Multi-Messenger Studies with AMANDA/IceCube: Observations and Strategies

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Four years of AMANDA-II data have been searched for neutrinos from point sources. No statistically significant excess of events has been detected, neither integrated in the years 2000 to 2003, nor in the searches for occasional signals. An interesting coincidence of neutrinos with gamma-ray flares emerges when inspecting the time of the events detected from the direction of the Blazar 1ES1959+650. The exceptional character of the gamma-ray observation provides a strong motivation for consolidating similar search strategies with AMANDA and its successor IceCube, as well as for multidisciplinary investigations of this and other gamma-ray sources. We report the outcomes of the most recent survey of the northern sky to search for neutrino point sources with AMANDA-II. We also discuss possible viable collaborations between the gamma-ray and the high energy neutrino observatories.

1 Introduction

The primary goal of a neutrino telescope is the discovery of extraterrestrial neutrinos with high energies. The research field contributes to the increased understanding of the nature, the origin and the propagation of cosmic rays. The detection of neutrinos is more challenging than that of cosmic rays and gamma-rays, due to the much smaller cross section for neutrino interaction and therefore the small detection probability. Neutrinos from point sources would provide an unambiguous signature of a hadronic component in the flux of particles accelerated
neutrinos can propagate freely over cosmological distances. This, combined with the intrinsic complementary nature of this observational window, motivates the search of cosmic neutrinos.

So far no excess of events ascribed to either a point-like or a diffuse extraterrestrial flux of neutrinos has been observed \[1\]-\[5\]. Recently, four years of AMANDA-II data, collected between 2000 and 2003, have been analyzed with improved reconstruction techniques and better background rejection power compared to previous publications. A large statistics sample of neutrinos with high energies has been selected, allowing to search for point sources with a sensitivity comparable to the observed gamma-ray fluxes of Blazars, when in “high state” \[6\]. This indicates that neutrino astrophysics is reaching discovery potential.

We report the results of a time-integrated search of point sources of neutrinos, which provides the most stringent flux upper limits currently available for the northern sky, and also the first attempts to search for neutrino flares with AMANDA-II. A section is dedicated to the observations of the Blazar 1ES1959+650. Finally, future perspectives of multidisciplinary investigations of this and other objects are discussed.

2 Operation principles of AMANDA and IceCube

AMANDA-II is currently the largest operating neutrino telescope. Located at the South Pole, the array comprises 677 optical modules to detect the Cherenkov photons from charged particles in the ice shelf. Each module consists of a 8 inch diameter photo-multiplier, housed in a pressure-tight glass sphere. The optical modules are located at depths between 1.5 and 2 kilometers, in a structure of 19 strings. The instrumented volume has a diameter of about 200 meters\[7\].

The ice overburden at the South Pole reduces the flux of cosmic muons to a rate less than 0.1 kHz, as measured with AMANDA-II. When muon neutrinos with energies above a few tens of GeV undergo charged current interactions in the ice surrounding or in the rock below the detector, muon tracks emerge, which can be reconstructed based on the arrival time of the Cherenkov photons at the optical modules. Due to the scattering of photons in ice, complex likelihood procedures are necessary to achieve good angular resolution (between 2° and 2.5° for the typical track lengths in AMANDA-II). The muon energy is estimated from the density of detected Cherenkov photons, with an accuracy of 0.4 in the logarithm of the energy.

AMANDA is operating since 1996 (since 2000 as the full-scale AMANDA-II). In January 2005, one string of IceCube was installed and started operation. IceCube will include 4800 optical modules (80 strings) in a volume of 1 km$^3$. Apart from various technological improvements compared to AMANDA, its geometry alone will ensure an angular resolution comparable to the neutrino-muon scattering angle (down to 0.5° at 5 TeV). IceCube is expected to achieve the sensitivity to detect neutrinos from Active Galactic Nuclei and Gamma Ray Bursts \[8\].

3 Search for point sources in the northern sky

Searches for astrophysical sources of neutrinos have to cope with the background from interactions of cosmic rays with the Earth’s atmosphere. The dominating component stems from down-going muons and is suppressed with angular cuts. This limits the searches for point
sources essentially to the northern sky. A more uniform flux of neutrinos from meson decay and a negligible fraction of mis-reconstructed cosmic muons remain, indistinguishable from cosmic neutrinos. These residual backgrounds are treated identically and their effect is evaluated statistically from the density of the detected events as a function of declination, i.e. adopting a similar approach as the "off-source" observations of gamma-ray astronomy\(^1\).

