Search for steady cosmic sources of high energy neutrinos in ANTARES

J P Gómez-González
Instituto de Física Corpuscular - IFIC (CSIC-Universitat de València), Edificio Institutos de Investigación, E-46980 Paterna, Spain
E-mail: jpablo@ific.uv.es

Abstract. ANTARES is the largest Neutrino Telescope operating in the Northern Hemisphere. Placed at the bottom of the Mediterranean Sea, about 40 km off the coast of Toulon (France), it is composed by 885 photomultiplier-tubes (PMTs) which detect the Cherenkov light emitted in the interaction of high energy neutrinos close or inside the detector. One of the main goals of the experiment is the identification of a source of cosmic neutrinos, which are likely to be produced in the interaction of high energy hadrons in several astrophysical scenarios. The discovery of a source of neutrinos will be, thus, a clear indication for hadronic acceleration mechanisms and shed light on the problem of the origin of cosmic rays (CRs). This works present such a search using 813 days of data collected in ANTARES between years 2007 and 2010. Not having found any significance excess of events upper limits to the $E^{-2}$ are given for sources in the Southern sky. Additionally, results using specific emission models for two well known gamma-ray TeV sources are discussed.

1. The ANTARES neutrino telescope

Neutrino telescopes aim to detect cosmic neutrinos coming from the decay of the secondary particles produced in the interaction of CRs near their sources of acceleration. The ANTARES detector [1] uses 885 PMTs, distributed in 12 lines and installed in a dark and optically transparent medium, to detect the Cherenkov photons emitted by the muons produced in the interaction of high energy neutrinos in its environment. The lines are divided in 25 floors formed by triplets of Optical Modules; high pressure resistant glass spheres housing a PMT together with the accompanying electronics. The distance between lines ranges from 60 to 75 m and between adjacent floors is of 14.5 m. ANTARES started data taking in 2007. The detector was completed in May 2008 and nowadays is the largest deep sea neutrino telescope in the world.

Using the data gathered in 4 years of operation a search for cosmic neutrinos (that extends the results presented in [2]) has been conducted. In Section 2 the event selection and track reconstruction are described. The detector performance and the search method used are reviewed in Sections 3 and 4 respectively. Finally, results and conclusions are given in Sections 5 and 6.

2. Event reconstruction and data selection

The muon events crossing the detector are accurately reconstructed using a track reconstruction method based on the maximisation of the likelihood function describing the probability density for the residuals, defined as the difference between the Cherenkov light hit times in the PMTs and the expected times assuming an arbitrary set of track parameters [3]. The fitting procedure...
consists of different steps of increasing sophistication that get closer to the solution. The final likelihood function uses parameterizations of the probability density functions (pdf) of the hit residuals including the effect of the scattering and of the late Cherenkov emission due to secondary particles. The quality of the track fit is given (basically) by the maximum value of the likelihood and is referred as the fit parameter of the reconstruction.

This analysis uses 813 days of data live time, out of which 183 days were collected with the initial 5 lines configuration. The total number of triggered events is of $4 \times 10^8$. A first cut is applied to select those events which are reconstructed as upgoing tracks. In order to reject downgoing events mis-reconstructed as upgoing, the fit value is required to be larger than -5.2. This value was chosen to optimize the discovery potential (see Section 4). Additionally, only events for which the uncertainty on the track direction (which is estimated from the width of the likelihood maximum), is smaller than one degree are accepted. The 3058 events that survive these quality cuts are the unblinded sample of neutrino candidate events.

3. Detector performance
The angular resolution and the effective area are the main parameters that characterize the response of the detector to the searched signal (that is assumed to follow a $E^{-2}$ spectrum). Both parameters need to be estimated using Monte Carlo simulations. In this analysis atmospheric muons and atmospheric neutrino events were simulated using the MUPAGE [4] and the GENHEN [5] packages respectively.

The angular resolution governs the capability for signal to background rejection. It is defined as the median value of the distribution of the angular difference between the reconstructed and generated events (figure 1), and in this analysis is of $0.46^\circ \pm 0.1^\circ$. The effective area is shown in figure 2 as a function of the neutrino energy and for three different declination bands. This magnitude allows to translate event rates into neutrino fluxes.

4. Search method
The search for time-integrated or steady sources of cosmic neutrinos represents the search for an excess of events (over the expected background) coming from a particular direction in the sky (forming clusters) and that have a characteristic energy spectrum. In this analysis it was used
an unbinned clustering method based on the maximisation of the likelihood function describing the events:

$$\log L_{s+b} = \sum_i \log[p \times F(\psi_i(\alpha_s, \delta_s)) \times N^s(N_{\text{hits}}^i) + B(\delta_i) \times N^b(N_{\text{hits}}^i)] - \mu_s - \mu_{bg}, \quad (1)$$

where $F$ and $B$ are, respectively, parameterisation of the signal pdf and of the background rate for the selected events, $\mu_s$ is the number of signal events and $N_{\text{hits}}$ is the number of hits used in the reconstruction. $N^s(N_{\text{hits}}^i)$ and $N^b(N_{\text{hits}}^i)$ are the probabilities of measuring $N_{\text{hits}}^i$ hits for signal and background. The parameters with respect to which the likelihood is maximised are the number of signal events emitted by the source and, in the blind search (see Section 5) the source coordinates as well.

