an event correlates with event energy. By using the difference in the distribution of number of hit channels, shown in figure 1 for various energy spectra, events are more accurately classified as signal or background.

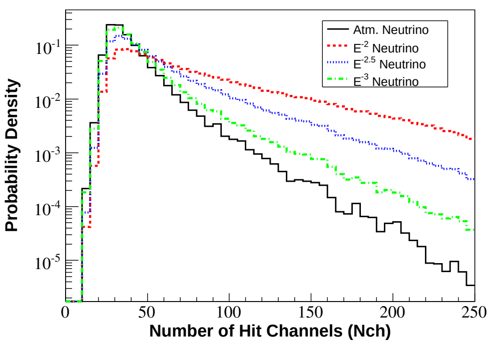

Figure 1: Number of hit channels (Nch) PDF for simulated atmospheric neutrinos and various signal spectra

At a hypothetical source position x_o, the data is modeled as an unknown mixture of background and events produced by the source. Each event near the source declination is assigned a likelihood of belonging to the source. This source PDF is the product of probability functions describing the detector point spread, which is zenith dependent, and number of channels hit (Nch):

$$\mathcal{S}_i(x_i, x_o, \theta, N_{ch}, \gamma) = P(x_i|x_o, \theta)P(N_{ch}|\gamma),$$

where γ is the source spectral index. The detector point spread is modeled as a 2-D Gaussian:

$$P(x_i|x_o, \theta) = \frac{e^{-\frac{|x_i - x_o|^2}{2\sigma^2(\theta)}}}{2\pi\sigma^2(\theta)}.$$

The gaussian width σ is fitted to simulation. The background PDF depends on $P(N_{ch}|Atmos.\nu)$, the probability of obtaining the observed Nch value from atmospheric neutrinos, and event density within the band. The full likelihood function is a combination of signal and background probabilities $\mathcal{S}$ and $\mathcal{B}$ over all events in the declination band ranging $\pm 5^o$ of the source position x_o and containing N total events:

$$\mathcal{L} = \prod_i^N \left(\frac{n_s}{N} \cdot \mathcal{S}_i(x_i, x_o, \theta, N_{ch}, \gamma) + (1 - \frac{n_s}{N}) \cdot \mathcal{B}_i(N_{ch}) \right).$$

The signal and background PDF are normalized such that the free parameter n_s describes the number of signal events present. The quantity $-log(\mathcal{L})$ is minimized with respect to n_s and γ, obtaining best estimates of signal strength $\hat{n}_s$ and spectral index $\hat{\gamma}$. The logarithm of the likelihood ratio

$$\lambda = log \frac{\mathcal{L}(\hat{n}_s, \hat{\gamma})}{\mathcal{L}(n_s = 0, Atmos.\nu)}$$

is used to determine significance and flux limits for each observation.

Significance is calculated by comparing the observed value of λ to the distribution obtained from randomized data. Adding a simulated signal flux shifts the distribution of λ to higher values, corresponding to higher significance. Discovery potential is measured by calculating the signal flux necessary to increase λ such that a given significance is exceeded in a given percentage of trials. Feldman-Cousins confidence intervals [4] are constructed knowing the response of λ to increasing signal flux and are used to calculate sensitivity and flux upper limits. A 30% improvement in sensitivity and discovery potential using the unbinned maximum likelihood method is shown in both sensitivity and discovery potential in figures 3 and 4.

Since signal spectral index is estimated simultaneously with flux, the obtained value of $\hat{\gamma}$ serves as an estimate of spectral index. The accuracy of $\hat{\gamma}$ is determined by evaluating spectral index using many sets of data randomized in right ascension with simulated signal events then added. The obtained distributions of $\hat{\gamma}$ yield confidence estimates in spectral index as a function of number of signal events, shown in figure 2 for E^{-2} and E$^{-2.5}$ sources of reasonable strength. For example, suppose Markarian 421 (δ = 38.2^o) produces 8 events in the detector with an E^{-2} energy spectrum. Application of this method to the coordinates of Markarian 421 would yield a 53% chance of discovery at 5σ confidence level. Preliminarily, 1σ spectral index confidence bounds for this source would be better than $\pm$0.5 around $\hat{\gamma}$.