A neutrino point source would manifest itself as a localized excess of events on top of the background. To ensure a high signal-to-noise ratio, the event reconstruction and selection are optimized in a way to provide tracks with good angular resolution, in a wide energy range. Details of the reconstruction algorithm can be found in \[9\]. Up-going events, induced by muon neutrinos, are selected by imposing track quality requirements. The total live-time considered is 807 days, after data quality selection and rejection of the periods of detector maintenance and station activities (between November and February). Event selection criteria were optimized to achieve the best average flux upper limit (sensitivity) for an assumed power-law signal energy spectrum with two extreme spectral indices: \(\gamma=2\) and \(\gamma=3\). Event cuts were optimized independently for different declination bands. The search bin radius was a free parameter and varies between 2.25\(^\circ\) and 3.75\(^\circ\), depending on declination. The optimization procedure accounts for the effective live-time, which allows to loosen cuts for dedicated investigations of sub-periods of data taking.

Our search for high energy cosmic neutrinos from known astrophysical objects mostly focuses on sources of high energy gamma-rays. This choice is supported by the fact that any object that accelerates charged hadrons to high energy is a likely source of neutrinos: the hadrons will interact with other nuclei or the ambient photon fields producing hadronic showers. In these scenarios, high energy photons and neutrinos are expected to be produced simultaneously.

### 3.1 Time-integrated search

The sensitivity to point sources of neutrinos, with a live-time of 807 days, is \(6 \cdot 10^{-8}\) GeVcm\(^{-2}\)s\(^{-1}\) for a spectral index \(\gamma=2\), weakly dependent on declination. A sample of 3329 up-going events was extracted, shown in Fig. 1-Left. Based on these events, we performed a search for coinci-

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\(^1\)Note that the geographic location of the detector ensures a uniform and constant exposition of portions of the sky at the same declination.
ences with the directions of a catalog of 33 selected objects, and also a full scan of the northern sky. In both cases all observed excesses are compatible with the background hypothesis. The significance of each observation was evaluated with repeated and equivalent “experiments” performed on samples of events obtained by randomizing the right ascension coordinates of the 3329 neutrinos. This method allows a correct evaluation of the trial factors in presence of multiple tested directions, and of the correlations due to partial overlapping of the search bins.

Table 1 summarizes the results of the test performed on the catalog of 33 sources. The highest excess corresponds to the direction of the Crab Nebula (1.7 $\sigma$). The probability to observe this or a larger excess due to a statistical fluctuation of the background, in any of the 33 bins, is 64%. The northern sky was scanned with a system of highly overlapping bins, to maximize the detection chance. The significance map is shown in Fig. 1-Right. The highest excess (3.4 $\sigma$) corresponds to a probability of a background fluctuation of 92%. The systematic uncertainty is under evaluation and the flux upper limits will be reported in a forthcoming publication. The preliminary results for the Blazars Markarian 421 and 1ES1959+650 are $0.7 \times 10^{-8} \text{cm}^{-2}\text{s}^{-1}$ and $1.0 \times 10^{-8} \text{cm}^{-2}\text{s}^{-1}$ respectively, for $\gamma=2$ and integrated above 10 GeV. These results refer to 807 days of exposure. To compare them to the observed high energy gamma-ray flares, for example from Markarian 421 [10], it is necessary to introduce assumptions on the time the source was in a high state and on the corresponding photon flux and spectral index. Considering X-ray light curves from [11] we estimate an integral time of the order of 200 days of “high activity” of Markarian 421 between 2000 and 2003 [12]. As gamma-ray flux and energy spectrum we assumed the results obtained for the flares observed in 2000 and 2001, reported in [10], and applied a correction for the infra-red absorption according to [13]. Including neutrino oscillation, we estimate a sensitivity to neutrinos from Markarian 421, for 200 days of live-time, less than a factor 3 of the corresponding gamma-ray flux, up to about 20 TeV.

### 3.2 Search for neutrino flares

The search of occasional flares of neutrinos in the sample of selected up-going events is motivated by the high variability which characterizes the electromagnetic emission of many neutrino candidate sources. The flux upper limits derived from the results reported in the previous section indicate that AMANDA-II has achieved a sensitivity to neutrino fluxes which is comparable to the observed high energy gamma-ray fluxes of Blazars in high states (e.g. the flares of Markarian 501 in 1997 [14] and Markarian 421 in 2000/2001 [10]). With the assumption that the (possible) neutrino emission would be characterized by a flux enhancement comparable to gamma-ray flares, neutrino flares could be extracted from the sample of selected events with a reasonable significance. Under these considerations we developed a search for time-variable neutrino signals from point sources following two different approaches:

a) **Search of clusters of neutrinos in coincidence with known periods of enhanced electromagnetic emission of selected objects:** The objects and/or the periods of interest were chosen on the basis of a compilation of the light curves reported at different wavelengths. Due to the limited availability of high energy gamma-rays observations, we referred to X-ray light curves for the two Blazars we considered (Markarian 421 and
Table 1: Results from the search for neutrinos from selected objects, from the analysis of AMANDA-II data between 2000 and 2003. $\delta$ is the declination in degrees, $\alpha$ the right ascension in hours, $n_{\text{obs}}$ is the number of observed events and $n_b$ the expected background.

