Search for Galactic Cosmic-Ray Accelerators with the Combined IceCube 40-strings and AMANDA Detector

THE ICECUBE COLLABORATION
[1] *see special section of these proceedings*

Abstract: During the season 2008/2009, IceCube took data as a combined detector with AMANDA embedded into the 40-string array. With a smaller spacing between the sensors compared to IceCube, AMANDA improved the effective area below a few TeV and acted as a first generation low-energy extension of IceCube. The data obtained in this configuration is used to search for neutrino sources within the Galaxy. The TeV γ-ray spectra of some potential galactic cosmic-ray accelerators show cut-offs in the energy spectrum at energies of a few TeV. In the case of transparent TeV γ-ray sources, high-energy neutrinos will follow similar spectra and an improved effective area below a few TeV improves the sensitivity for these of sources.

Several tests including a scan of the galactic plane in the Northern Hemisphere and a dedicated analysis for the Cygnus region are presented. In the absence of a significant signal, upper limits are reported. The results provide the most restrictive upper limits for the Cygnus region obtained so far. Depending on the assumed energy cut-off, the upper limits obtained with this analysis are only a factor of two to three above the expected neutrino flux if all the TeV γ-rays observed in the region were of hadronic origin. This implies that during the coming years, IceCube will be able to either detect neutrinos from the Cygnus region, or to constrain the nature of the high-energy γ-ray emission in the region, and thus the fraction of interacting cosmic rays produced in one of the most active parts of the Galaxy.

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1 High-Energy Neutrino Production in the Galaxy

One of the primary goals of the IceCube experiment [1] is the detection of astrophysical sources of high-energy neutrinos. A neutrino signal uniquely identifies the sites of hadron acceleration and interaction and thereby the sites of cosmic-ray production.

If protons are accelerated to sufficiently high energies in (galactic) sources, high-energy neutrinos can be produced through proton-proton interactions with the ambient gas. If such sources are transparent and the γ-ray emission from high-energy electrons is small compared to the total γ-ray emission, the high-energy neutrino spectra can be inferred from the γ-ray spectra [2].

Several objects within the Galaxy such as supernova remnants and pulsar wind nebulae, binary systems and the collective winds of massive stars might accelerate protons up to PeV energies [3]. Even though γ-rays up to several TeV have been observed from several of these objects, many of the observed γ-ray spectra have energy cut-offs below 10 TeV and/or their energy spectra are significantly steeper than an E^{-2} spectrum as expected from shock acceleration. A search for neutrino emission from within the Galaxy thus requires an approach that is optimized to retain a high efficiency for neutrinos with energies below 10 TeV. The predicted neutrino flux from galactic sources is very low and single point-like sources might elude a detection in the near future. In star forming regions, it is however possible that several (weak) sources produce an integrated signal strong enough for a discovery. In particular the Cygnus region as the most active part of the Galaxy in the Northern Hemisphere is of primary interest to IceCube in this context.

2 Methods and Targets

At energies between a few hundred GeV and a few TeV, the field of view of the 2008/2009 configuration of Ice-

Cube is restricted to the Northern Hemisphere where the atmospheric muon background is suppressed by several orders of magnitude by the shielding provided by the Earth. Within this field of view, a search for point-like, steady high-energy neutrino sources has been performed. We search for a significant excess of neutrinos over the uniform background of atmospheric neutrinos by a maximum likelihood ratio hypothesis test, described in [4]. The search is performed on a $0.25°$ grid covering the galactic plane within the field of view ($37.5° < l < 212.5°$, $-5° < b < 5°$). Since the angular grid size is smaller than the angular resolution of the detector, this search may be regarded as an unbinned analysis. The energy term in [4] is omitted as it is not relevant for soft spectra sources.

In addition, the same likelihood ratio hypothesis test is applied to six prominent γ-ray sources: the Crab Nebula, LSI +61 303, CasA, W51, SS433 and IC443. The sources were chosen due to their brightness in γ-rays and/or the presence of target material for proton-proton interactions in or near the sources.

To search for high-energy neutrino emission within the Cygnus region, a dedicated test based on a 2-point correlation function has been developed [5]. A search for a spatial clustering of events inside a 7°x11° region ($72° < l < 83°$, $-3° < b < 4°$) around the most active part of the Cygnus region is performed. The method is able to take advantage of extended emission regions and the emission of any sources within the region. If applied to the data sample used in this work, the discovery flux per point source is lower than in a standard search if more than two point sources are present within the region.

The analyzed data set is dominated by atmospheric neutrinos. Any potential astrophysical signal presents only a very small contribution in number of events. A data driven background estimation can thus be obtained by randomizing the arrival directions of the events, compatible with a homogeneous spatial distribution. All statistical tests reported here use this technique for the construction of their respective null hypothesis.

3 The Combined IceCube 40-string and AMANDA Detector

The full IceCube [1] neutrino telescope at the South Pole consists of a volume of approximately one cubic kilometer of clear Antarctic ice instrumented with light sensors. This instrumentation allows to detect muons from charged current interactions of neutrinos. 5160 digital optical modules are deployed in the ice along 86 strings that hold 60 optical modules each. The detector has been built in several stages and new strings have been added each Antarctic summer since 2004/2005.

