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The IceCube neutrino observatory: latest results on the search for point sources and status of IceCube construction

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Abstract. The AMANDA neutrino telescope, prototype instrument of the IceCube neutrino observatory at South Pole, has collected data since 2000 in its final configuration. A period of 1001 days of livetime between 2000 and 2004 has been analysed in order to find evidence of a neutrino signal coming from point-like sources such as *microquasars*, *active galactic nuclei*, *supernovae remnants* or *gamma ray bursts*. A sensitivity to fluxes of $\nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$ of $d\Phi/dE = 1.0 \cdot 10^{-10} (E/\mathrm{TeV})^{-2} \cdot \mathrm{TeV}^{-1} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ was reached in the energy range between 1.6 TeV and 1.6 PeV. No significant excess over the background has been found so far. Flux upper limits infered from this study can constrain certain neutrino emission models of X-ray binaries. IceCube will have a substantially higher sensitivity. Currently at 10 % of its final extension, it will comprise 4800 optical sensors deployed along 80 strings by early 2011, instrumenting one cubic kilometre volume of ice and 1 km^2 at the surface.

Keywords. Neutrinos, cosmic rays, point sources, gamma rays

1. Introduction

High energy neutrinos constitute highly valuable astronomical messengers. Unlike photons or protons, they can travel cosmic distances without being absorbed or deflected from their initial direction of propagation and deliver unaltered information related to the site of their emission. The Universe being transparent to photons only up to modest energies of order 1 TeV, neutrinos thus can be the indispensable partners of "conventional" astronomy to probe the most violent astrophysical objects.

Another major potential of neutrino astronomy resides in the fact that neutrinos could help us to understand the origin of cosmic rays. Indeed, these are thought to be accelerated in the expanding shocks of supernovae remnants, active galactic nuclei, gamma ray bursts or microquasars. In the vicinity of these extremely energetic sources, cosmic rays have the opportunity to interact with local hadronic matter or radiation fields giving rise to a flux of neutrinos and gamma rays (respectively by decay of charged or uncharged pions):

$$\begin{aligned} p + (p\ or\ \gamma) &\rightarrow \pi^0 \ \rightarrow \gamma\gamma \\ &\rightarrow \pi^\pm \rightarrow \nu_e\, \nu_\mu \rightarrow \nu_e\, \nu_\mu\, \nu_\tau \ \text{(after oscillations)} \end{aligned}$$

The discovery of neutrino point sources would thus unambiguously reveal the sites of cosmic ray acceleration in the Universe.

† <http://icecube.wisc.edu/science/publications/vulcano2006.html>

Table 1. Flux upper limits for the sources in the catalog of potential neutrino emitters. From left to right are given the source name, its sky position, the number of observed and expected events, the upper limit on the contribution from signal events at 90 % confidence level μ_{90} and the expected number of events from muon neutrino s_{ν_μ} and tau neutrino interaction s_{ν_τ} for a differential flux of $d\Phi/dE = 10^{-11}$ $\mathrm{TeV^{-1}cm^{-2}s^{-1}}(E/\mathrm{TeV})^{-2}$. In the last three columns, upper limits are presented on the differential flux $d\Phi/dE = \Phi_0^\nu(E/\mathrm{TeV})^{-2}$ of muon neutrinos, tau neutrinos and both channels combined in units of 10^{-11} $\mathrm{TeV^{-1}cm^{-2}s^{-1}}$.

Source name	RA[h]	Dec[°]	N_{obs}/N_{bg}	μ_{90}	s_{ν_μ} / s_{ν_τ}	$\mathbf{\Phi_0^{\nu_\mu}}$	$\Phi_0^{\nu_\tau}$	$\mathbf{\Phi_0^{\nu_\mu+\nu_\tau}}$
			TeV Blazars					
Markarian 421	11.1	38.2	6 / 7.37	4.1	0.97 / 0.15	**4.2**	27.8	**7.4**
1ES 1426+428	14.5	42.7	5 / 5.52	4.8	0.90 / 0.13	**5.4**	36.6	**9.4**
Markarian 501	16.9	39.8	8 / 6.39	7.9	0.93 / 0.14	**8.5**	57.2	**14.7**
1ES 1959+650	20.0	65.1	5 / 4.77	5.6	0.71 / 0.11	**7.8**	52.2	**13.5**
1ES 2344+514	23.8	51.7	4 / 6.18	3.1	0.89 / 0.15	**3.5**	20.9	**5.9**
			GeV Blazars					
QSO 0219+428	2.4	42.9	5 / 5.52	4.9	0.89 / 0.13	**5.5**	37.6	**9.6**
QSO 0528+134	5.5	13.4	4 / 6.08	3.2	1.06 / 0.14	**3.0**	22.8	**5.3**
QSO 0954+556	9.9	55.0	2 / 6.26	1.4	0.91 / 0.15	**1.6**	9.2	**2.7**
3C273	12.5	2.1	8 / 4.72	9.6	0.96 / 0.10	**10.0**	94.3	**18.0**
			other AGN					
NGC 1275	3.3	41.5	4 / 6.75	2.7	0.95 / 0.14	**2.9**	19.7	**5.0**
M87	12.5	12.4	6 / 6.08	5.3	1.07 / 0.14	**4.9**	38.6	**8.7**
			Microquasars & Neutron star binaries					
LSI +61 303	2.7	61.2	5 / 4.81	5.6	0.75 / 0.13	**7.4**	44.0	**12.6**
SS433	19.2	5.0	4 / 6.14	3.1	1.16 / 0.13	**2.7**	23.6	**4.8**
Cygnus X-1	20.0	35.2	8 / 7.01	7.3	0.95 / 0.15	**7.7**	48.4	**13.2**
Cygnus X-3	20.5	41.0	7 / 6.48	6.4	0.95 / 0.14	**6.8**	46.7	**11.8**
			Supernova Remnants & Pulsars					
Crab Nebula	5.6	22.0	10 / 6.74	10.1	0.98 / 0.15	**10.2**	68.9	**17.8**
Geminga	6.6	17.9	3 / 6.23	2.0	1.01 / 0.14	**2.0**	14.0	**3.5**
PSR 1951+32	19.9	3.3	4 / 6.72	2.7	0.94 / 0.14	**2.9**	19.0	**5.0**
Cassiopeia A	23.4	58.8	5 / 6.00	4.4	0.86 / 0.13	**5.1**	33.2	**8.9**
			Unidentified high energy gamma-ray sources					
3EG J0450+1105	4.8	11.4	8 / 5.94	8.4	1.08 / 0.14	**7.8**	61.6	**13.8**
TeV J2032+4131	20.5	41.5	7 / 6.75	6.1	0.95 / 0.14	**6.4**	43.8	**11.2**