1ES1959+650 [11]). For the third object, the Micro-quasar Cygnus X3, we instead used radio light curves [15]. A proper re-optimization of the neutrino event selection was performed, to account for shorter integrated exposures compared to 807 days. The integrated periods-of-interests were 141 days for Markarian 421, 283 days for 1ES1959+650 and 114 days for Cygnus X3, based on threshold cuts on the X-ray/radio intensity curve.

b) **Search of occasional neutrino flares from selected objects**: Twelve sources were considered, known to manifest a character of high variability in the corresponding gamma-ray emission. We considered four Blazars, four Micro-quasars and four EGRET sources with exceptional variability in the MeV gamma-ray emission. Neutrino flares have been searched for by comparing the observed events with the time-dependent background, using sliding time-windows fixed to 20 days duration for galactic objects and 40 days duration for extragalactic objects. This approach entails a higher trial factor penalty than case a). As a merit, neutrino flares which are not accompanied by an observed electromagnetic counterparts are not automatically excluded. This approach is also less dependent on models for the correlation between the neutrino and the electromagnetic emission and not dependent on the availability of multi-wavelength information. The test was performed on the sample of 3329 up-going events. The choice of both the window duration and the test data sample was based on the outcome of a dedicated Monte Carlo simulation. We considered the information reported in Tab. 1 and assumed hidden neutrino flares with
strengths compatible with the flux upper limits derived from Tab. 1. In other words, we considered the maximum signal strength still compatible with the background hypothesis at a 50% confidence level. The search criteria were optimized following a blind approach. Events belonging to subsequent doublets are assigned for simplicity to those clusters showing the highest multiplicity or those occurring first, if having the same multiplicity.

The significance of each observation was evaluated in a similar way as described in the previous section. A proper treatment of the time variability of the background was carried out. In all cases no statistically significant excess was found.

Event doublets were observed from the directions of the Blazars 1ES1959+650, QSO 0235+164, the Micro-quasar GRS 1915+105 and the EGRET sources 3EG J0450+1105, 3EG J1227+4302 and 3EG J1928+1733, each with a background probability larger than 32%. No doublets were observed from the directions of the Blazars Markarian 421 and QSO 0528+134, of the Micro-quasars GRO J0422+32, Cygnus X1 and Cygnus X3, and the EGRET source 3EG J1828+1928.

3.3 Neutrinos from the direction of the Blazar 1ES1959+650

The Blazar 1ES1959+650 belongs to the catalog of the 33 tested objects, reported in section 3.1. The search bin used (2.25°) contains between 65% and 75% of the Monte Carlo events passing the selection criteria. Five events have been selected between 2000 and 2003, three out of five within 66 days in the year 2002 (MJD 52394.0, 52429.0, 52460.3). This interval partly overlaps with a period of exceptional activity of the source, monitored by a multi-wavelength campaign (MJD between 52410 and 52500 [16]). A high energy gamma-ray flare was observed without a corresponding counterpart in the X-ray light curve. This event, referred to as an “orphan flare” is generally considered as an indication of hadronic processes occurring in the Blazar jet. Coincident high energy neutrinos are expected in this case, although theoretical estimates of the expected fluxes and of the discovery potential for AMANDA-II vary strongly [18, 19].

One of the AMANDA-II neutrino events was recorded within a few hours from the “orphan flare”. The arrival times of the observed neutrino events are plotted in Fig. 2-Left and compared to the integrated background per 40-day windows. The significance of the coincidence is low and it can not be easily quantified, due to the trial factors arising from a-posteriori choices of the time windows to be used for the statistical test. More observations are necessary to shed light on the possible hadronic nature of the particles emitted in the jet of this source.

