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# Multiwavelength comparison of selected neutrino point source candidates

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In this paper, we report the first results of an analysis of AMANDA-II data to search for time-variable neutrino point sources. A large sample of 3329 neutrino candidate events from the northern hemisphere was analyzed. The investigation is based on the observation that many cosmic sources have violent variations in their electromagnetic emission. We have tested the hypothesis that neutrino production in such sources is correlated with the electromagnetic activity. Using an independent approach, we have also searched for occasional neutrino flares using a sliding-window technique. Such flares might be detectable with a dedicated time variability investigation and under favorable conditions of signal enhancement and duration. The two search methods will be described and the results reported.

## 1. Introduction

TeV neutrino candidate sources often show large and violent variations in the electromagnetic emission. Under the assumption that neutrino emission shows a similar variability, a set of methods that test the flare behavior of a source have been developed. Under favorable conditions of signal enhancement and period duration, such flares might be detectable with a dedicated time-variability investigation and still not be evident in the time-integrated point-source search [1].
The driving criteria used for the selection of the sources considered in this analysis are: the source presents an evident variable character in one or more wavelengths, flares are plausible in the period of interest for this analysis (2000-2003) and the total time of the flare periods is long enough in order to allow a reasonable detection probability. Three categories of sources have been selected: blazars, microquasars and variable sources from the EGRET catalog.
Two different methods have been developed in order to search for a variable neutrino signal from these families of sources: (A) a multiwavelength comparison when the source presents a resolved variability in one or more wavelengths, (B) a search for neutrino flare with a sliding-time window when the variable character of the source is evident but electromagnetic observations are limited.
The test data sample is provided by the time-integrated point source search [1]. In the multiwavelength method (A) an appropriate re-optimization for shorter live-times is performed. The complete catalog of sources used in this approach with the results obtained are reported in Table 1. The analysis has been performed following the principle of ”blind analysis” to avoid the introduction of biases that cannot be statistically quantified. Details about this topic are discussed in [1].

## 2. Method A: Multiwavelength Comparison

A multiwavelength comparison has been developed in order to analyze TeV blazars and microquasars in the scenario of non-steady-state neutrino emission. Details of the method that are specific to these families of sources are reported below.

**TeV blazars** show dramatic variability correlated between multiple wavelengths of the electromagnetic spectrum; correlations between TeV $\gamma$-rays and X-rays occur on time-scales of hours or less. This correlated variability is often interpreted as a strong argument in favor of pure electromagnetic models (leptonic models) in which the same population of ultra-relativistic electrons is responsible for production of both X-rays and TeV $\gamma$-rays. In fact, these observations do not rule out models involving the acceleration and interaction of protons (hadronic models see e.g. [3]). In hadronic models, pions produced by $p\gamma$ or $pp$ interaction result in the simultaneous emission of $\gamma$-rays and neutrinos. Imaging atmospheric Cherenkov telescopes have detected various $\gamma$-ray flares in the energy region GeV to TeV. If it were not for large gaps in time between the measurements of these flaring periods, the measured on-times of the $\gamma$-rays would clearly define the high state of activity of the sources. On the contrary, the use of the $\gamma$-ray measurements in this context is quite limited. TeV and X-ray flares are, with few exceptions, well correlated (see e.g. [6]), and all-sky X-ray measurements guarantee a quasi-continuous data record. Therefore a reasonable strategy, which we used, is to select the periods of interest on the basis of the X-ray light curves provided by ASM/RXTE [4], see Fig. 1. We have looked for an excess of events in the on-source direction by comparing the integrated number of neutrino counts versus the estimated atmospheric neutrino background for the selected time periods. The optimization was performed over the entire 4 years of data. Quantitative results are reported in Tab. 1.