The likelihood ratio defined in equation (2) is used as a test statistic. Larger values of $Q$ are less likely to be produced by the background only. Comparing the observed value of the test statistic with a $Q$ distribution obtained by simulating a large number of background only experiments the significance or p-value is obtained.

$$Q = \log L_{s+b}^{\text{max}} - \log L_{b}, \quad (2)$$

The number of hits in the fitted track is introduced to improve the sensitivity of the method. Using this information the gain in terms of discovery potential (signal events needed to reach a certain significance) is of $\sim 25\%$. In the absence of a discovery, upper limits at the 90\% C.L. are obtained using the Feldman-Cousins prescription [6]. Systematic effects are taken into account in their computation.

5. Searches performed and results

Two searches have been performed in this analysis. A full-sky search anywhere in the visible sky [-90°, -48°] where clusters of events are found to have at least 4 events within a 3 degrees diameter cone. A candidate list search where the likelihood is evaluated at the direction of an a priori selected list of sources which are known to be TeV gamma-ray emitters.

No statistically significant excess of events was found neither in the full-sky search nor in the candidate list search. The most signal-like cluster was obtained in the full-sky search and has the fitted coordinates $(\alpha, \delta) = (-46.5°, -65.0°)$. The maximum likelihood assigns $\mu_s = 5.1$ as signal events and the observed value of the test statistic has 2.6\% probability to occur in the background only experiments. The results of the search using an a priori selected list of sources are shown in figure 3. The largest deviation from background was found in correspondence with the galactic source HESS J1023-575. The post-trial significance of this cluster is of 41\%, which is well compatible with the only-background hypothesis.

5.1. Limits using specific models

The morphology and energy spectrum of the sources studied with gamma-ray observatories like H.E.S.S can be used to estimate with higher accuracy neutrino fluxes and event rates at Earth. Recent models [7] for the neutrino emission of the supernova remnant RX J1713.7-3946 and the pulsar wind nebulae Vela X were used to compute the corresponding Model Rejection Factor (MRF), i.e., the ratio between the 90\% of the upper limit obtained assuming the model and the expected number of events. The results obtained (figure 4) are MRF = 8.8 for RX J1713.7-3946 and MRF = 9.1 for Vela X. Although the limits measured are several times higher, these are the most restrictive ones obtained up to date for the considered models.
Figure 3. Limits set on the $E^{-2}$ flux normalization for the sources in the candidate list. Upper limits produced by other neutrino experiments for both the Southern and Northern Hemisphere are included. The ANTARES sensitivity as well as the IceCube 40 sensitivity are shown as dashed lines.

Figure 4. Models on the neutrino flux (dashed lines) and Feldman-Cousins 90% C.L. upper limits (solid lines) for RX J1713.7-3946 and Vela X.

6. Conclusions
Results of a search for cosmic neutrinos using 813 days of data collected with the ANTARES detector during years 2007-2010 have been presented. The most significant (2.2 $\sigma$, 2-sided convention) cluster of events was found at coordinates ($\alpha, \delta$) = (-46.5°, -65.0°) in the full-sky search. In the candidate list search HESS J1023-575 is the most signal-like cluster with 41% probability of being produced by the background. Upper limits on the $E^{-2}$ flux were obtained for 51 sources in the Southern sky, which are a factor $\sim 2$ more restrictive than those in [2]. Limits have also been calculated for recent emission models on RX J1713.7-3946 and Vela X.

Acknowledgments
We gratefully acknowledge the financial support of the Spanish Ministerio de Ciencia e Innovación (MICINN), grants FPA2009-13983-C02-01, ACI2009-1020 and Consolider MultiDark CSD2009-00064 and of the Generalitat Valenciana, Prometeo/2009/026.

[1] Ageron M et al 2011 Nucl. Inst. and Meth. in Phys. Res. A 656 11-38
[2] Adrián-Martínez S et al 2011 ApJ 743 L14
[3] Heijboer A 2004 phD thesis U. van Amsterdam
[4] Carminati G, Bazzotti M, Margiotta A and Spurio M 2008 Comp. Phys. Comm. 179 915-923
[5] Bailey D 2002 phD thesis U. of Oxford
[6] Feldman G J and Cousins R D 1998 Phys. Rev. D 57 3873
[7] Kappes A, Hinton J, Stegmann C and Aharonian F A 2007 ApJ 656 870