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 of events seen, an upper limit of $E^2 \frac{d N}{d E} < 7.4 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ was obtained. A sensitivity of the diffuse analysis of IceCube 9 string 137 days is calculated as $E^2 \frac{d N}{d E} < 1.3 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. No excess of events confirmed the AMANDA-II upper limit.

1. Introduction
Extra-terrestrial neutrinos have been regarded as one of the promising tool to investigate non-thermal Universe, nevertheless it’s difficulty of detection. Because of their low interaction cross section, neutrinos retain their original information at source such as direction and energy spectrum. This advantage rises drawback when one try to detect them: the neutrino telescopes have sensitivity only when a neutrino makes interactions within or near by the telescope. The size of telescope must thus be large enough to probe the extra-terrestrial sources.

The AMANDA-II is a photomultiplier-based neutrino telescope completed in 2000 and has been successfully recording atmospheric neutrinos. It consist of 677 optical modules attached on 19 strings, deployed between 1500m to 1950m depth $\times$ 200m diameter in glacial ice at the south pole. Following the success of AMANDA-II, a kilo-meter cubic neutrino observatory called IceCube started in 2005. Until the spring of 2007, 1320 digital optical modules out of 4600 had been deployed with 22 strings, at a depth of 1450m-2450m around the AMANDA-II.

With these observatory numerous analysis are performed to search for extra-terrestrial neutrinos. Targets 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, 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 [1]. 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 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. To separate atmospheric neutrinos from extra-terrestrial neutrinos, we use number of optical modules (channels) that reported at least one Cherenkov photon during an event ($N_{\text{ch}}$) as the energy estimator. The number of events above an $N_{\text{ch}}$ cut has been compared with sets of monte-carlo prediction for $E^{-2}$ and atmospheric neutrino models (Bartol [2] [3], Honda [4]). The $N_{\text{ch}}$ cut was optimized to produce the best limit setting sensitivity [5]. In order not to bias the analysis, data above the resulting $N_{\text{ch}}$ cut were kept hidden from analyzer while the lower $N_{\text{ch}}$ 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). The result is also published from Phys.Rev.D [7]. The observed $N_{\text{ch}}$ distribution is compared to the atmospheric neutrino background calculations in Figure 1. For the $N_{\text{ch}} > 100$ 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 [6] leads to an upper limit on a $\Phi \propto E^{-2}$ flux of muon neutrinos at Earth of $E^2_\nu \times dN_\nu/dE_\nu = 7.4 \times 10^{-8}$ 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 4-year analysis is a factor of four above the Waxman-Bahcall upper bound [1].

4. IceCube 9 String diffuse muon searches
The first nine IceCube strings(IC9) data with livetime 137days are used to apply diffuse analysis technique which used by AMANDA–II diffuse neutrino searches. The atmospheric muon rejection and $N_{\text{ch}}$ cut threshold are re-optimized [8] to accommodate the new detector geometry. The optimized $N_{\text{ch}}$ cut = 33 for IC9 137 days gives a sensitivity $E^2_\nu \times dN_\nu/dE_\nu = 1.3 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ from the neutrino energy range of 25TeV to 10PeV, which is factor two above the AMANDA-II upper limit.
Since the sensitivity of IC9 137 days was enough behind the AMANDA-II 807 days limit, the high-energy events ($N_{\text{ch}} > 46$) was revealed for the sake of verification study of detector. 6 events were observed while 6.5 were expected with Bartol conventional atmospheric neutrino model, which indicates no signal observation and thereby consistent with the AMANDA-II upper limit.

5. Outlook for IceCube 22-strings
It is encouraging sign that the IC9 137 days observation potentially corresponds to 400 days of AMANDA-II observations. With same atmospheric muon rejection and $N_{\text{ch}}$ cut threshold as IC9, the sensitivity of IceCube 22 strings (IC22) for 137 days reaches to $E_\mu^2 \times dN_{\nu}/dE_{\nu} = 4.0 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This number is already factor three better than IC9, however, improvements of event separation method between atmospheric neutrinos and extra-terrestrial neutrinos [9] are ongoing together with the optimization of background muon rejection for IC22 geometry.

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References