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A Search for High-energy Muon Neutrinos from the Galactic Plane with AMANDA-II

J.L. Kelley[a] for the IceCube Collaboration
(a) Physics Department, University of Wisconsin, Madison, WI 53706 USA
Presenter: J.L. Kelley (jkelley@icecube.wisc.edu), usa-kelley-j-abs1-og25-oral

Interactions of cosmic rays with the galactic interstellar medium produce high-energy neutrinos through the decay of charged pions and kaons. We report on a search with the AMANDA-II detector for muon neutrinos from the region of the galactic plane below the horizon from the South Pole ($33^\circ <$ galactic longitude $< 213^\circ$). Data from 2000 to 2003 were used for the search, representing a total of 807 days of livetime and 3329 candidate muon neutrino events. No excess of events was observed. For a spectrum of $E^{-2.7}$ and Gaussian spatial distribution ($\sigma = 2.1^\circ$) around the galactic equator, we calculate a flux limit of $4.8 \times 10^{-4}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ in the energy range from 0.2 to 40 TeV.

1. Introduction

High-energy neutrinos are produced in the disk of the Galaxy as cosmic rays interact with the interstellar medium (ISM), creating charged pions and kaons. Because of the low density of the ISM, the particles produced typically decay before interacting again, and the energy spectrum of the neutrinos follows the primary cosmic ray spectrum of $E^{-2.7}$. Most models of this emission predict a flux that is proportional to the column density of the ISM, and thus highest towards the Galactic Center [1], [2].

The AMANDA-II detector, a subdetector of the IceCube experiment, is an array of 677 optical modules buried in the ice at the geographic South Pole which detects the Čerenkov radiation from charged particles produced in neutrino interactions with matter [3]. In particular, muons produced in charged-current ν_μ and $\bar{\nu}_\mu$ interactions deposit light in the detector with a track-like topology, allowing us to use directional reconstruction to reject the large background of down-going atmospheric muon events. Up-going atmospheric neutrinos are the primary remaining background for this search. Because we restrict ourselves to events originating below the horizon, we are not sensitive to the region near the Galactic Center; rather, we perform a search for neutrinos from the outer region of the galactic plane, $33^\circ <$ galactic longitude $< 213^\circ$. Using the parametrization in ref. [2] with an average ISM column density in this region of $0.8 \times 10^{22}\ \mathrm{cm}^{-2}$, we expect at Earth an average $\nu_\mu + \bar{\nu}_\mu$ flux of $3.9 \times 10^{-6}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$.

2. Signal Hypothesis and Simulation

The actual distribution of the ISM in the galactic plane is quite irregular [4], so we use a simplified signal hypothesis. Because the ISM column density in the outer Galaxy does not vary too much (see e.g. the map by Bloemen in ref. [1]), we model the neutrino flux as isotropic in galactic longitude. The expected profile in galactic latitude has not been discussed in detail in the literature, although we can study models of γ-ray emission as a guide. A recent model by Strong *et al.* of the γ-ray emission from π^0 decay in a somewhat lower energy range (4-10 GeV) has an approximately Gaussian profile with $\sigma \approx 2.1^\circ$ around the galactic equator [5].

For our initial signal hypothesis, we have simulated a line source from the galactic equator that is isotropic in galactic longitude. As discussed later, we also use two other spatial profiles: a diffuse flux near the galactic equator, and a Gaussian with $\sigma = 2.1^\circ$. The spectral slope is assumed to be -2.7, but other values ranging from

-2.4 to -2.9 are also tested (for specific models, see e.g. [5]). We do not model the change of slope at the knee of the cosmic ray spectrum, since the resulting difference in number of events is negligible. Possible point sources in the galactic plane have also not been considered. To produce the signal Monte Carlo (MC), we use a reweighting method to transform an isotropic distribution of simulated events [6] to a line source originating from the galactic equator. The absolute normalization of the simulated signal flux is adjusted after normalizing the atmospheric neutrino MC to the data sample.