AMANDA [8] is located at the same site as IceCube and consists of 677 optical modules deployed on 19 strings, most of them at depths between 1500 and 2000 m. Both the vertical and horizontal spacing of the optical modules in AMANDA are smaller than in IceCube. This provides a lower energy threshold and a higher collection efficiency for muons below a few TeV. As AMANDA is the precursor experiment to IceCube, many of the techniques employed in IceCube were developed and tested in AMANDA [9]. AMANDA took data as a stand-alone neutrino telescope until December 2006. Since 2007, AMANDA is fully surrounded by IceCube strings and was integrated into the IceCube data acquisition system as a low-energy extension of the IceCube detector until 2009 [10].

In the combined data taking mode, AMANDA initiates a read-out of IceCube whenever a multiplicity trigger condition in AMANDA is fulfilled. The data collected from both parts of the combined detector is then merged into a single event and reconstructions can be applied to either the full event information or to the IceCube or AMANDA information separately. The analysis presented here uses the information from both IceCube and AMANDA.

4 Neutrino Sample

The targets of this analysis are soft-spectrum sources or sources with high-energy cut-offs below the PeV range within the Galaxy. The event selection is thus aimed to improve the effective area for neutrino energies below this scale. This is achieved both through the use of AMANDA as an embedded array inside the 40 IceCube strings and through an event selection optimized for a larger acceptance of events below 10 TeV compared to the analysis presented in [11].

The current analysis uses data collected from April 5, 2008 to May 20, 2009. Both parts of the combined IceCube-AMANDA detector operated very stably during this time. For IceCube $\sim$ 375 days of data were collected. AMANDA was decommissioned before the end of the IceCube 40-string data taking period and $\sim$306 days of combined IceCube-AMANDA data were collected . The main causes for detector downtime were scheduled operations in the course of the integration of new strings into the detector.

The dominant class of recorded events are atmospheric muons incident from the atmosphere above the detector. The majority of this background is suppressed by a cut on the reconstructed direction such that only events from the Northern Hemisphere are accepted. Even after this cut, the atmospheric muons dominate over the atmospheric neutrinos by several orders of magnitude as a fraction of atmospheric muons are not well-reconstructed and as such end up as up-going muons. In particular coincidences between two muons from different air showers can mimic up-going events. An event selection is then applied to reduce this background by rejecting events with poor reconstruction quality and/or events with a high probability to be composed of two separate particles. An overview of reconstruction quality estimators and other event parameters that allow to distinguish signal from background is given in [11]. A subset of these parameters is used in this work.

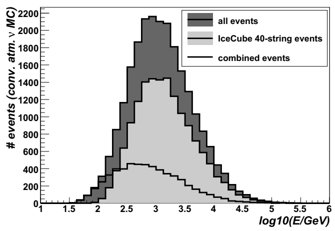

Figure 1: Energy distribution of atmospheric neutrino events in the combined IceCube 40-strings and AMANDA point source sample. Events with AMANDA trigger ("combined events") peak at lower energies than events with IceCube trigger. 90% of the events are contained in a central interval from 130 GeV to 7.5 TeV.

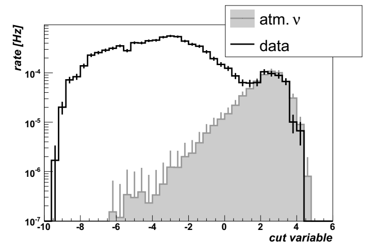

Figure 2: Distribution of the main cut variable for IceCube-triggered events before final cuts are applied. Shown are the data in black and atmospheric neutrino simulation based on the atmospheric neutrino flux model of [6] in gray. The final cut is placed at 1.0 as result of an optimization of the discovery potential [7].

The data collected in 2008/2009 contains events that triggered AMANDA, events that triggered IceCube and events that triggered both detectors. Most analyses performed on the data sample, such as [11], use only the events that triggered IceCube. The approach presented here extracts a neutrino sample from all three kinds of events. Combined IceCube-AMANDA events are selected by different event selection criteria than events that only have an IceCube trigger, as outlined below.

IceCube events without AMANDA trigger are selected by a series of one-dimensional cuts on event quality parameters followed by a multivariate classification based on the Neyman-Pearson rule (see for example [12]). The probability density functions for five quality parameters are generated from atmospheric muon-dominated data as background and from atmospheric neutrino simulation and combined in the cut. The main cut variable is the likelihood ratio between the atmospheric neutrino and the atmospheric muon hypothesis. The distribution of this main cut variable is shown in Figure 2 for data and for atmospheric neutrino simulation. For combined IceCube-AMANDA events, the Neyman-Pearson rule is not applied because a series of a series of one-dimensional cuts resulted in a similar performance for these events.

The energy distribution at the final event selection level is shown in Figure 1. The combined IceCube-AMANDA events peak at lower energies. The angular resolution of the sample depends on the energy of the events. An unbroken E^{-3} power law spectrum has been used to benchmark the performance of the analysis. For this very soft spectrum, a median angular resolution of $1.2°$ is achieved. From simulation of single and double coincident cosmic-ray air showers with CORSIKA [13], the atmospheric muon contamination of the cleaned data sample used in this analysis is estimated between 2% and 3%.