4 Viable perspectives for the multi-messenger approach

Both the neutrino and the high energy gamma-ray community aim to classify the nature of observed astrophysical objects and to answer the intriguing question whether the population of the accelerated particles is purely electromagnetic, or mixed hadronic and electromagnetic. In this context, the ”orphan flares” detected from several Active Galactic Nuclei are of particular interest. An estimation of the frequency of these phenomena would have strong implications on the understanding of the origin of the observed cosmic rays. The overlap of interests of the two communities extends even further when other objects are considered, like for example the unidentified EGRET sources.
Neutrino astrophysics is entering a new phase, with detectors like AMANDA-II reaching a sensitivity region with discovery potential and cubic-kilometer detectors being designed or – like IceCube – already under construction and starting data-taking. A coordination of the efforts between the gamma-ray and the neutrino communities is going to be feasible and it should be of mutual benefit in several ways.

First, the dramatically increased availability of data on high energy gamma-ray emission will allow a more qualified selection of neutrino candidate sources and favorable periods than hitherto. A reduced set of cases, with better founded expectations for the corresponding neutrino emission, would limit the penalization from trial factors and enhance the discovery chance.

Second, neutrino observations might provide a target-of-opportunity trigger to gamma-ray detectors. With AMANDA-II we would look for neutrino signals in coincidence with intense gamma-ray flares which could be observed by small telescopes like HEGRA, as well as by the third-generation gamma-ray telescopes like CANGAROO, H.E.S.S., MAGIC, and VERITAS. AMANDA-II is a continuously sensitive and large field-of-view telescope, which allows the simultaneous and non-interrupted monitoring of all sources located in the northern sky. Data is typically analyzed off-line, following a blind procedure, i.e. event selections are optimized in a way which avoids the introduction of statistical biases (for example by adopting the “off-source” methodologies of gamma-ray astronomy). An on-line reconstruction procedure has been developed and its performance is being tested. ”Neutrino triggers” based on the on-line reconstruction could be provided to gamma-ray and X-ray observatories within at most a few hours. If, for a limited set of most promising objects, a neutrino would be detected from the direction of one of these sources, gamma-ray telescopes could promptly verify the corresponding level of activity. Given a resolution for the neutrino direction of about $2^\circ$, most of the events will stem from atmospheric neutrinos. Therefore a careful study of the expected ratio between true and false alarms and the sustainable rate of false alarms have to precede the implementation.
of such a “hadronic trigger”.

In case of sources which are already included in the scientific program of the involved experiments, neutrino-based target-of-opportunity measurements may entail no extra observation time. Table 1 provides an indication of the trigger rate of neutrino events from the direction of selected objects, with the cut strength adopted for this analysis. In particular the chosen sky bins contain a fraction of the signal Monte Carlo events, passing the same selection, which varies between about 60% up to about 85%, according to the source declination and the assumed spectral index.

In conclusion, we encourage the long-term and unbiased monitoring at different wavelengths of those neutrino candidate sources which show an evident character of variability in the high energy gamma-ray emission (Blazars in particular). We also encourage the establishment of working groups to further develop the multi-messenger approach, i.e. to involve neutrino observations within the already effective multi-wavelength campaigns, and, in general, multidisciplinary investigations of objects like the Blazar 1ES1959+650 and similar.

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References

[1] J. Ahrens et al., Phys. Rev. Lett. 92, 071102 (2004).
[2] M. Ackermann et al., Phys. Rev. D 71, 077102 (2005).
[3] J. Ahrens et al., Phys. Rev. Lett. 90, 251101 (2003).
[4] M. Ackermann et al., Astropart.Phys. 22, 127 (2004).
[5] M. Ackermann et al., Astropart.Phys. 22, 339 (2005).
[6] M. Ackermann et al., Proc. 29th ICRC (Pune), ger-ackermann-M-abs2-og25-poster.
[7] E. Andrés, et al., Astropart. Phys. 13, 1 (2000).
[8] J. G. Learned and K. Mannheim, Ann. Rev. Nucl. Part. Sci. 50, 679 (2000).
[9] J. Ahrens et al., Nucl. Inst. Meth. A524, 169 (2004).
[10] F. Aharonian et al., A&A 393, 89 (2002).
[11]  http://xte/mit.edu/asmle/
[12] M. Ackermann et al., Proc. 29th ICRC (Pune), ger-ackermann-M-abs1-og25-oral.
[13] O.C. de Jager and F.W. Stecker, ApJ 566, 738 (2002).
[14] F. Aharonian et al., A&A 346, 913 (1999).
[15] Ryle Telescope radio data, courtesy of Guy Pooley.
[16] H. Krawczynski et al., ApJ 601, 151 (2004).
[17] D. Holder et al., ApJ 583, L9 (2003).
[18] F. Halzen, D. Hooper, astro-ph/0502449.
[19] A. Reimer et al., astro-ph/0505233.