AMANDA and IceCube: neutrino astronomy at the south pole

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Abstract. AMANDA is a high energy neutrino telescope consisting of 677 optical modules at 1.5-2 km depth in glacial ice at the south pole. We summarize AMANDA results for observation of atmospheric neutrinos and searches of extraterrestrial neutrinos from point sources, gamma ray bursts and diffuse fluxes. Upper limits at 90%CL are presented. The status of IceCube, the 1 km$^3$ successor to AMANDA currently under construction is presented.

1. Status of AMANDA and IceCube

AMANDA and IceCube are high energy ($E_\nu > 100$ GeV) neutrino telescopes located deep in glacial ice at the geographic south pole. Both experiments use optical modules, consisting of a PMT and a pressure sphere, to detect Cherenkov light produced by charged particles traveling through ice.

AMANDA-II, the current incarnation of AMANDA, was commissioned in 2000 with a total of 677 optical modules arranged on 19 strings, at depths between 1500 m and 2000 m. With AMANDA we have observed atmospheric $\nu_\mu$ and we have conducted numerous searches for extraterrestrial neutrinos. So far we have not found evidence for extraterrestrial neutrinos. Here, we present upper limits from point sources, gamma ray bursts and diffuse fluxes. We do not present results on searches for WIMPs, monopoles, $\nu$ from the galactic plane or from supernovae. For a comprehensive list of AMANDA and IceCube results see [1].

IceCube will succeed and incorporate AMANDA. The deep ice component of IceCube will have a total of 80 strings and 4800 Digital Optical Modules at depths between 1450 m and 2450 m. IceTop, the surface component of IceCube, will consist of a pair of ice filled tanks, each tank with two Digital Optical Modules, located on top of each of the deep ice strings. In 2005 a deep ice string and eight IceTop tanks were deployed. For 2006 we expect to deploy up to twelve deep ice strings and 24 tanks. IceCube is expected to be completed by 2010. Once finished, the deep ice component of IceCube will have an instrumented volume of almost 1 km$^3$ or $\approx 60$ times larger than AMANDA. Signals from the PMTs will be digitized in-situ and sent digitally to the surface electronics. IceTop will be used to study cosmic ray composition and will provide a calibrated source of muons to understand the angular resolution and pointing accuracy of the deep ice array. IceCube will have an angular resolution of $\approx 1^\circ$ or three times better than AMANDA. After three years of operation IceCube will have a sensitivity of $\approx 2 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for an $E^{-2}$ diffuse fluxes and $\approx 2 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$ for an $E^{-2}$ spectrum from point sources [2]. The leading models for extraterrestrial neutrino production in the range TeV-PeV will be testable with IceCube.
2. Atmospheric Neutrinos

The atmosphere is a known source of high energy neutrinos. AMANDA has measured the atmospheric $\nu_\mu$ flux up to an energy of 300 TeV [3]. The $\nu_\mu$ energy spectrum is shown in figure 1. Since diffuse fluxes of neutrinos are expected to have harder spectrum than atmospheric neutrinos ($E^{-2}$ versus $E^{-3.7}$), an upper limit on the event excess over the observed atmospheric flux can be placed. We have used this method to place a 90%CL limit on a $E^{-2}$ diffuse flux of $\nu_\mu$ between 100 TeV and 300 TeV (see table 1).

3. Search for high energy extraterrestrial neutrinos

We have performed searches for diffuse fluxes of neutrinos using both the muon [4] and the cascade channel [5] in several energy ranges from a few TeV to PeV. Since the Earth is opaque to neutrinos at energies above $\approx$1 PeV we have also conducted a search that focuses on horizontal-going events at the range PeV to EeV [6]. We optimize our searches for spectrum of the form $E^{-2}$ and we also calculate the model rejection factor for specific theoretical predictions. We present a summary of the most recent limits on diffuse fluxes in table 1.

Point sources are searched for by looking for statistical excess over the atmospheric neutrino background in narrow sections of the northern sky. We have used 807 days of effective live-time and 3369 $\nu_\mu$ events [7]. The search has been done by looking for hot-spots and by studying a specific set of 33 candidate sources. The candidate sources are gamma or X-ray sources like blazars, e.g. Markarian 421, microquasars, e.g. Cygnus X1, and supernova remnants, e.g. Cassiopeia A. The searches are done exclusively with the muon channel since the cascade channel doesn’t have a good angular resolution. For specific sources the 90%CL upper limits range from 0.20 to $1.5 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$ supposing $E^{-2}$ spectrum and integrating above 10 GeV. The declination average sensitivity to neutrino point sources above 10 GeV is $9 \times 10^{-9}$ cm$^{-2}$ s$^{-1}$.

Figure two shows the significance sky for the hot-spot search. The sensitivity for a specific set of point sources can be increased by using source-stacking. In this type of analysis a statistical excess is searched for from the combined set of directions. An
Table 1. 90%CL upper limits on diffuse fluxes of neutrinos. (a) All flavor limit supposing 1:1:1 flavor flux ratios. (b) Limits on $\nu_\mu$+$\bar{\nu}_\mu$. (*) Preliminary results.

| Data Year | Lifetime | Channel | $\nu$ Energy range | $E^2d\phi/dE$ limit | ref. |
|-----------|----------|---------|-------------------|----------------------|-----|
| 2000      | 174      | muon    | 100 TeV - 300 PeV | $2.6 \times 10^{-7}$ (b,*) | [3] |
| 2000-03   | 807      | muon    | 13 TeV - 3.2 PeV  | $9.5 \times 10^{-8}$ (b,*) | [4] |
| 2000      | 174      | cascade | 50 TeV - 3 PeV    | $8.6 \times 10^{-7}$ (a)  | [5] |
| 1997      | 131      | horizontal | 1 PeV - 3 EeV | $9.9 \times 10^{-7}$ (a)  | [6] |

analysis like this has been performed for the data years 2000-2003 [8]. For AGNs the sensitivity of the stacked search is three times better that the previous strategies.

GRBs are a subclass of point sources. Sky localization and accurate timing are available. This information allows a significant suppression of background. Background is measured experimentally with off-time and/or off-source measurements. Motivated by the Waxman-Bahcall model [9], we have performed searches with the muon channel in coincidence with 312 bursts reported by BATSE in the period 1997-2000 [10], 139 BATSE+IPN bursts in the period 2000-2003 [11], and in coincidence with GRB-030329 [12]. We have also looked for precursor $\nu_\mu$ [13] with 50 BATSE+IPN bursts in the period 2000-2003 [11]. In addition we have performed a search in coincidence with 73 BATSE bursts in 2000 with the cascade channel [14]. Finally we have looked for a statistical excess in cascade-like events from GRBs using a two rolling time windows of 1 s and 100 s [14]. The Model rejection factors for all these searches range from 5 to 200 depending on the search.

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