19797 neutrino candidates are selected from IceCube and AMANDA triggered events. This sample is predominantly background atmospheric neutrinos, which cannot be distinguished from the cosmic neutrino signal on an event-by-event basis [1]. These events are analyzed with the hypothesis tests described in the previous section to search for spatial clustering of events over the uniform atmospheric neutrino background.

5 Results

The results of the galactic plane scan are presented in Figure 3, from which it is seen that all observations are compatible with the background expectation. The largest clustering of events was observed at $(85.5°, -2, 0°)$ with a (pre-trial) probability to observe an equal or stronger excess at this position of 0.0935% due to background fluctuations only. Accounting for the trials introduced by the repetition of the test along the galactic plane, an equivalent or more significant observation is made in 88.02% of randomized data samples. Thus the observed excess in the scan is consistent with fluctuations of background. Also the results for the six γ-ray sources are compatible with the background expectation and preliminary 90% flux upper limits are summarized in Table 1 assuming a power-law with a spectral index of 3. The preliminary limits do not include the systematic uncertainty of the signal efficiency. The strongest preliminary flux limit can be set for Cas A at a flux of $5.9 \cdot 10^{-11}$ TeV^{-1} cm^{-2} s^{-1}. The upper limits are calculated using the approach of Feldman and Cousins [15].

With 55 events observed within the box defined around the most active part of the Cygnus region compared to a background expectation of 60 events, strong flux upper limits could be extracted for this region. Assuming an $E^{-2.6}$ spectrum as was fit to the MILAGRO γ-ray observations [16], a preliminary 90% flux upper limit of $3 \cdot 10^{-11}$ TeV^{-1}cm^{-2}s^{-1} (without systematic uncertainties) is obtained provided the astrophysical signal from the region has an exponential energy cutoff at or above 1 TeV.

1. An exception could be the use of a veto against atmospheric neutrinos as proposed in [14]

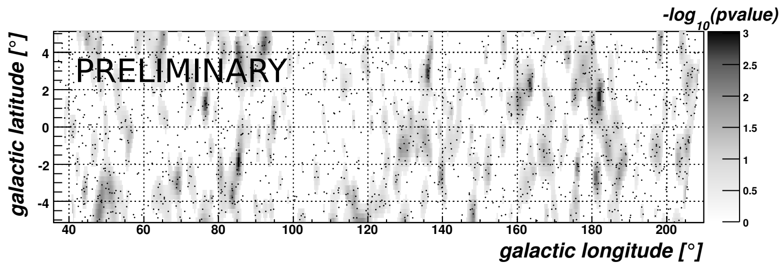

Figure 3: Result of the galactic plane scan using data collected by IceCube 40-strings as a combined detector with AMANDA. The significance of the observation at each grid point is expressed by the (pre-trial) pvalue which is shown together with the distribution of the events shown as black dots. The most significant excess of events is located at $(85.5°, -2, 0°)$ with a (pre-trial) pvalue of 0.000935 (-log10(pvalue)=3.03). The probability to observe a similar or stronger excess of events at any point of the galactic Plane is 88.02%. No neutrino sources have been detected.

	ra	dec	ns	upper limit
Crab	83.63°	22.01°	0	7.3
CasA	350.85°	58.82°	0	5.9
LSI +61 303	40.13°	61.23°	1.6	7.8
SS433	287.94°	4.983°	0	9.7
IC443	94.18°	22.53°	0	7.3
W51	290.82°	14.15°	0.6	8.3

Table 1: Position, best fit number of source events (ns) and **preliminary** 90% upper limits on the flux of muon neutrinos for each of the tested objects in units of 10^{-11} TeV^{-1} cm^{-2} s^{-1}. The upper limits are calculated without systematic uncertainties under the assumption of an E^{-3}-spectrum.

6 Outlook

The installation of the IceCube detector has been completed in 2010 and IceCube is now taking data in its final configuration of 86 strings. The collaboration continues to search for neutrino sources within and outside of the Galaxy. With the substantially larger detector, the sensitivity to galactic neutrino sources will improve significantly with respect to the analysis presented here.

In particular IceCube's observations of the Cygnus region will enter an interesting regime in the next few years. We have shown that the IceCube 40-string/AMANDA limits for the Cygnus region are only a factor of two to three above the expected flux if all of the γ-rays in the region were of hadronic origin. Applying the same test to the data obtained with larger configurations of IceCube, it will thus be possible to either detect neutrino emission in this region or to constrain the hadronic component in the γ-ray emission.

AMANDA has been decommissioned in 2009 and replaced by the DeepCore extension of IceCube. The positioning of a more densely instrumented volume in the deepest and clearest ice around the central IceCube string offers several advantages with respect to AMANDA. In particular, it offers the possibility to use veto techniques that allow the suppression of downgoing atmospheric muons and might open the Southern Hemisphere to neutrino astronomy below several tens of TeV from the South Pole.

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