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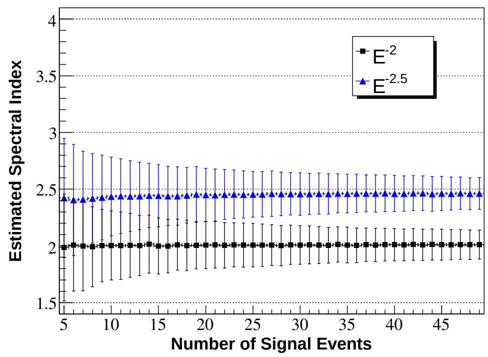

Figure 2: Preliminary pectral index estimation for simulated E^{-2} and $E^{-2.5}$ sources at δ=22.5^o as a function of number of observed signal events. Error bars indicate 1σ uncertainty in ability to measure spectral index.

Another benefit is the ability to combine data from detectors with different angular resolution. A binned search regards each event equally and bin radius must be optimized given the combination of datasets; however, this method can recognize which dataset the event is from and use the appropriate point spread distribution to more accurately describe the event. This benefit is particulary important during the construction phase of IceCube, as detector resolution will improve each year.

Data Sample

Data are taken during the austral winter from mid-February 2005 through October 2005. Accounting for the time the detector is down and a brief time the detector is dead following each event yields 199.3 days of detector livetime and $1.8{\cdot}10^9$ events. Most events are recorded from a multiplicity trigger requiring at least 24 optical modules register photon hits within 2.5 μs. False hits produced by crosstalk, isolated hits caused by PMT dark noise, and hits from 154 modules with either an abnormal dark noise rate or position outside the main detector volume are removed. Remaining hits from 523 optical modules are reconstructed as muon tracks with increasing accuracy and cpu requirements [3], and zenith filters are applied to remove the majority of cosmic ray muon background. Filtering is divided into levels to maximize CPU efficiency while retaining the vast majority of neutrino events [2]. 5.2 million events remain in the final filtered sample, mostly misreconstructed muons. Neutrino events are chosen from this sample to minimize average flux upper limit [6] based on reconstruction and topological criteria including a track angular resolution estimate [7], the ratio of upgoing reconstruction likelihood to downgoing likelihood, the distribution of hits along the track, and track length. Events are divided into 5^o declination bands, and optimization is performed simultaneously on all parameters for E^{-2} and $E^{-2.5}$ source spectra. A compromise cut is applied between the E^{-2} – $E^{-2.5}$ optimization. Optimized point source sensitivity (figure 3) shows a $\sim$30% improvement against the binned method uniform over the sky. Discovery potential shown in figure 4 is similarly improved. After the cut, 887 events remain above $\delta = 10^o$, with any 10^o declination band containing 50-150 events. A large number of misreconstructed muons add to atmospheric neutrinos in the final sample below $\delta = 10^o$.

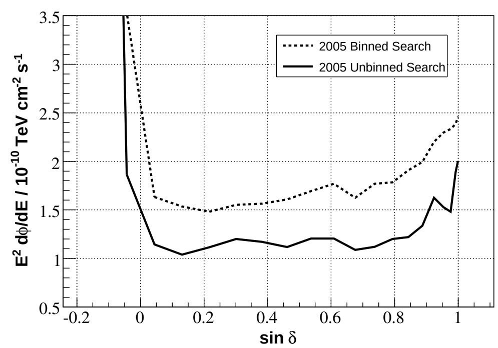

Figure 3: Preliminary point source sensitivity to E^{-2} energy spectra

Results

The method is applied to a catalog of candidate neutrino sources including microquasars, supernova remnants, TeV blasars, and other objects of interest. Results for a selected subset of objects are summarized in table 1. A scan of the entire sky at points spaced by 0.25^o is also performed using this method. The resulting p-value map is shown in figure 6. The highest obtained p-value corre-

