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Search for high-energy neutrinos from GRB130427A with the ANTARES neutrino telescope

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Abstract. ANTARES is the first deep under-sea high-energy astrophysical neutrino telescope, in operation since 2008, in the Northern Hemisphere. In the light of a multi-messenger approach, one of the most ever intense (photon fluence $F_\gamma \simeq 10^{-3}$ erg/cm^2) and close (redshift $z = 0.34$) transient γ-source, GRB130427A, is considered in the ANTARES physics program for a co-incident search for photons and high-energy neutrinos. The first time-dependent analysis on GRBs neutrino emissions has been performed for this source: Konus-Wind parameters of the γ time-dependent spectrum are used to predict the expected neutrino flux from each peak of the burst, through the numerical calculation code NeuCosmA. An extended maximum likelihood ratio search is performed in order to maximize the discovery probability of prompt neutrinos from the burst: at the end, ANTARES sensitivity to this source is evaluated to be $E^2\phi_\nu \sim 1-10$ GeV/cm^2 in the energy range from 2×10^5 GeV to 2×10^7 GeV.

1. Introduction

The ANTARES neutrino telescope [1] is a three dimensional array of photo-multiplier tubes (PMTs), located at a depth of 2475 m in the Mediterranean Sea, offshore Toulon (France). The detector consists of 12 vertical strings, equipped with 885 PMTs for an instrumented volume of $\simeq 0.02$ km^3. The main scientific goals of ANTARES are the identification of neutrino astrophysical sources and the observation of a neutrino flux exceeding the atmospheric one. Neutrinos are detected through the Cherenkov radiation that is induced by the path in water of ultra-relativistic particles created in a neutrino interaction: track-like signatures are mainly produced by muons from charged-current ν_μ interactions. The PMTs are oriented at 45° downwards in order to maximize the sensitivity to Cherenkov light from upward-going muons: for these events the main background component is constituted of muons induced by atmospheric neutrinos. The typical median resolution achieved for muon tracks is better than 0.4°, allowing neutrino astronomy to be performed.

Neutrinos are unique messengers to study the high-energy Universe as they are neutral and stable, interact weakly and therefore travel directly from the emitting source to the Earth, without being deflected or absorbed. Neutrinos could play an important role in understanding the mechanisms of cosmic rays acceleration and their detection from an astrophysical source would be a direct evidence of the presence of hadronic processes, beyond the well known leptonic ones. Indeed, in the fireball model [2] of Gamma-Ray Bursts (GRBs), the observed electromagnetic radiation is explained as synchrotron emission, followed by inverse Compton

scattering of relativistic shock-accelerated electrons. If protons are also accelerated in the shock outflow, high-energy neutrinos would accompany the electromagnetic signal of the burst [3]. Therefore GRBs are cosmic candidate sources for neutrino telescopes.
In this paper, a time-dependent search is presented: through it, the most intense state of the burst γ emission is selected in order to highly reduce the background and improve the sensitivity by about a factor two with respect to a standard time-integrated point source search.

2. Analysis method

On April 27$^{\text{th}}$ 2013, one of the brightest Gamma-Ray Bursts ever detected lit up the high-energy sky: with a photon fluence of the order of 10^{-3} erg/cm^2, GRB130427A turned out to be the strongest burst since 1983. A variability time scale of 0.04 s and a redshift of only 0.34 were measured: assuming the standard ΛCDM cosmological model, this implies an isotropic energy release $E_{\text{iso}} \sim 8.5 \times 10^{53}$ erg. The detection of two high-energy photons, of 95 GeV and 73 GeV [4], soon opened the way to scenarios of hadronic material within the ejecta. Nevertheless, the IceCube Collaboration announced the non-observation of any coincident neutrino signal in their data within ± 1 day around the burst [5].
The GRB130427A light curve exhibited an extremely bright phase, followed by a slow decay of the γ emission: the first pulse alone constituted more than 95% of the burst γ-fluence and was actually released in one twelfth of the whole burst's duration, as can be seen in Fig. 1. The *Konus-Wind* Collaboration analysed the burst in the energy range from 0.02 MeV to 1.2 MeV and provided the time-dependent spectral parameters of each peak, as reported in Table 1 [6].
Since the burst was found to be below ANTARES horizon at the satellite trigger time, a point-like source analysis with data from this neutrino telescope can be performed with up-going events, searching for ν-γ coincident emissions.

