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Nine-String IceCube Point Source Analysis

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Abstract: The construction of the IceCube Neutrino Observatory began during the austral summer of 2004-05, and is expected to continue through 2011. During 2006, nine of the projected 80 strings were already deployed and taking data, making IceCube an operational neutrino observatory while still at about 10% of its final size. We present the first results of a point-source search based on the analysis of this year of data, and characterize the angular resolution and effective area of the nine string configuration. With 137.4 days of detector livetime, 233 neutrino candidate events were selected in the analysis; the sky-averaged point-source sensitivity for an E^{-2} spectrum is $\frac{d\Phi}{dE} = 12 \times 10^{-11}\ \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\ (E/\mathrm{TeV})^{-2}$. No significant point-source is found. We also discuss how the performance is expected to improve as the detector moves toward completion.

Introduction

The IceCube Neutrino Observatory is a cubic kilometer-scale detector under construction at the geographic South Pole. Its primary mission is the search for high energy extraterrestrial neutrinos, which may reveal the origin of cosmic rays and offer insight into the most energetic phenomena in the universe. The detector consists of an array of digital optical modules: 60 modules are connected on one string, and a planned total of up to 80 strings are to be deployed in the Antarctic ice at depths between 1.5 and 2.5 kilometers beneath the ice surface. Construction is limited to the austral summer time, and therefore is spread over a number of years. As the detector grows, commissioning of the new strings and data-taking occur during the rest of the year.

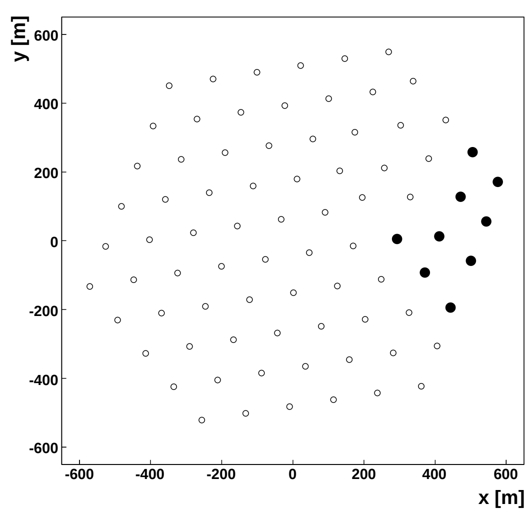

Figure 1: Configuration of IceCube strings; filled markers indicate the location of the nine strings already deployed and taking data in 2006.

Nine strings were in operation during 2006, shown in Figure 1. At about 10% of its completed size, the partial detector configuration is not optimal: muon tracks which traverse the long axis of the detector can be reconstructed much more accurately than those which pass through from other directions. Nevertheless, high-quality data was obtained between June and November, providing the first opportunity to perform a search for extraterrestrial neutrinos with the IceCube detector. Point source searches like the one presented here are the simplest and most direct way to distinguish an extraterrestrial neutrino signal from the experimental backgrounds. Discovery of point sources would also directly indicate the sites of cosmic ray acceleration.

Method

An unbinned maximum likelihood method is used to search for point sources. For a specified, hypothetical source location x_s and total number of events $n_{\rm tot}$, the source hypothesis is that the data set is a mixture of n_s signal events (distributed around the source according to their individual angular uncertainty) and $n_{\rm tot} - n_s$ background events (distributed over the sky according to the detector background distributions). This can be expressed as the partial probability P_i of each event:

$$P_i(x, x_s, n_s) = \frac{n_s}{n_{\rm tot}} S_i(x, x_s) + \left(1 - \frac{n_s}{n_{\rm tot}}\right) B_i(x)$$

where $S_i(x, x_s)$ is the source pdf of the event (determined by its angular uncertainty) and $B_i(x)$ is the background pdf. The background pdf is determined by using the declination distribution of the real data set.

The likelihood $\mathcal{L}$ is defined as the product of all individual event pdf's evaluated at the event and source coordinates:

$$\mathcal{L}(x_s, n_s) = \prod P_i(x_i, x_s, n_s)$$

The best estimate for the number of signal events $\hat{n}_s$ is found by maximizing the log likelihood ratio λ with respect to the null hypothesis $n_s = 0$:

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

$\log\ \lambda$ is the test statistic which determines the significance of an observed deviation from the null hypothesis.

