PROCEEDINGS OF SCIENCE

Search for Neutrino Flares with the ANTARES Telescope

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The ANTARES Neutrino Telescope operated from the Mediterranean Sea and has collected valuable neutrino data from potential sources located in the equatorial Southern hemisphere and Galactic Center with a duty factor of over 70 %. Despite its small size, the ANTARES telescope has proved to be a powerful tool in neutrino astronomy benefiting from the good scattering properties of the Mediterranean water. In this contribution we have performed a time-dependent analysis in which the addition of temporal information from external observatories allows us to constrain the neutrino arrival time, reducing the expected background and boosting the detection potential of emitting sources. Being the nature or neutrino production still a mystery, we performed a complementary neutrino-to-neutrino follow-up of potential neutrino flares detected by the IceCube Telescope. We present the analysis strategy, optimisation procedure and results using the available ANTARES data from January 2007 to February 2020 with a brief discussion of their implications for the current state of multi-messenger and neutrino astronomy.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)1480

1. Introduction

The ANTARES neutrino telescope was an underwater neutrino observatory which aimed at the detection of high-energy cosmic neutrinos. ANTARES was deployed at a depth of 2500 meters below the surface level in the Mediterranean Sea, and 40 km off the coast of Toulon, France [1]. ANTARES operated for 14 years since its completition in 2008. Although it is already decommissioned, the ANTARES data is still valuable for studying unexplored neutrino emission patterns.

In 2017, the combined detection of a very high energy neutrino by the IceCube observatory in time and spatial coincidence with the γ-ray flaring blazar TXS 0506+056 [2], along with the subsequent discovery of neutrino emission from the same source prior to that event [3] confirmed the possibility of performing multi-messenger astronomy using high-energy neutrinos.

However, the neutrino emission from TXS 0506+056 is still not well understood [4]. This, together with the lack of convincing association of neutrinos with very energetic γ-ray emission has made the community switch their interest to other wavelengths of the electromagnetic spectrum as X-rays [5, 6] or radio-waves [7, 8]. Moreover, the second evidence of a cosmic neutrino source, the nearby galaxy NGC 1068, shows a suppressed emission in gamma rays compared to the expected emission derived from the observed neutrino flux [9].

In this contribution, we have taken a more pragmatic approach. We use the time profile information obtained from the searches for neutrino flares done by IceCube [10], and we use that information as input for our search method.

2. Apparatus and Data Sample

The water-Cherenkov neutrino telescope ANTARES consisted of 12 lines horizontally separated 70 m from each other. Every line was composed of 25 storeys with three optical modules (OM) each. The OM is the main detection element of the detector, housing a 10 inch photomultiplier facing 45° downward to improve detection of upgoing light resulting from neutrinos passing through the Earth. As it was located on the Northern hemisphere, ANTARES was suited for the observation of neutrino sources on the southern celestial sky, including the Galactic centre and the Galactic plane. However observations up to 45° on the declination could be done even with a low duty cycle.

In a transparent medium as the water of the Mediterranean Sea, high-energy leptons emitted by the neutrino interaction produce a characteristic light emission that is detected with the ANTARES telescope and used to reconstruct the original neutrino direction. ANTARES is sensitive to two different light topologies called tracks and showers. The former are detected when a high-energy muon, produced by the charged-current interaction of a muon neutrino ν_μ, crosses the detector or passes nearby at very high speeds emitting Cherenkov radiation along its trajectory. However, charged-current interaction for electron neutrinos ν_e and tau neutrinos ν_τ, together with neutral current interactions for all three neutrino flavours have as an end product of the interaction electromagnetic or hadronic showers, hence being called shower events.

For this analysis, the data collected from January 2007 to February 2020 are used, as the results of [10] do not extend further in time. This period of time correspond to an effective livetime of

3901 days. However, unlike previous point-source searches [11, 12] data selection criteria is set individually for each of the sources.

The addition of temporal information in the analysis makes the expected background for each source dependant on the flare duration. Since lower levels of backgrounds are expected compared to the time integrated searches, the selection criteria of the ANTARES data can be re-optimized for each given flare duration. For each source, the best selection is determined maximising the model discovery potential for a flux proportional to E_ν^{-2} spectrum during the flaring period.