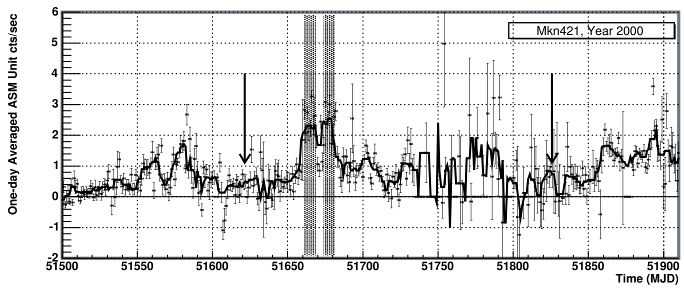


**Figure 1.** The periods of interest for TeV blazars have been selected based on the X-ray light curves provided by ASM/RXTE [4] (points with error bars). A median filter is first applied to the light curves in order to make the trend of the curve more evident (continues line). The arrows represent the arrival time of the neutrino events. The shaded regions are the periods of high activity selected. For space reason, only the result of Mkn421 and the year 2000 is shown, however the optimization runs on the entire 4 years of data.

**Microquasars** are galactic X-ray binary (XRB) systems, which exhibit relativistic radio jets [8]. Microquasars are associated with several classes of XRBs and variable time behavior. The observed radiation from microquasar jets, typically in the radio, in some cases also in the IR band, is consistent with non thermal synchrotron radiation emitted by a population of relativistic, shock-accelerated electrons. The composition of microquasar jets is still an open issue. An indication of e-p jets is the presence of Doppler-shifted spectral lines proving the presence of nuclei in the jets of this source. Neutrino bursts are predicted in such sources. The duration should be of the order of the ejection time of the blob. It should precede the associated radio outburst by several hours. Radio data are used as identification time of the emission of the jets and of the emission of the possible neutrino production. Following these observations we have decided to include one microquasar (Cygnus X-3) in the search for neutrino bursts. In this case, periods of high activity are selected based on the radio light curve from the Ryle telescope, which has a nearly constant record of the source (data available courtesy from Guy Pooley). A window of three days is added prior to this period in order to take into account that the neutrino signal should precede the radio emission.

## 3. Method B: Flare Search

In this section a search method sensitive to occasional neutrino flares, whose times and durations are unknown, is described. Observations of strong variability in the electromagnetic emission exist for various TeV neutrino candidate sources. However, often there is no continuous observation of the flux (e.g. the EGRET sources) and/or no prediction for a time correlation between the photon and neutrino emission.
The data selection has been optimized with the help of toy Monte Carlo events. The data sample produced by the time-integrated point source search [1] without any re-optimization gives the highest detection probability. A method based on a sliding window of fixed duration has been investigated, where the length of the window is a parameter to be optimized. As the flare duration is not known the detection probability in dependence of the time window length has to be calculated. Note that short flares will be not detectable if the peak to valley ratio is much higher than the one observed in $\gamma$-rays. The signal contribution in very long windows is limited by the number of events observed in the time-integrated search. The optimum choice is a 20 days window for galactic objects and a 40 days window for extra-galactic ones. The three categories of sources selected are a subset of the standard list of TeV neutrino candidate sources used in the time-integrated point source analysis [1]. Moreover, we have included in our analysis three sources from the EGRET catalog which show extraordinarily large variations in the MeV $\gamma$-ray flux.

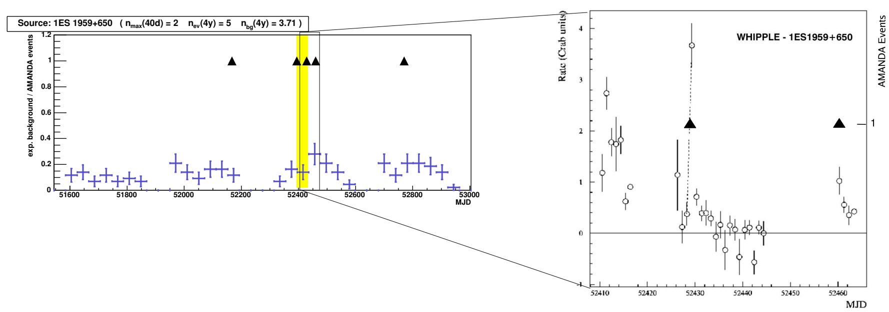


**Figure 2.** Left: AMANDA-II neutrino candidates within $2.25^o$ from the direction of the blazar 1ES 1959+650. The triangles indicate the arrival time of the observed events; the crosses refer to the background events in the 40-days windows. The window showing the highest multiplicity is highlighted. Right: Zoom-in of the time-window MJD 52410-52460. The arrival time of two out of the five AMANDA-II events is compared with the Whipple light curve from [5].