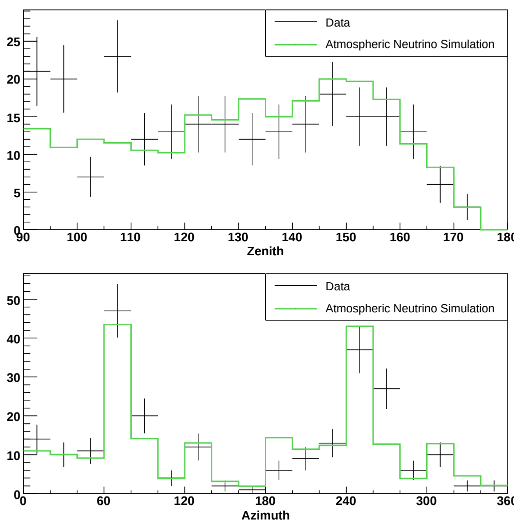

Figure 2: Distribution of data events in zenith and azimuth after analysis cuts have been applied, compared with simulated atmospheric neutrino events. (Note: declination $\delta = \theta_{\rm zen} - 90°$.)

Event Selection

Data in this analysis first passed two levels of filtering to reject down-going muon events; these filter levels are described in [1]. The remaining events were reconstructed using a likelihood algorithm that also provides an angular uncertainty estimate by evaluation of the likelihood function around the direction of the best fit. After filtering, the main background is still mis-reconstructed down-going muons and muon bundles from cosmic ray showers. To reduce this mis-reconstructed background, a tight cut on each track's angular uncertainty was used, and only tracks which reconstructed as up-going (zenith angle greater than $90°$) are kept in the analysis. A second cut on the minimum number of modules which were hit by direct Cherenkov photons (as estimated for the reconstructed track, using a time window of -15 to $+75$ ns around the expected arrival time) provides additional background rejection, primarily of down-going muons from two different cosmic ray showers which trigger the detector in coincidence and reconstruct as a single upward-going event. What remains after tight cuts on both of these pa-

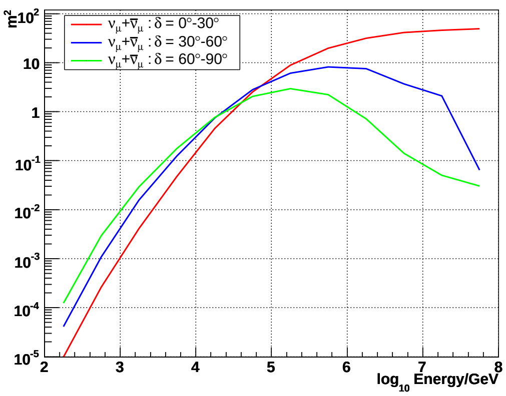

Figure 3: IC-9 effective area to a flux of $\nu_\mu + \bar{\nu}_\mu$, averaged over different declination ranges.

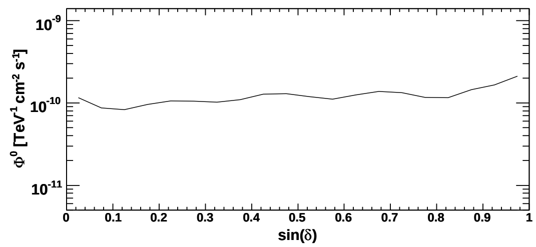

Figure 4: IC-9 sensitivity as a function of declination to a point source with differential flux $\frac{d\Phi}{dE} = \Phi^0(E/\mathrm{TeV})^{-2}$. Specifically, Φ^0 is the minimum source flux normalization (assuming E^{-2} spectrum) such that 90% of simulated trials result in a log likelihood ratio $\log\lambda$ greater than the median log likelihood ratio in background-only trials ($\log\lambda = 0$).

rameters is the "irreducible" background of well-reconstructed upward-going atmospheric neutrino events, the product of cosmic ray showers in the northern hemisphere.

To determine the final cut values, the point source analysis was performed on simulated data sets, consisting of simulated source events added to real data scrambled in right ascension. The cuts were optimized for discovery potential: the combination of cuts which could detect the smallest source flux at $5\,\sigma$ significance in 50% of the trials. For most possible source declinations and a range of spectra ($\frac{d\Phi}{dE} \propto E^{-\gamma}$ for the range $\gamma = 2$ to $\gamma = 3$) the optimal cuts were the same.

Data Sample

Data taking occurred between June and November 2006. The detector livetime was 137.4 days. The zenith distribution of data events is shown after final cuts and compared with simulated atmospheric neutrino events (using the spectrum predicted by the Bartol group[2]) in Figure 2. The final sample is restricted to events with declination less than $85°$, because the right-ascension scrambling technique for estimating background does not work near the pole, where statistics are low and the events cannot be scrambled. After cuts, there are 233 events in the data sample, and 227 predicted atmospheric neutrino events. The excess of data events at low zenith angles is most likely mis-reconstructed down-going muons, which are increasingly hard to reject near the horizon. Because the cut optimization was performed using scrambled real data, this residue of mis-reconstructed events indicates that harder cuts, which could eliminate these events entirely, would ultimately decrease the discovery potential.