3. Sources and analysis method

The IceCube Collaboration parametrises the neutrino flare of the sources as Gaussian functions centred around a central time of emission $\widehat{T}_0$ and with a width $\widehat{\sigma}_T$. This analysis searches for a neutrino signal correlated in time and space with a total of 36 sources resulting from the original 110 [10] after applying the following selection criteria:

- Only sources that are within the ANTARES field of view are selected being the threshold of visibility 45° in the source declination δ.
- For each source, the flare duration is defined as $2\widehat{\sigma}_T$, and rounded up to have integer days, to remove the right ascension dependence when the analysis is carried out in equatorial coordinates. For this reason, sources for which their duration fulfil the condition $2\widehat{\sigma}_T < 1$ day are not considered, with the exception of source M87 as it is fitted with a pre-trial significance over 3σ.

For the simplicity of the analysis, each flare is transformed from a Gaussian shape to a box shaped function where the width of the box is set to $2\widehat{\sigma}_T$. This is done to remove any shape related effect from the analysis and use the fitted neutrino flares as flags for potential neutrino emission.

This box flares are then converted into time probability density functions (PDF) $P^j_{\text{Sig}}(t)$ for the expected neutrino signal and used in the following log-likelihood definition:

$$\log \mathcal{L} = \sum_{j}^{N_{\text{sam}}} \sum_{i}^{N_j} \log \left[\frac{\mu^j_{\text{sig}}}{N_j} \mathcal{S}^j_i \times P^j_{\text{Sig}}(t_i) + (1 - \frac{\mu^j_{\text{sig}}}{N_j}) \mathcal{B}^j_i \times P^j_{\text{Bkg}}(t_i) \right] \tag{1}$$

where the appropriate time PDF for background events $P^j_{\text{Bkg}}(t)$ has to the be added to the corresponding background term of the likelihood. The other terms in equation (1) correspond to the standard definition of the log-likelihood for time-integrated searches [12]: The sum over j represents all considered samples, tracks and showers in this work. Then, for each j-th sample, $\mathcal{S}^j_i$ and $\mathcal{B}^j_i$ are the values of the product of signal and background directional and energy PDFs of the i-th event. Finally, N^j is the total number of events observed in the j-th sample.

The log-likelihood is then maximised searching for the best value of the fitted signal events: $\mu_{\text{sig}} = \mu^{\text{track}}_{\text{sig}} + \mu^{\text{shower}}_{\text{sig}}$. To estimate the significance of the fit the following test statistic (TS) Q is defined:

$$Q = \log \mathcal{L}(\mu^j_{\text{sig}} = \mu^j_{\text{max}}) - \log \mathcal{L}(\mu^j_{\text{sig}} = 0), \tag{2}$$

which is the difference between the value of the log-likelihood for the best fitted signal value $\mu^{j}_{\rm max}$ and the case when only background is present, $\mu^{j}_{\rm sig} = 0$. The significance of the fit is quoted as the p-value of the obtained $Q_{\rm data}$ compared to the distribution of $Q_{\rm Bkg}$. This distribution is obtained from pseudo-experiments where the same analysis is repeated 10^8 times on simulated date sets composed of background events only.

4. Results

The results of the search for neutrinos in the direction of the 36 sources and in coincidence with the neutrino emission profiles published by IceCube are presented in Table 1. For all the sources an upper limit on the neutrino fluence $\mathcal{F}_\nu$ is provided, which is computed as:

$$\mathcal{F}_\nu = \int E \times \phi_E \, dE \, dt = \Phi_0 \int \frac{1}{E} \, dE \, dt = \Phi_0 \, T \, (\log E_{\rm max} - \log E_{\rm min}) \quad (3)$$

where $\phi_E = \Phi_0 \times E^{-2}$, with no temporal dependency. The parameter T is the duration of the flare in seconds. The values of $E_{\rm min}$ and $E_{\rm max}$ define the range of energies for which the detector is sensitive and their values depend on the selection used, usually around 1 TeV and 1 PeV respectively.

Only 4 sources, namely NGC 598, TXS 0506+056, PKS 1502+106, and B3 0609+413 (listed in order of increasing pre-trial p-value), have a fitted signal during the flare. Figure 1 shows the skymap around these sources, along with a time profile of the events occurring near each source.

5. Conclusions

The first time-dependent neutrino search from a list of sources using temporal information on the neutrino emission from another neutrino observatory has been performed by ANTARES. A source-by-source optimisation of the data selection criteria based on the flare duration and model discovery potential for a E^{-2} flux has also been implemented. No evidence of neutrino emission in coincidence with the sources and studied time profiles has been found. Therefore upper limits in the neutrino fluence for each source are presented in this work. However, some signal events are found for four of the sources, three of which have a pre-trial significance in the one sided convention over 2σ: NGC 598 (2.2σ), TXS 0506p56 (2.1σ), PKS 1502+106 (2.1σ) and B3 0609+413 (1.67σ).

