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Follow-up of high energy neutrinos detected by the ANTARES telescope

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Abstract. The ANTARES telescope is well-suited to detect high energy neutrinos produced in astrophysical transient sources as it can observe a full hemisphere of the sky with a high duty cycle. Potential neutrino sources are gamma-ray bursts, core-collapse supernovae and flaring active galactic nuclei. To enhance the sensitivity of ANTARES to such sources, a detection method based on follow-up observations from the neutrino direction has been developed. This program, denoted as TAToO, includes a network of robotic optical telescopes (TAROT, Zadko and MASTER) and the *Swift*-XRT telescope, which are triggered when an "interesting" neutrino is detected by ANTARES. A follow-up of special events, such as neutrino doublets in time/space coincidence or a single neutrino having a very high energy or in the specific direction of a local galaxy, significantly improves the perspective for the detection of transient sources. The analysis of early and long term follow-up observations to search for fast and slowly varying transient sources, respectively, has been performed and the results covering optical and X-ray data are presented in this contribution.

1. Introduction

High energy neutrinos are unique messengers to study the high energy Universe, as they are neutral, stable and weakly interacting. They are thought to be produced in violent astrophysical phenomena when accelerated hadronic cosmic rays interact with matter or radiation fields surrounding their astrophysical sources. Promising candidate sources are gamma-ray bursts (GRBs), active galactic nuclei or core-collapse supernovae (CCSNe). However, even with the recent detection of high energy cosmic neutrino events by the IceCube experiment [1, 2], no high energy neutrino source has been identified up to now.

The ANTARES telescope [3], completed in 2008 in the Mediterranean Sea, aims at detecting these high energy neutrino sources with a 3-dimensional array of 885 photomultiplier tubes distributed on twelve lines. The detection of Cherenkov light induced by the propagation of up-going muons in water is used as a signature of muon neutrino interaction close or within the instrumented volume.

The identification of steady neutrino sources is challenging due to the very small number of expected events and a large background contamination from atmospheric muons and neutrinos. A way to overcome this difficulty is to search for neutrinos from flaring astrophysical sources of photons. Searches for transient phenomena offer very promising opportunities for high energy neutrino telescopes, as

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the combination of information in a limited space/time window around the transient event allows the background to be significantly reduced. Furthermore, as a neutrino telescope has an instant coverage of at least a hemisphere with a high duty cycle, a neutrino detection can be used to trigger electromagnetic observations at various wavelengths, which enhance the detection sensitivity.

2. TAToO

TAToO (Telescopes-ANTARES Target Of Opportunity) [4] is the multi-wavelength follow-up program operating within the ANTARES experiment since 2009. This alert system allows a network of robotic optical telescopes (TAROT [5], Zadko [6], MASTER [7], and ROTSE [8] until the end of 2014) and, since mid 2013, the X-ray telescope on board the *Swift* satellite [9] to be triggered soon after the detection of a special neutrino event. Three online criteria, tuned to match the rate of $\sim$25 alerts per year accepted by the optical telescopes, are currently implemented to trigger the system:

- High energy: detection of a single high energy neutrino event ($< E >\sim$7 TeV).
- Directional: detection of a single neutrino event having direction consistent ($< 0.4^\circ$) with the position of galaxies within 20 Mpc of Earth.
- Multiplet: detection of at least two neutrinos spatially coincident ($< 3^\circ$) within a predefined time window ($<$ 15 minutes).

Since the beginning of TAToO, more than 160 neutrino triggers have been sent to the telescope network with a minimum delay of $\sim$5 seconds after the neutrino detection, and with the incoming neutrino direction reconstructed to a precision better than 0.5° for high energy events. Among them, 10 alerts have been forwarded to the *Swift*-XRT, following the very high energy trigger criterion that selects a subsample of high energy events to comply with the rate of 6 alerts per year accepted by *Swift*. Follow-up observations of ANTARES neutrino alerts have been performed according to two strategies: a prompt strategy dedicated to the search for fast transient sources, such as gamma-ray bursts (GRBs), with images taken in a maximum delay of 24 hours after the neutrino detection, and a long term follow-up strategy with images taken up to two months after the trigger and well-suited to the search for slowly varying transient sources, such as core-collapse supernovae (CCSNe).

