Diffuse high-energy neutrino searches in AMANDA-II and IceCube: Results and future prospects

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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 events seen, an upper limit of $E^2 dN/dE < 7.4 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ was obtained. The sensitivity of the diffuse analysis of IceCube 9 string for 137 days of data is calculated to be $E^2 dN/dE < 1.3 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. No excess events are observed, which confirms the AMANDA-II upper limit.

1. Introduction
Extra-terrestrial neutrinos have been regarded as one of the most promising tools to investigate the non-thermal Universe. Due to their low interaction cross section, neutrinos retain their original source information such as direction and energy spectrum. However, the low interaction cross section makes it difficult to detect neutrinos which must interact within or near the telescope. The size of the telescope must thus be large enough to collect a sufficient number of neutrinos to find and probe extra-terrestrial sources.

AMANDA-II is a neutrino telescope consisting of 677 optical modules attached to 19 strings, deployed between 1500 m to 1950 m depth within a 200 m diameter in glacial ice at the South Pole. Following the success of AMANDA-II, the cubic kilometer-sized IceCube experiment started construction in 2005. By the spring of 2007, 22 strings with 1320 digital optical modules (DOMs) out of the 4800 planned had been deployed, at a depth of 1450 m - 2450 m surrounding AMANDA-II.

With these observatories numerous analyses are performed to search for extra-terrestrial neutrinos [1, 2, 3]. The target of diffuse analysis are neutrinos from unresolved sources. If the neutrino flux from an individual source is too small to be detected by point source search techniques [1], it is nevertheless possible to investigate their characteristics by combining events from isotropically distributed sources. The extra-terrestrial neutrinos are predicted to follow a $\Phi \propto E^{-2}$ energy spectrum resulting from shock acceleration processes [4]. Since the atmospheric neutrino flux has a much softer energy spectrum, an excess of events at higher energy over the expected atmospheric neutrino background would be indicative of an extra-terrestrial neutrino flux.

In this paper we present analyses with AMANDA-II data collected during the period 2000–2003 and IceCube data obtained with 9 strings (IC9) in 2006.
2. 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 [5]. To separate atmospheric neutrinos from extra-terrestrial neutrinos, we make use of the number of optical modules that reported at least one Cherenkov photon during an event ($N_{ch}$) as the energy estimator. The number of events above an $N_{ch}$ cut has been compared with sets of monte-carlo prediction for $E^{-2}$ and atmospheric neutrino models (Bartol [6, 7], Honda [8]). The $N_{ch}$ cut was optimized to produce the best limit setting sensitivity [9]. In order not to bias the analysis, data above the resulting $N_{ch}$ cut were kept hidden from analyzer while the lower $N_{ch}$ events were compared to atmospheric neutrino expectations from Bartol and Honda.

3. AMANDA-II diffuse muon searches
Searches for a diffuse flux have been performed with AMANDA-II data obtained 2000-2003 (807 days livetime) [11]. The observed $N_{ch}$ distribution is compared to the atmospheric neutrino background calculations in Figure 1. For $N_{ch} > 100$ 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 [10] leads to an upper limit on a $\Phi \propto E^{-2}$ flux of muon neutrinos at Earth of $E_\nu^2 \times dN_\nu/dE_\nu = 7.4 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This upper limit is valid in the energy range 16–2500 TeV. Figure 3 shows the upper limit on the $\nu_\mu$ flux from sources with an $E^{-2}$ energy spectrum. The limit from the AMANDA-II 807 days analysis is a factor of four above the Waxman-Bahcall upper bound [4].

4. IceCube 9 String diffuse muon searches
Data from the first nine IceCube strings (IC9), with livetime 137 days, was analyzed to search for a diffuse flux. The atmospheric muon rejection and $N_{ch}$ cut threshold are re-optimized [13] to accommodate the new detector geometry. The finalized $N_{ch}$ cut=33 for the IC9 137 days gives a sensitivity $E_\nu^2 \times dN_\nu/dE_\nu = 1.3 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ on the neutrino energy range of 25 TeV to 10 PeV, which is a factor of two above the AMANDA-II 807 day upper limit.

Since the sensitivity of IC9 137 days was well above the AMANDA-II upper limit, we revealed...
Figure 3. Upper limit on the $\nu_\mu$ flux from sources with an $E^{-2}$ energy spectrum are shown for single and all-flavor analyses [11, 12].

the high-energy events ($N_{\text{ch}} > 33$) for the sake of a verification study of the detector. 6 events were observed while 6.5 were expected from the Bartol atmospheric neutrino model [7], which indicates no signal observation, consistent with the better AMANDA-II upper limit.

5. Outlook for IceCube 22 strings
It is an encouraging sign that the IC9 137 day is within a factor of two of the 807 day AMANDA-II result. With same atmospheric muon rejection and $N_{\text{ch}}$ cut as IC9, a sensitivity of IceCube 22 strings (IC22) for 137 days is expected to reach $E^2 \times \frac{dN_\nu}{dE_\nu} = 4.0 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This is already a factor of three better than IC9. Improvements of event separation to extract extra-terrestrial neutrinos from atmospheric neutrinos [14] are ongoing together with the optimization of background muon rejection for the IC22 geometry, which should improve the sensitivity further.

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