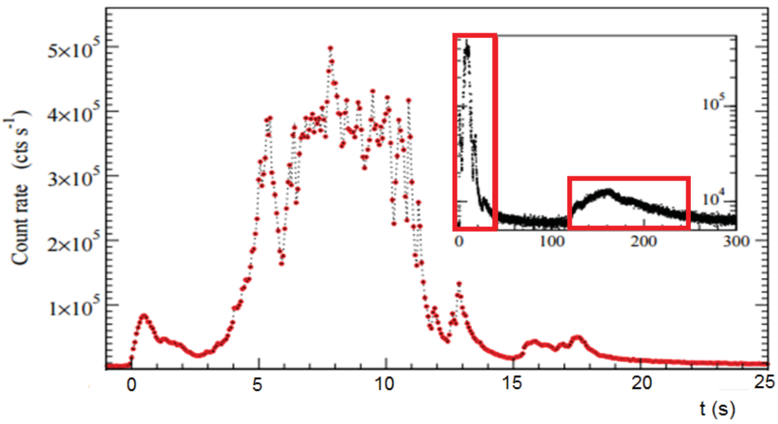


Figure 1. GRB130427A light curve in the energy range from 15 keV to 350 keV: the central panel shows the first peak of the burst, while the upper insert shows the whole burst, with the red boxes representing the two peaks considered in the *Konus-Wind* time-dependent analysis, adopted in this work. (Fig. from [7]).

2.1. High-energy neutrinos from GRB130427A

The theoretical neutrinos flux of the burst is the result of the interaction between a proton, accelerated thanks to the Fermi mechanism, and the observed radiation field. Fluxes from both the first and the second peak of the burst have been calculated through 'Neutrinos from

Table 1. In the table are reported the duration T, the fluence F_γ, the low energy photon index α, the high energy photon index β and the break energy of the spectrum E_γ provided by the γ time-dependent analysis of *Konus-Wind* Collaboration in the energy range from 0.02 MeV to 1.2 MeV.

	T (s)	F_γ (erg/cm^2)	α	β	E_γ (keV)
1st Peak	19	3×10^{-3}	-0.96	-4.17	1028
2nd Peak	130	9×10^{-5}	-1.60	-2.60	240

Cosmic Accelerators' or NeuCosmA code [8]: this is a detailed numerical simulation of the photohadronic interaction processes, accounting for the full proton-photon cross section and including not only the interaction via the Δ^+ resonance, but also kaons and multiple pions production leading to a high-energy component in the neutrino flux. The interaction products and their energy losses are treated individually and the mixing of neutrino flavors on their way to Earth is included. Assumptions were made on the bulk Lorentz factor $\Gamma = 316$, on the jet baryonic load $f_P = 10$ and on the energy fraction going into electrons and magnetic field $e_E = e_B = 0.1$: these parameters can change the neutrino yield for several orders of magnitude, since they affect both the shape and the normalization of the neutrino spectrum [9]. Fig. 2 shows the spectra for track-like events, revealable as muons and antimuons traversing the detector, from each peak: the neutrino spectrum is a broken power law, where the lowest energy break is linked to the break in the photons spectrum, while the higher breaks are due to synchrotron losses of secondary particles. Even in case of neutrinos, the first peak of the burst gives the main contribution. Therefore, the analysis method implemented over it is presented in the following.