3. Data Sample

The data sample used for this analysis consists of 3329 candidate muon neutrino events collected from 2000 to 2003, representing 807 days of livetime. The event selection involved a number of quality criteria to reject mis-reconstructed down-going muon events, and was optimized for a broad sensitivity to an E^{-2} to E^{-3} spectrum. This sample was originally used for a point-source neutrino search, and details of the data selection procedure are presented elsewhere in these proceedings [7]. During the design and optimization of event selection criteria, the right ascension of the data events was scrambled in accordance with our blind analysis procedures.

4. Background Estimation and Optimization of Selection Criteria

Because of our isotropic detector response in right ascension, we can use the data to estimate the background in a point-source search by counting events in a declination band around the sky. For this analysis, however, the source is extended across a large range of declinations, requiring a modification of this technique. We define the *on-source region* as the band of sky within B degrees of the galactic equator. The on-source region is first divided into slices of equal declination $5°$ wide, and the background is estimated by counting the number of events in the declination band outside the on-source region and scaling by the solid angle ratio. The total number of on-source and background events is then calculated by summing over the declination bands.

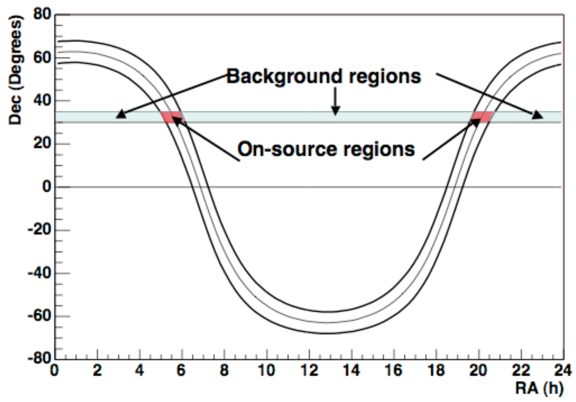

Figure 1. Regions of the sky used for on-source event counting and background estimation for a particular declination slice.

The direction of the events is the most useful parameter in distinguishing a galactic signal, and we optimize our sensitivity by varying the size of the on-source region. The region size is chosen to minimize the model rejection potential [8], the ratio of the average event upper limit at the 90% confidence level to the number of expected signal events at a given reference flux.

The optimal on-source region size for a line source was found to be $B = 2°$. This optimization is, however, a bit artificial since it is primarily determined by our line spread function. To obtain a value for more realistic flux distributions, we use an analytical method to estimate the sensitivity to a diffuse flux in the on-source region, as well as to a Gaussian signal profile of a given width. Our sensitivity to another signal profile is the flux level at which the total number of events in the on-source region is equal to that of the original line-source flux. This approximation is valid as long as the zenith angle does not vary too much over the on-source region.

First, we convert the line-flux sensitivity Φ_{line} (angular units of rad^{-1}) to a diffuse-flux sensitivity Φ_{diff} (angular units of sr^{-1}). We integrate the line flux over π radians of galactic longitude, divide by the solid angle Ω_{gal} of the on-source region, and include an efficiency factor η as the fraction of signal events in that region:

$$\Phi_{diff} = \eta \, \pi \, \Phi_{line} \, / \, \Omega_{gal} \, . \tag{1}$$

A similar procedure can be used to estimate the sensitivity to a Gaussian signal profile. The convolution of a Gaussian signal of width σ_{sig} with the line spread function (also approximated as a Gaussian, of width $\sigma_{lsf} \approx 1.5°$) results in a wider Gaussian. As before, by integrating to equalize the number of events in the angular region, we solve for the Gaussian peak sensitivity Φ_{peak} in terms of the line source sensitivity Φ_{line}:

$$\Phi_{peak}(B) = \frac{\Phi_{line}(B)}{\sqrt{2\pi(\sigma_{lsf}^2 + \sigma_{sig}^2)}} \; \mathrm{erf}(B/\sqrt{2}\sigma_{lsf}) \; / \; \mathrm{erf}(B/\sqrt{2(\sigma_{lsf}^2 + \sigma_{sig}^2)}) \, . \tag{2}$$

Using the relationship between the line-flux region size B and the sensitivity Φ_{line}, we can reoptimize for the wider Gaussian signal profile. For a Gaussian with $\sigma_{sig} = 2.1°$, we find an optimal on-source region of $B = 4.4°$.

