ICRC'07 Mérida, México

Searches for a diffuse flux of extra-terrestrial muon neutrinos with AMANDA-II and IceCube

KOTOYO HOSHINA[1], JESSICA HODGES[1], GARY C. HILL[1] FOR THE ICECUBE COLLABORATION[2]
[1] *Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA*
[2] *See special section of these proceedings.*
kotoyo.hoshina@icecube.wisc.edu

Abstract: The AMANDA-II data collected during the period 2000–2003 have been analysed in a search for a diffuse flux of high-energy extra-terrestrial muon neutrinos from the sum of all sources in the Universe. With no excess of events seen, an upper limit of $\mathrm{E}_\nu^2 \times \mathrm{dN}_\nu/\mathrm{dE}_\nu < 7.4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}was obtained. The astrophysical implications of this upper bound are discussed, in addition to results from the search for signals with other energy spectra. The sensitivity of the diffuse analysis of IceCube 9-string is presented.

Introduction

High energy photons have been used to paint a picture of the non-thermal Universe, but a more complete image of the hot and dense regions of space can potentially be obtained by studying astrophysical neutrinos. Neutrinos can provide valuable information because they are undeflected by magnetic fields and hence their paths point back to the particle's source. Unlike photons, neutrinos are only rarely absorbed when traveling through matter. However, their low interaction cross section also makes their detection more challenging. The observation of astrophysical neutrinos would confirm predictions that hadrons are accelerated in objects such as active galactic nuclei or gamma-ray bursts [1, 2].

Instead of searching for neutrinos from either a specific time or location in the sky, diffuse analyses search for extra-terrestrial neutrinos from unresolved sources. If the neutrino flux from an individual source is too small to be detected by point source search techniques, it is nevertheless possible that many sources, isotropically distributed throughout the Universe, could combine to make a detectable signal. This search method assumes that the signal has a harder energy spectrum than atmospheric neutrinos. When examining an energy-related parameter, an excess of events over the expected atmospheric neutrino background would be indicative of an extra-terrestrial neutrino flux.

Search Method

Cosmic ray interactions in the atmosphere create pions, kaons and charmed hadrons which can later decay into muons and neutrinos. The main background for this analysis consists of atmospheric muons traveling downward through the ice. Diffuse analyses use the Earth as a filter to search for upgoing astrophysical neutrino-induced events. Once the background muons have been rejected, the data set mainly consists of neutrino-induced upward events. To separate atmospheric neutrinos from extra-terrestrial neutrinos, we use an energy-related observable as a final filter. This procedure is based on the assumption that the signal neutrinos follow a $\Phi \propto \mathrm{E}^{-2}$ energy spectrum resulting from shock acceleration processes. The atmospheric neutrino flux has a much softer energy spectrum (typically $\Phi \propto \mathrm{E}^{-3.7}$ for light meson induced, $\Phi \propto \mathrm{E}^{-2.7}$ for charmed hadron induced).

AMANDA-II diffuse muon searches

Searches for a diffuse flux have been performed with through-going muon events from

1997 AMANDA-B10 data [3] and 2000–2003 AMANDA-II data (807 days livetime) [4]. A search based on a regularized unfolding of the energy spectrum is also reported in these proceedings [5]. The energy estimator used by the 2000–2003 muon analysis was the number of optical modules (channels) that reported at least one Cherenkov photon during an event ($N_{\rm ch}$). Due to their harder energy spectrum, extra-terrestrial neutrinos are expected to produce a flatter $N_{\rm ch}$ distribution than atmospheric neutrinos (see Figure 1).

The search for an extra-terrestrial neutrino component used the number of events above an $N_{\rm ch}$ cut, after subtracting a calculated contribution from atmospheric neutrinos. The cut was optimized to produce the best limit setting sensitivity [6]. In order not to bias the analysis, data above the resulting cut ($N_{\rm ch} > 100$) were kept hidden from the analyzer while the lower $N_{\rm ch}$ events were compared to atmospheric neutrino expectations from Bartol [7] and Honda [8]. The various atmospheric neutrino calculations (Bartol and Honda models, with and without systematic uncertainties) were normalized to the low $N_{\rm ch}$ data, and the resulting spread in the number of events predicted with $N_{\rm ch} > 100$ was figured as an uncertainty in the limit calculation.