3. Early follow-up analysis

Early follow-up observations have been performed by optical and X-ray telescopes for 42 and 10 neutrino triggers, respectively. Optical observations have been performed by the TAROT and ROTSE telescopes with a minimum delay of 17 seconds after the neutrino detection. For each observation, between 6 and 30 images have been taken with 60 or 180 seconds exposure. All these images have then been analysed with a dedicated pipeline based on a subtraction method [10].

For each trigger followed by the *Swift*-XRT, four observations lasting 2000 seconds each have been made around the neutrino position after a mean delay of 6.3 hours. X-ray data have been automatically analysed at the UK Swift Science Data Centre with dedicated pipelines.

In both optical and X-ray wavelengths, no transient source has been identified as the counterpart to a neutrino trigger. Therefore, upper limits on the magnitude and on the flux density from a potential optical and X-ray counterpart have been derived [10]. These limits correspond to the sensitivity reached by the instruments for each observation.

3.1 Limit on a GRB association

Among the population of fast transient sources, GRBs are one of the most promising sources for high energy neutrino emission. Because in this analysis no optical or X-ray counterpart has been observed in

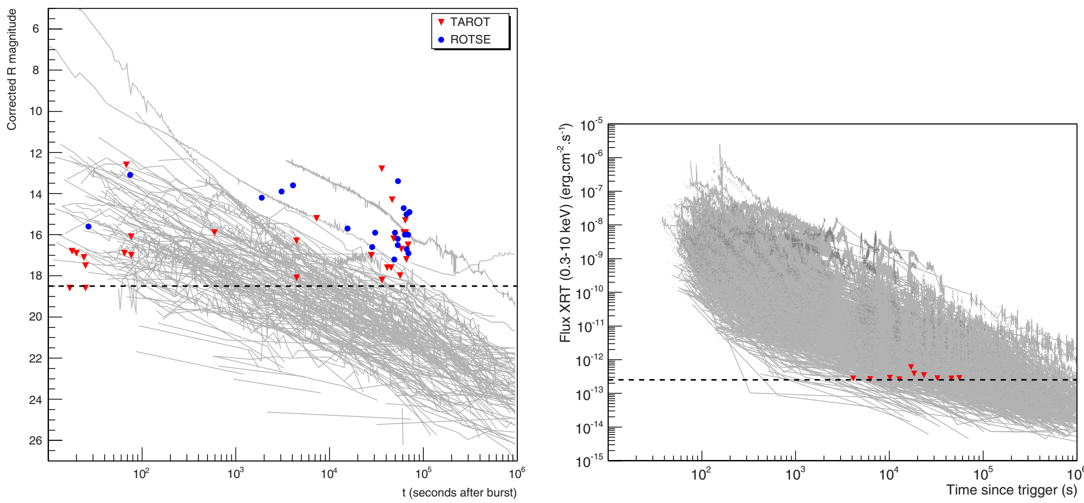


Figure 1. Left: upper limits (red and blue) on optical GRB magnitudes based on a comparison with 301 GRB afterglow light curves (grey) observed from 1997 to 2014 by optical telescopes. Right: upper limits (red) on X-ray afterglow fluxes compared to 689 X-ray light curves (grey) of GRBs detected by the *Swift*-XRT from 2007 to 2015. On each plot, the horizontal dashed line corresponds to the maximum sensitivity reached by the optical and X-ray telescopes for this analysis.

coincidence with the neutrino alerts, the probability to reject a GRB origin for these neutrinos can be estimated. To do so, a comparison with optical and X-ray upper limits obtained for each neutrino alerts and GRB afterglow light curves has been made (Fig. 1).