2. Different strategies to search for extraterrestrial neutrinos

Completed in 2000, AMANDA has demonstrated the capability to detect neutrinos and determine their direction of origin (Andres *et al.* 2000). Five years of data have been accumulated between 2000 and 2004, corresponding to a livetime of 1001 days. After applying the reduction procedure aimed to reject the atmospheric muon background (Ahrens *et al.* 2004a), a sample of 4282 candidate neutrinos was selected in the northern hemisphere.

In a first step, a search for neutrinos was done by looking for excesses of events with respect to background coming from selected potential sources. Table 1 shows the different candidate sources reviewed as well as the number of observed and expected events. All the observations are compatible with the atmospheric neutrino background hypothesis. The highest excess found corresponds to the direction of 3C 273 with eight observed events compared to an average of 4.72 expected background (1.2 σ).

A complete survey of the northern hemisphere neutrino sky was then achieved by means of a grid search (Ackermann 2006). The highest significance (3.74 σ) obtained is located at $\alpha = 12.6$ h and $\delta = 4°$. However, the probability to observe this or a higher

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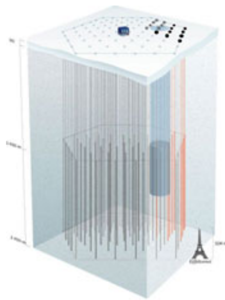

Figure 1. Representation of the IceCube neutrino observatory in its final extension. AMANDA is shown as a darker cylinder.

excess from a random fluctuation of the background, taking into account the trial factor, is 69 %. There is thus no claim of discovery.

As no evidence of a neutrino signal was found in the previous analyses, upper limits on the neutrino flux were determined (cf. Table 1) and compared to specific theoretical predictions. In the case of SS 433, the limit infered in this analysis excludes 0.4 times the corresponding flux predicted in Distefano *et al.* (2002). The upper limit for Cygnus X-3 and the predicted flux in Bednarek (2005) are of the same order of magnitude. However, the upper limits obtained for pulsar wind nebulae and AGN's are at least one order of magnitude above predictions, except for the most optimistic case of neutrino production in the jets of *EGRET* blazars predicted by Neronov & Semikoz (2002) and Neronov *et al.* (2002).

Finally, in order to further increase the sensitivity to particular AGN classes, a stacking analysis was developed: the cumulative signal coming from several AGN's of the same class was evaluated and compared to the corresponding background level (Achterberg *et al.* 2006a). No particular excess was found but the limits could be significantly improved.

3. IceCube status and prospects

The deployment of the IceCube neutrino observatory has started at South Pole during the austral summer 2004–05 (Achterberg *et al.* 2006b). IceCube is currently composed of 9 strings deployed in the ice and 16 IceTop surface cosmic ray air shower detector units (cf. Fig. 1). The strings consist of 60 optical sensors each deployed at a depth between 1450 m and 2450 m. Once completed in early 2011, one cubic kilometre volume of ice will be instrumented with 80 strings (4800 optical modules) and an array of one square kilometre will be covered by IceTop stations at the surface (320 optical modules). The 604 deployed sensors consist of 25 cm diameter photomultipliers and associated electronics, housed in a transparent pressure vessel. The first data taken with the 9 string array (about 140 events/second) are consistent with expectations based on detailed computer simulations.

According to initial potential performance studies (Ahrens *et al.* 2004b), the angular resolution of IceCube will be better than 1° for muon energies above 1 TeV and the effective area for muon detection will exceed 1 km^2 above 10 TeV. It is expected that the limit on an E^{-2} flux of diffuse neutrinos will be about thirty times smaller than the limit reached during a similar period of observation with AMANDA.

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First tests show that the deployed hardware meets its performance goals (Achterberg *et al.* 2006b). IceCube is already producing physics data and will rapidly reach an unprecedented sensitivity to sources of extra-terrestrial neutrinos in the next few years.

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