The observed $N_{\rm ch}$ distribution is compared to the atmospheric neutrino background calculations in Figure 1. For the $N_{\rm ch} > 100$ region, 6 events were seen, while 7.0 were expected. Using the range of atmospheric uncertainty (shaded band in Figure 1) in the limit calculation [9] leads to an upper limit on a $\Phi \propto E^{-2}$ flux of muon neutrinos at Earth of $\mathrm{E}_\nu^2 \times \mathrm{dN}_\nu/\mathrm{dE}_\nu = 7.4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}. This upper limit is valid in the energy range 16–2500 TeV. In comparison, an unfolding of the atmospheric neutrino spectrum with this same data set leads to an upper limit of $\mathrm{E}_\nu^2 \times \mathrm{dN}_\nu/\mathrm{dE}_\nu = 2.6 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} for the energy range 300–1000 TeV [5]. With this analysis, limits were also placed on specific extra-terrestrial models and on the flux of prompt, charmed hadron neutrinos from Earth's atmosphere [4].

Figure 4 shows the upper limit on the ν_μ flux from sources with an E^{-2} energy spectrum. The limit from the AMANDA-II 4-year analysis is a factor of four above the Waxman-Bahcall upper bound [1].

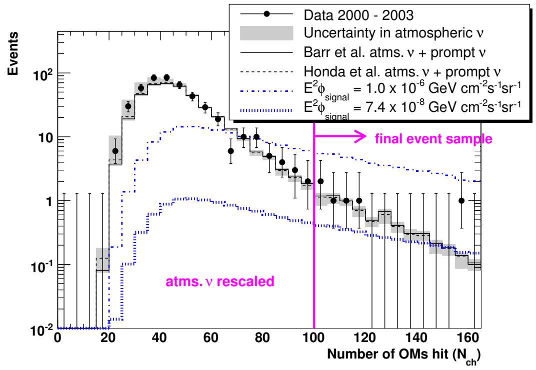

Figure 1: $N_{\rm ch}$, the number of OMs triggered, for the AMANDA-II 2000–2003 diffuse muon neutrino analysis. The data is compared to atmospheric neutrino expectations [7, 8]. The signal prediction for a $\Phi \propto E^{-2}$ flux is rescaled to reflect the upper limit derived from this analysis.

IceCube 9 String

The IceCube neutrino observatory is under construction and will be completed within the next four years. In 2006, the first nine IceCube strings were operated as a physics detector for 137 days. The IceCube 9-string detector (IC9) has an instrumented volume four times larger than AMANDA-II. Each string contains 60 digital optical modules (DOMs) in ice, spaced in 17 m intervals between depths of 1450 to 2450 m. The distance between strings is 125 m, approximately three times greater than in AMANDA-II.

Muon Background Rejection

Like the 2000–2003 AMANDA-II analysis, the IC9 analysis uses the number of hit DOMs ($N_{\rm ch}$) as an energy-related observable to distinguish atmospheric neutrinos from extra-terrestrial neutrinos. This method requires atmospheric muon backgrounds to be removed first. For IC9, the atmospheric muon rejection has been re-optimized to preserve more near-horizontal signal events (now covering 80–180 degrees in zenith) and accommodate the new detector geometry.