## 4. Results and Discussion

The results obtained with the two methods discussed in section 2 and section 3 are reported in Tab. 1. In both cases, no statistically significant excess of events over the background expected has been observed.

Although the results obtained are not significant, the time structure of the neutrino candidates from the direction of the blazar 1ES 1959+650 (within $2.25^o$) merits a dedicated discussion. The sample is composed of five events in the entire four-years period. They have been identified by the blind analysis as described previously (see Fig. 2). The following has been noticed: 1) Three events out of the five fall within 66 days (MJD 52394.0, 52429.0, 52460.3).
2) The period of time in which these three events fall is partially overlapping with a period of exceptional high activity of the source. The activity of the source has been monitored by a multiwavelength campaign during the period MJD 52410-52500. The detailed analysis of the campaign was reported earlier [6].
3) In the paper cited, the detection of a $\gamma$-ray flare without its X-ray counterpart is reported (MJD 52429.3).

**Table 1.** Results from the search of neutrinos from selected variable sources. $n_{obs}$ is the number of observed events in four years and $n_{bg}$ is the expected, corresponding background. $n_{obs}/n_{bg}$ are the event numbers observed during to the periods of high X-ray activity for the two blazars and in the radio band for the micro-quasar. $n_{doublets}$ corresponds to the cluster of two events within the time window (20/40 days).

| Source | | Multiwavelength | | | Sliding Window | |
|---|---|---|---|---|---|---|
| | $n_{obs}$ | $n_{bg}$ | $n_{obs}/n_{bg}$ | $n_{obs}$ | $n_{bg}$ | $n_{doublets}$ |
| Mkn421 | 7 | 9.44 | 0/1.63 | 6 | 5.58 | 0 |
| 1ES 1959+650 | 5 | 4.67 | 2/1.57 | 5 | 3.71 | 1 |
| QSO 0235+164 | | | | 6 | 5.04 | 1 |
| QSO 0528+134 | | | | 4 | 4.98 | 0 |
| Cygnus X-3 | 13 | 9.86 | 2/1.39 | 6 | 5.04 | 0 |
| Cygnus X-1 | | | | 4 | 5.21 | 0 |
| GRS 1915+105 | | | | 6 | 4.76 | 1 |
| GRO J0422+32 | | | | 5 | 5.12 | 0 |
| 3EG J0450+1105 | | | | 6 | 4.67 | 1 |
| 3EG J1227+4302 | | | | 6 | 4.37 | 1 |
| 3EG J1828+1928 | | | | 3 | 3.32 | 0 |
| 3EG J1928+1733 | | | | 7 | 5.01 | 1 |

This event has been defined as the first unambiguous example of an “orphan” $\gamma$-ray flare from a blazar. The main conclusion from the observation of the ”orphan” flare is that it cannot be explained with a conventional one-zone synchrotron self-Compton model. Several authors interpret such ”orphan” as indicators of hadronic processes occurring in the blazar jet. High energy neutrinos are expected in this case. One of the five events of our sample (MJD 52429.0) is within few hours from the ”orphan” flare.

On the base of these observations different authors discussed the possible neutrino emission during the ”orphan” flare (see [7]). The IceCube collaboration is currently working on methods to search for neutrinos connected to phenomena similar to the case of 1ES 1959+650. To achieve that, a close collaboration with the $\gamma$-ray community is essential. So, we encourage extensive multidisciplinary investigations and extended $\gamma$-ray monitoring of this and similar sources.

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