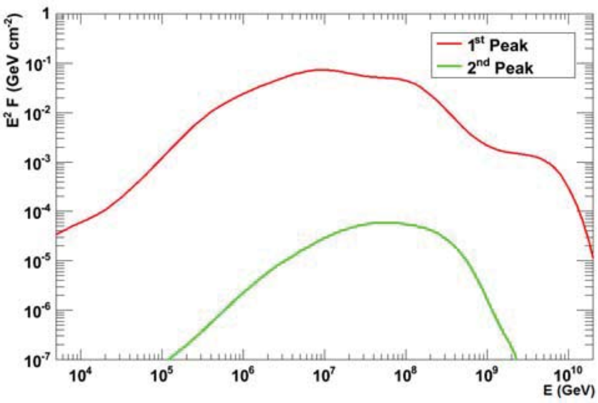


Figure 2. GRB130427A time-dependent NeuCosmA expectations for track-like events: the red curve represents expectations from the first pulse of GRB130427A obtained through *Konus-Wind* γ parameters of Table 1, while the green one represents the second pulse expectations.

2.2. Signal and background Probability Density Functions

For each peak of the burst, signal events due to neutrino interaction according to the expected NeuCosmA fluxes are generated with high statistics through a Run By Run Monte Carlo simulation. These events are then reconstructed in order to compute the detector Point Spread

Function (PSF): the signal Probability Density Function (PDF) is therefore obtained and denoted as $S(\alpha)$, where α represents the space angle between the reconstructed event direction and the GRB's coordinates. In Fig. 3 the cumulative PSF distribution for track-like events is reported: it shows that about 85% of the expected signal events are reconstructed inside an half cone angle of 10°. Since GRBs are transient sources, the angular window of the search can be extended with respect to steady sources search: indeed, the expected background in space-time coincidence with the burst is low due to the small selected time window. Therefore, $\alpha = 10°$ is adopted in the following. The time window is defined to be equal to each peak duration T, where the values for T are shown in Table 1, plus a symmetric extension of 2 s.

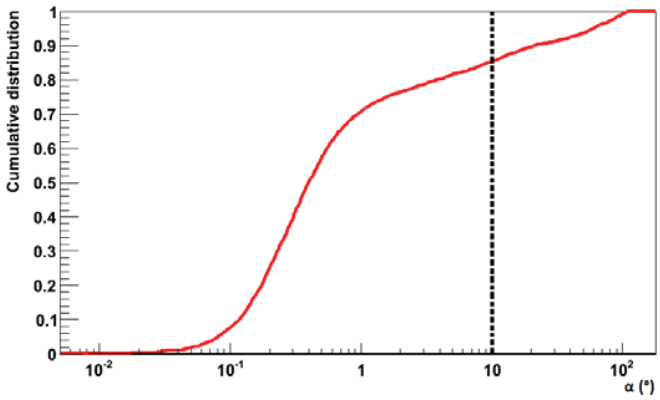


Figure 3. Cumulative distribution of reconstructed events from GRB130427A first peak around its position: the vertical line at $\alpha = 10°$ corresponds to the half cone angle selected for the analysis, since it contains 85% of the expected signal events.

The background PDF $B(\alpha)$ is assumed flat within the defined search cone. In order to estimate the expected mean number of background events μ_b inside the selected search windows, off-time data collected by ANTARES in 2013 are used: the average reconstructed event rate in the direction of the GRB is then corrected in order to take into account the detector efficiency during the run at which the burst triggered.
The track reconstruction algorithm [10] returns the fit quality parameter Λ: a cut on this parameter selects well reconstructed events and is therefore used to optimize the analysis. Both $S(\alpha)$ and $B(\alpha)$ depend on the final choice of the Λ cut.