For the background study, atmospheric muons were simulated using CORSIKA. In addition, co-

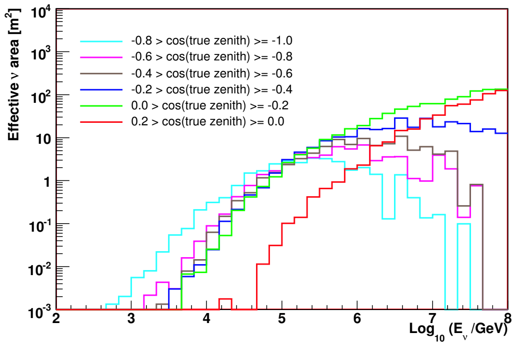

Figure 2: Effective area after final background-rejection. The curve for $\cos(\text{zenith}) > 0$ shows an increased energy threshold because of the cut on average hit distance.

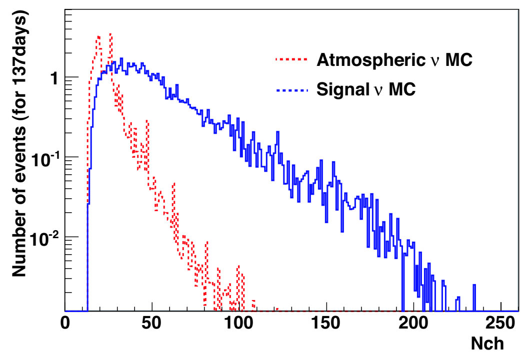

Figure 3: $N_{\rm ch}$ distribution in IC9 after background atmospheric muon rejection. The IC9 cuts raise the energy threshold relative to AMANDA-II, leading to a lower atmospheric neutrino rate compared to Figure 1. The signal curve corresponds to a test flux of 1×10^{-6}E^{-2} GeV cm^{-2} s^{-1} sr^{-1}.

incident muon events were generated, in which muons from two independent atmospheric showers are detected during the same trigger window. For atmospheric neutrinos, 1.6×10^7 ν_μ events were generated and re-weighted with the Bartol flux [7].

Atmospheric muons can enter the sample when they are mis-reconstructed as upgoing or when they arrive from near the horizon. One of the most effective parameters for rejecting mis-reconstructed events is the number of direct hits ($N_{\rm dir}$). These are hits close to the reconstructed track so they are assumed to result mostly from unscattered Cherenkov photons. The AMANDA-II analysis selected well-reconstructed tracks based on an $N_{\rm dir}$ cut and the distribution of hits along the length of the track. With its larger string spacing, the IC9 analysis uses a relaxed $N_{\rm dir}$ cut complemented by new requirements on the calculated precision of the zenith angle reconstruction and the number of strings hit. Besides rejecting mis-reconstructed muons, these cuts lead to the energy threshold behavior visible in Figure 2. Therefore lower energy atmospheric muons as well as atmospheric neutrinos are further suppressed.

Preserving signal events near the horizon is important because the effective area for high energy ν_μ is greatest there (Figure 2). This enhancement is strengthened in IC9 by the large height to width ratio. However, atmospheric muon tracks at these zenith angles are generally well-reconstructed and often survive the other cuts. Therefore another energy-related parameter was introduced, namely the average perpendicular distance between all hit DOMs and the reconstructed track. The higher light yield for energetic tracks means light can reach far away DOMs, so a cut on the average hit distance distinguishes strongly against the lower energy atmospheric muon events. This cut is applied only for events above the horizon.

Sensitivity

After the atmospheric muon rejection cuts, simulated events are dominated by atmospheric and extra-terrestrial neutrinos. Figure 3 shows the $N_{\rm ch}$ distribution for these events. The best $N_{\rm ch}$ cut was determined to be 60 for IC9 (137 days) by optimizing the Model Rejection Factor [6]. Assuming no extra-terrestrial signal, the expected upper limit was calculated using the Feldman-Cousins method [9], giving a sensitivity of 1.4×10^{-7}GeV cm^{-2} s^{-1} sr^{-1}. Figure 4 shows the IC9 sensitivity in relation to sources with an E^{-2} energy spectrum and the AMANDA-II search. The IC9 sensitivity is only a factor 2 above AMANDA-II 4-year, despite its much lower integrated livetime. Further improvements may be expected, both from longer term operation of the full IceCube detector and refinements of the analysis such as new energy reconstruction methods.