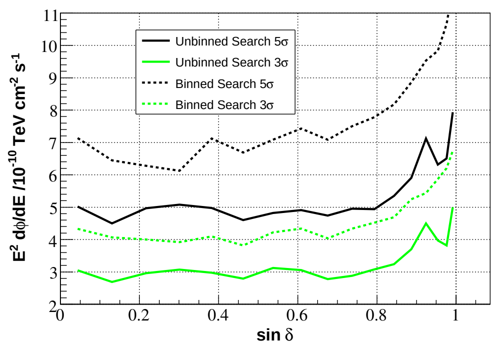

Figure 4: Preliminary point source discovery flux for E^{-2} energy spectra. 90% of sources with this flux are detected at the stated significance, excluding trial factors.

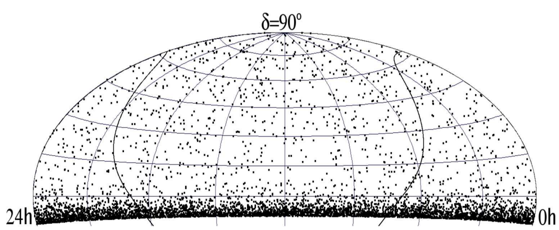

Figure 5: Preliminary sky map of neutrino candidate events

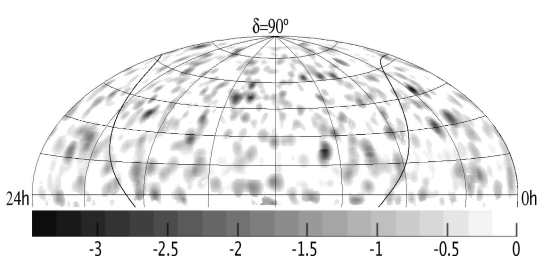

Figure 6: Preliminary sky map of $\log_{10}$(p-value)

sponds to 3.6σ. The probability of this deviation due to background alone is evaluated by comparing against 100 simulated experiments with randomized right ascension, and is found to be 69%.

Candidate	$\delta(^o)$	μ_{90}	p
Markarian 421	38.2	5.87	$\sim$1
Markarian 501	39.8	18.1	0.184
Cygnus X-1	35.2	12.9	0.414
Cygnus X-3	41.0	11.0	0.458
LS I +61 303	61.2	3.81	$\sim$1
Crab Nebula	22.0	9.24	$\sim$1
MGRO J2109+37	36.8	20.1	0.152

Table 1: Preliminary flux upper limits for selected neutrino source candidates over 199.3 days livetime: source declination δ in degrees, flux 90% confidence level upper limits for E^{-2} spectra ($E^2 \cdot \phi < \mu_{90} \cdot 10^{-11}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}$), probability of observed or higher likelihood given random chance

Acknowledgements

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References

[1] "One Year IceCube Point Source Analysis". This conference.

[2] A. Achterberg et al. *astro-ph 0611063*, 2006.

[3] J. Ahrens et al. *Nucl. Instr. Meth. A*, 524:169, 2004.

[4] G. Feldman and R. Cousins. *Phys. Rev. D*, 57:3873, 1998.

[5] A. Heijboer. 2004. Ph.D. Thesis, Universiteit van Amsterdam, Amsterdam, The Netherlands.

[6] G. C. Hill and K. Rawlins. *Astropart. Phys.*, 19:393, 2003.

[7] T. Neunhöffer. *Astropart. Phys.*, 25:220–225, 2006.

[8] T. Neunhöffer and L. Köpke. *Nucl. Instr. Meth. A*, 558:561, 2006.