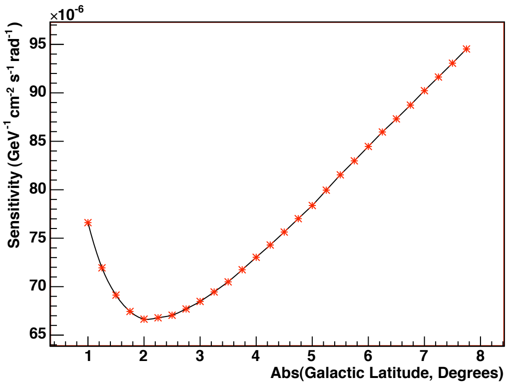

Figure 2. Sensitivity to a line source as a function of on-source region size.

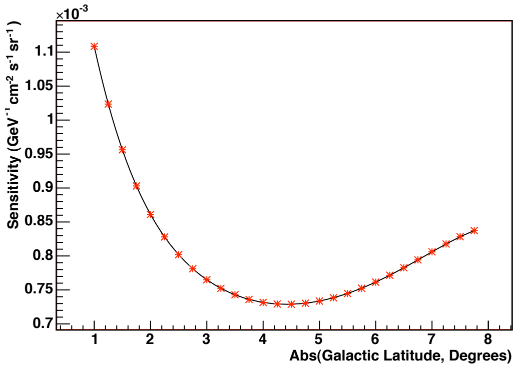

Figure 3. Sensitivity to a Gaussian source ($\sigma = 2.1°$) as a function of on-source region size.

5. Results

After unblinding the data, we observe no excess of events. We first calculate a limit on the line source flux at the 90% confidence level, and then calculate corresponding limits for diffuse and Gaussian spatial profiles using the analytical expressions above (eqns. 1 and 2). These results are presented in table 1 for a signal spectrum of $E^{-2.7}$. The energy range of these limits, incorporating the central 90% of the signal spectrum after all selection criteria, is 0.2 to 40 TeV. The calculation has been repeated using spectral slopes from -2.4 to -2.9, resulting in diffuse-flux limits ranging from 5.3×10^{-5} to 3.1×10^{-3} $\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$.

Because the signal flux is normalized using atmospheric neutrino MC, the largest systematic error is the uncertainty of $\sim$30% on the absolute atmospheric neutrino flux, and this has been incorporated into the limits [9],[10]. Possible unquantified sources of error are variations in the width of the Gaussian signal profile, and the offset of the peak flux from the galactic equator.

On-source region	On-source events	Expected background	Event upper limit	Line source limit	Diffuse limit	Gaussian limit
±2.0°	128	129.4	19.8	6.3×10^{-5}	6.6×10^{-4}	–
±4.4°	272	283.3	20.0	–	–	4.8×10^{-4}

Table 1. Preliminary limits on the $\nu_\mu + \bar{\nu}_\mu$ flux at Earth from the outer galactic plane, for an $E^{-2.7}$ spectrum (systematic errors included). Units on the line source limit are $\mathrm{GeV^{-1}cm^{-2}s^{-1}rad^{-1}}$; units on the other two limits are $\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$.

6. Conclusions

Comparing the limit for a Gaussian flux profile in table 1 with the model prediction in section 1, we find that the sensitivity of this analysis is approximately two orders of magnitude above the predicted flux. IceCube, the km^3-scale successor to AMANDA-II, will have a larger effective area and better angular resolution [11]. Only for the most optimistic case, in which the source profile is nearly a line, will the increase in angular resolution allow a significantly smaller on-source window. For five years of data from the complete detector, the total improvement in sensitivity is just over one order of magnitude. Other approaches may be more sensitive – for example, we can focus only on dense areas of the ISM, such as the Cygnus region. Also, recent calculations by Candia suggest that IceCube may be sensitive to the flux from the Galactic Center using cascades from down-going neutrinos [12]. Detection of specific sources within the plane may well precede discovery of a truly diffuse flux from the galactic disk.

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