In the optical band, a GRB association is rejected, with a confidence level above 80%, if the optical observation is started within one minute after the neutrino trigger, while for follow-up observations started later than a few minutes after the trigger, the derived upper limits do not constrain a GRB origin for the detected neutrinos, due to the limited sensitivity of the TAROT and ROTSE telescopes.

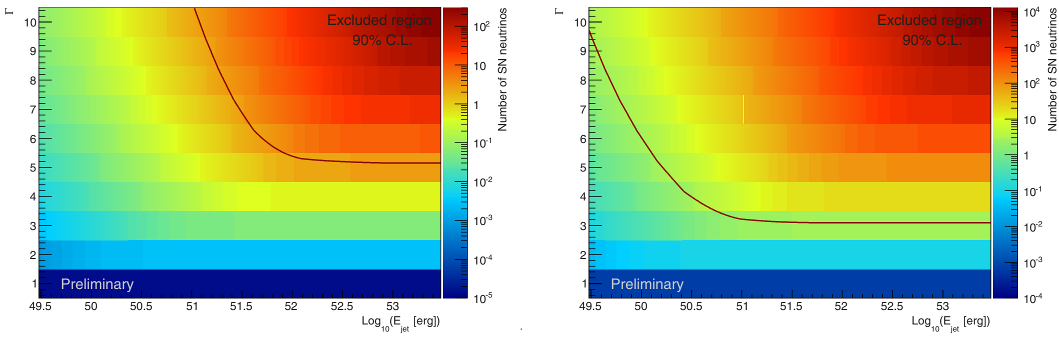
Concerning the X-ray follow-up, the probability to reject a GRB origin is as high as 71% only for observations carried out within 1.1 hours after the trigger. For later observations, a GRB origin is very unlikely for the neutrino events, as few GRBs are known to have weaker X-ray afterglows than the upper limits.

4. Long term follow-up analysis

Follow-up images have been taken up to two months after the neutrino detection by optical telescopes according to the long term strategy. The optical counterpart search has been performed with the dedicated image subtraction pipeline for 71 alerts followed from October 2009 to January 2015. Up to 12 nights have been processed for each alert with limiting magnitudes ranging from 14.0 to 19.4. No transient source has been identified as the counterpart associated with one of the 71 detected neutrinos.

4.1 Limit calculation in the case of CCSNe

The non-observation of an optical transient in coincidence with a neutrino event allows constraints on the Ando & Beacom model parameters [11] to be placed. This model predicts the production of high energy neutrinos in mildly relativistic jets of CCSNe, with a flux depending on the jet energy E_{jet} and the Lorentz boost factor of the jet Γ.



(a) d = 3 Mpc.

(b) d = 460 kpc.

Figure 2. Expected number of neutrinos detectable with ANTARES from a CCSN at different distances for different Ando & Beacom model parameter combinations. The red line indicates the limit above which combinations of $E_{\text{jet}} - \Gamma$ are excluded at 90% C.L. as no CCSN neutrinos have been detected.

Figure 2 shows the number of expected neutrinos in ANTARES for a CCSN with a jet pointing towards Earth at a distance of 3 Mpc and 460 kpc. The number of neutrinos is calculated for Γ from 1 to 10, and for jet energies in the range 3×10^{49} erg $< E_{\text{jet}} < 3 \times 10^{53}$ erg. As no optical CCSN has been observed for the 71 alerts, combinations of model parameters producing a detectable signal in ANTARES can be excluded. A red line on each plot indicates the limit above which parameter combinations are excluded at the 90% C.L.. Figure 2 (b) shows that a CCSN with standard values for mildly relativistic jets ($E_{\text{jet}} = 3 \times 10^{51}$ erg and $\Gamma = 3$) is excluded up to 460 kpc.

5. Conclusion

TAToO is a promising multi-messenger approach to detect transient sources, as it is able to send alerts within a few seconds after the neutrino detection and with an angular resolution better than 0.5°. The image analysis has not yet allowed transient sources associated with the selected neutrino events to be discovered. However, stringent limits on the GRB origin of individual neutrinos have been placed, as well as constraints on the CCSN parameters from the Ando & Beacom model.

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