2.3. Search optimization

Pseudo-experiments are generated in order to simulate n_{tot} signal and background events with space angle α_i, according to the normalised PDFs $S(\alpha)$ and $B(\alpha)$ corresponding to each Λ cut. An extended maximum likelihood ratio [11] is defined as test statistic Q and computed for each pseudo-experiment as:

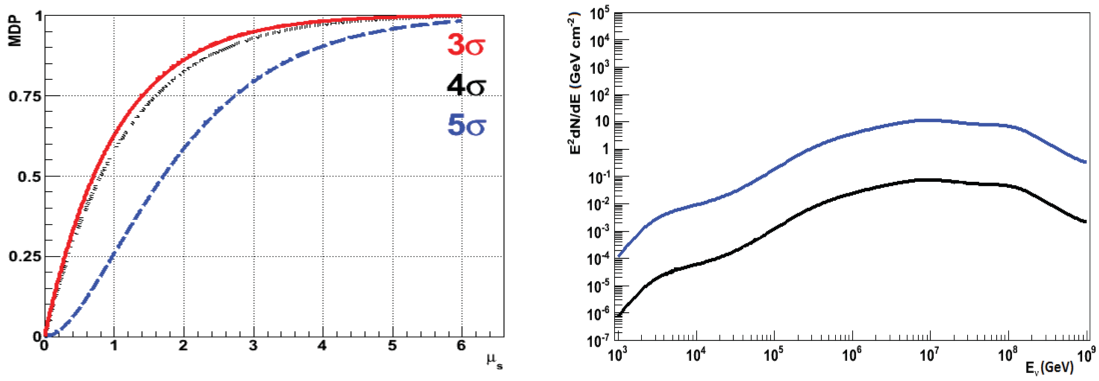
$$Q = \max_{\mu_s' \in [0;n_{tot}]} \left(\sum_{i=1}^{n_{tot}} \log \frac{\mu_s' S(\alpha_i) + \mu_b B(\alpha_i)}{\mu_b B(\alpha_i)} - \mu_s' \right)$$

where the expected number of background events inside the search windows μ_b is fixed from the previous background evaluation.
The distributions of the test statistic for different numbers of injected events are used to evaluate the Model Discovery Potential (MDP) for a given number of expected signal events μ_s as predicted by the NeuCosmA model. The cut on the quality parameter Λ is then chosen as the

one that maximizes the MDP. Fig. 4(a) shows the MDP as a function of an arbitrary number of expected signal events μ_s, obtained using the PDFs with the optimized cuts for the first peak analysis at 3σ significance.

3. Results

Performing the 3σ optimized analysis presented above on both peaks of GRB130427A, the expected number of signal and background events inside the defined angular and time search windows are $\mu_s = 1.55 \times 10^{-2}$ and $\mu_b = 4.07 \times 10^{-3}$ from the first peak and $\mu_s = 2.87 \times 10^{-6}$ and $\mu_b = 3.54 \times 10^{-2}$ from the second one, with a discovery potential of respectively 2% and 0.3%. It is possible to estimate the ANTARES sensitivity to this source, focusing on the first peak of the emission: in the energy range where 90% of signal events are expected to be detected in ANTARES (from 2×10^5 GeV to 2×10^7 GeV), the sensitivity, evaluated as $E^2\phi_\nu$, is in the range $1 - 10$ GeV/cm^2, a factor 150 above the expected flux, as shown in Fig. 4(b). Even if this burst has been one of the most intense ever, it is not possible to constrain the fireball paradigm with it only: improved results on the detector sensitivity can be obtained through the stacking of more sources, as for example in [12]. Moreover, a km^3-sized detector, like the under-construction neutrino telescopes KM3NeT, will certainly allow the fireball paradigm to be probed in the near future.



(a) (b)

Figure 4. (a) Model Discovery Potential as a function of the signal flux μ_s for 3σ (red solid), 4σ (black dotted) and 5σ (blue dashed) significance on the first peak of GRB130427A. (b) Expected tracks flux from the first peak of GRB130427A (black) and ANTARES sensitivity to it (blue).

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