Once the IceCube neutrino observatory releases new neutrino time profiles covering the whole ANTARES data set (until February 2022) with improved directional reconstruction as shown on [9], this study will be updated. This kind of analyses are a very robust way of proving neutrino emissions independently of the model and will grow on relevance as neutrino detectors increment their sensitivities and collect more data. As a matter of fact, ANTARES has already performed a temporal profiling of neutrino emissions coming from radio-bright blazars [7]. Using independent data sets can meaningfully boost the significance of a detection making neutrino-to-neutrino searches a powerful tool in astroparticle physics in the close future. This is especially relevant as we anticipate the simultaneous operation of multiple neutrino observatories, such as KM3NeT [13], IceCube-Gen2 [14], P-ONE [15], and TRIDENT [16].

Figure 1: Skymap (left) and arrival time (right) of the events found within 5° of the direction of the studied sources. A color code is used in both plots to indicate the contribution of the events to the fitted signal of each analysis. The inner (outer) dashed purple line on the skymap depicts the 1° (5°) degree distance from the position of the source location. Additionaly, every event is accompanied with a teal (light red) circle indicating the estimated angular uncertainty of the track (shower) event. Along the arrival time of the events, the IceCube neutrino-flare time profile is shown together with the characterisation used for the analysis, both in arbitrary units. The number of fitted signal events, and the pre-trial significance of the space-time correlation is indicated over every skymap.