The azimuth distribution of data and simulation is also shown in Figure 2. The two directions corresponding to the long axis of the nine-string detector are clearly visible. For other directions, it is more difficult to reconstruct tracks with high accuracy and to reject background.

The effective area to an equal-ratio flux of $\nu_\mu + \bar{\nu}_\mu$ is shown in Figure 3. In Figure 4, the sensitivity (median flux upper limit) is shown as a function of declination. The sky-averaged point-source sensitivity to an E^{-2} source spectrum is $\frac{d\Phi}{dE} = 12 \times 10^{-11}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ (E/\mathrm{TeV})^{-2}$. The median angular reconstruction error is $2.0°$.

Results

The analysis consists of an all-sky point source search, and individual point source searches using a pre-defined source list. The result of the all-sky search is shown in Figure 5. The maximum upward

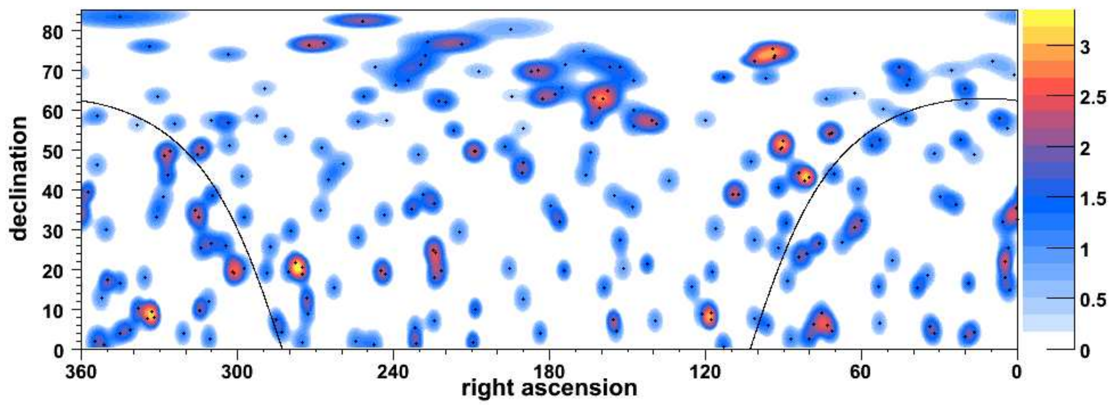

Figure 5: Sky map of the significance [σ] of deviations from background, estimated from the maximum likelihood point-source search. (Black points are reconstructed event directions.)

deviation from background is at r.a. $= 276.6°$, dec $= 20.4°$, with $3.35\,\sigma$ significance. This is consistent with random fluctuations: in simulations of background-only data sets (data scrambled in right ascension), 60% have a maximum deviation (anywhere) of $3.35\,\sigma$ or greater.

Twenty-six galactic and extragalactic objects were included in the pre-defined source list. Of these, the most significant excess over background was $1.77\,\sigma$, found for the Crab Nebula. This is also consistent with random fluctuations: the probability for at least one out of 26 source directions to have an excess of $1.77\,\sigma$ or greater is 65%. The 90% confidence level flux upper limit for the Crab Nebula is $\frac{d\Phi}{dE} = 22 \times 10^{-11}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ (E/\mathrm{TeV})^{-2}$.

Discussion

Nine IceCube strings (out of a projected total of 80) were operating and taking data in 2006. Analysis of this first year of data indicates that the point-source sensitivity of the nine string detector is comparable to an equivalent livetime of the AMANDA-II detector. This is a promising result, given that the configuration of the nine-string detector is far from optimal. For example, as seen in Fig. 2, more than half of the well-reconstructed events arrive from less than 10% of the full range of azimuth. Therefore as construction continues, enlarging the array will not only increase the detector volume, but also greatly improve the angular resolution in all directions. This should become apparent with the 22-string configuration which began operating this year. Continued software development should also deliver more advanced track reconstruction algorithms and background rejection techniques. The current analysis can serve as a benchmark for evaluating the performance of these new tools. Extrapolating the present rate of growth, the IceCube Neutrino Observatory will begin to deliver results of unsurpassed sensitivity well before detector construction is completed.

Acknowledgments

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References

[1] A. Achterberg, et al., Detection of atmospheric muon neutrinos with the IceCube 9-string detector, Phys. Rev. D76 (2007) 027101.

[2] G. D. Barr, T. K. Gaisser, P. Lipari, S. Robbins, T. Stanev, A three-dimensional calculation of atmospheric neutrinos, Phys. Rev. D70 (2004) 023006.