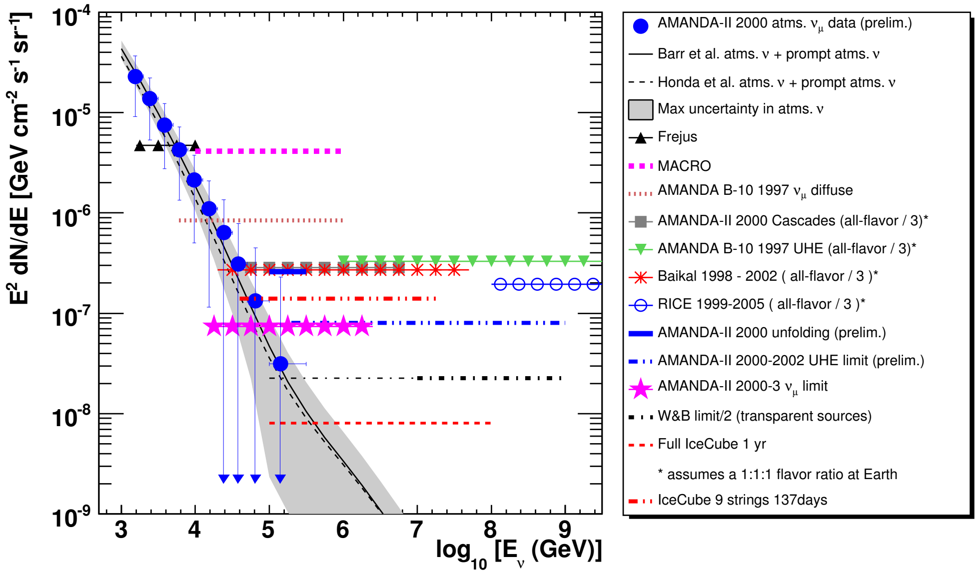

Figure 4: Upper limit on the ν_μ flux from sources with an E^{-2} energy spectrum for the 2000–2003 AMANDA-II data, and expected sensitivity of IC9 for 137 days.

Conclusion

The AMANDA-II data collected during the period 2000–2003 have been analysed in a search for a diffuse flux of high-energy extra-terrestrial muon neutrinos. With no excess of events seen, an upper limit of $E_\nu^2 \times dN_\nu/dE_\nu < 7.4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}was obtained. The sensitivity of 9 IceCube strings for 137 days livetime was studied with simulated data, making use of new cuts to improve acceptance near the horizon. The expected sensitivity is 1.4×10^{-7}GeV cm^{-2} s^{-1} sr^{-1}.

Acknowledgements

This work is supported by the Office of Polar Programs of the National Science Foundation.

References

[1] E. Waxman and J. Bahcall, *Phys. Rev.* D **59**, 023002 (1998).

[2] K. Mannheim, R.J. Protheroe, and J.P. Rachen, *Phys. Rev.* D **63**, 023003 (2000).

[3] J. Ahrens et al. *Phys. Rev.* D **66**, 012005 (2002)

[4] A. Achterberg et al., *Phys. Rev.* D, submitted, arXiv:0705.1315 (2007).

[5] K. Münich for the IceCube Collaboration, these proceedings

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

[7] G.D. Barr, T.K. Gaisser, P. Lipari, S. Robbins, and T. Stanev, *Phys. Rev.* D **70**, 023006 (2004).

[8] M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, *Phys. Rev.* D **70**, 043008 (2004).

[9] Cousins R D and Highland V L 1992 *Nucl. Ins. Meth. Phys. Res.* **A320** 331, Feldman G and Cousins R 1998 *Phys. Rev.* D **57** 3873, Conrad J, Botner O, Hallgren A and de los Heros C 2003 *Phys. Rev.* D **67** 012002, Hill G C 2003 *Phys. Rev.* D 118101