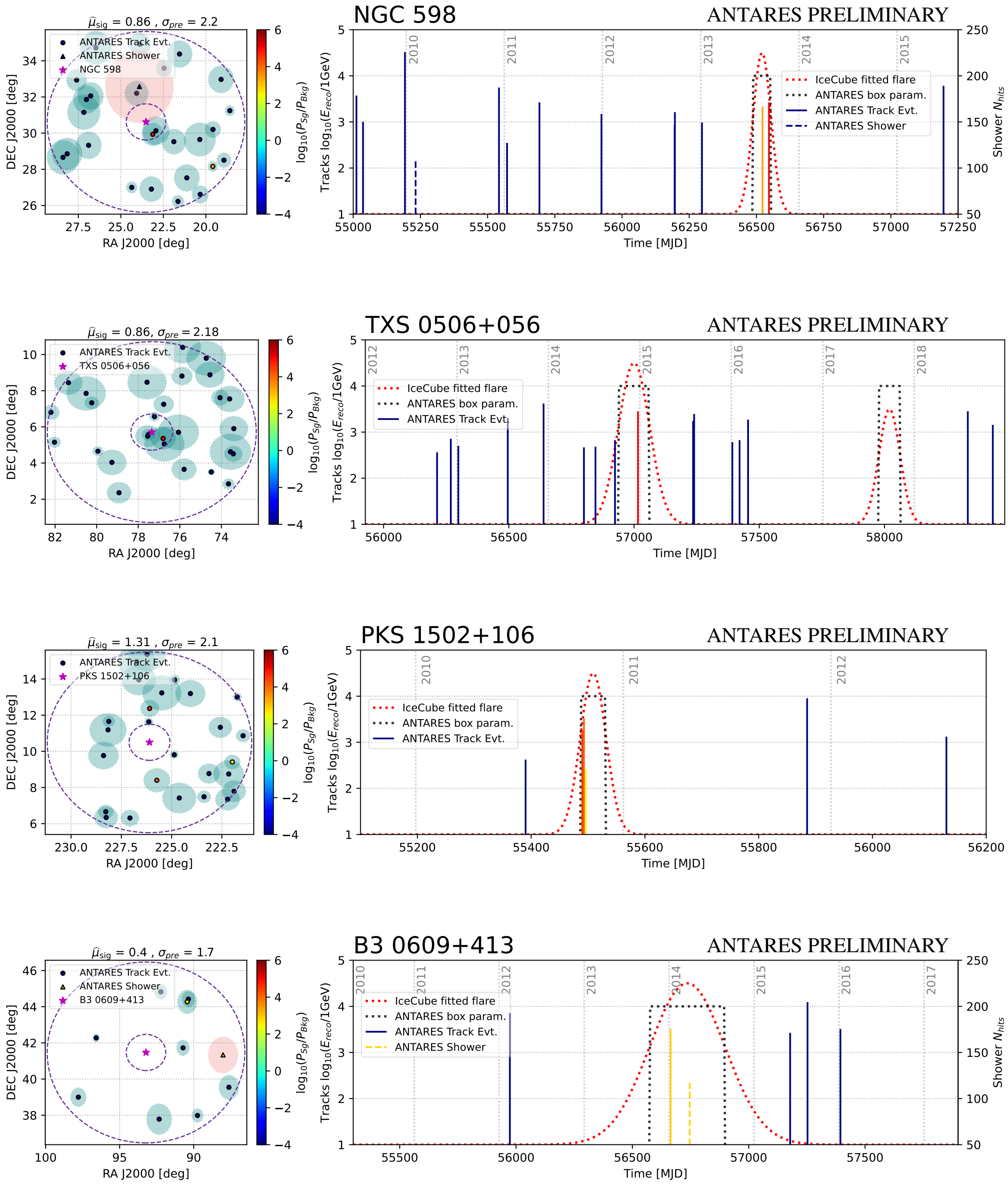

Table 1: List of analysed sources ordered from lower to higher declination δ. The table shows in the following order the name, declination δ and right ascension α of the source, duration of the flare in days, number of fitted signal events $\widehat{\mu}_{\rm sig}$, pre-trial p-value of the fit, and 90% C.L in the all-flavour neutrino fluence $\mathcal{F}_\nu$ for an E^{-2} spectrum (in units of GeVcm^2). Source which had any fitted number of signal events are highlighted in bold case, while dashes (–) indicate null fitted signal.

Source name	$\delta[°]$	$\alpha[°]$	Dur [d]	$\widehat{\mu}_{\rm sig}$	p-value	$\mathcal{F}_\nu^{90\%\rm C.L.}$
NGC 253	-25.9	11.9	46	–	–	3.5
PKS 2320-035	-3.29	350.88	321	–	–	3.5
S3 0458-02	-1.97	75.3	3	–	–	5.0
PKS 0440-00	-0.29	70.66	124	–	–	6.0
NGC 1068	-0.01	40.76	396	–	–	5.0
HESS J1852-000	0	283.0	202	–	–	2.6
GRS 1285.0	0.69	283.15	175	–	–	3.9
PKS 0502+049	5	76.34	4	–	–	5.8
TXS 0506+056	**5.7**	**77.35**	**208**	**0.86**	**0.031**	**7.8**
MGRO J1908+06	6.18	287.17	10	–	–	5.0
OT 081	9.65	267.87	93	–	–	6.0
PKS 1502+106	**10.5**	**223.10**	**45**	**1.31**	**0.037**	**6.1**
1RXS J194246.3+1	10.56	295.7	50	–	–	3.4
MG1 J021114+1051	10.86	32.81	3	–	–	5.9
M87	12.39	187.71	2	–	–	4.1
4C+14.23	14.42	111.33	3	–	–	6.0
3C 454.3	16.15	343.5	401	–	–	4.0
OJ 287	20.12	133.71	3	–	–	3.9
RGB J2243+203	20.36	340.99	67	–	–	4.8
S2 0109+22	22.75	18.03	3	–	–	4.7
PKS 1424+240	23.8	216.76	401	–	–	5.0
PKS 1441+25	25.03	220.99	212	–	–	5.0
W Comae	28.24	185.38	4	–	–	2.5
NGC 598	**30.62**	**23.52**	**67**	**0.86**	**0.029**	**8.5**
B2 1520+31	31.74	230.55	6	–	–	4.1
MGRO J2019+37	36.80	304.85	271	–	–	6.5
MG2 J201534+3710	37.19	303.92	260	–	–	6.3
4C+38.41	38.14	248.82	19	–	–	5.3
Mkn 421	38.21	166.12	2	–	–	5.5
Gamma Cygni	40.26	305.56	27	–	–	5.7
M31	41.42	10.82	34	–	–	6.4
B3 0609+413	**41.47**	**93.22**	**328**	**0.40**	**0.094**	**10.7**
2HWC J2031+415	41.5	307.93	229	–	–	6.4
BL Lac	42.28	330.69	12	–	–	5.8
S4 0814+42	42.38	124.56	7	–	–	6.7
MG4 J200112+4352	43.89	300.30	213	–	–	7.3

Acknowledgement

The authors of this work acknowledge the financial support of grant PRE2019-087798 funded by MCIN/AEI/10.13039/501100011033 and by ESF Investing in your future, and by grant of the Generalitat Valenciana, Pla GenT: references CIDEGENT/2018/034 & 2020/049.

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PoS(ICRC2023)1480