Neutrino rates in ANTARES from the blazar PKS 2155-304

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1 Introduction

Over the last five years, the number of blazars that have been determined to emit gamma-rays in the TeV region of the spectrum has gone from 6 to around 28 by the beginning of 2010 [1].

Out of these 23 blazars, only 7 of them are located in the southern hemisphere. One of the closest ones observed so far is PKS 2155-304, which has a z=0.116.

Its location in the southern hemisphere, together with the extreme variability of the blazar across two orders of magnitude in luminosity in gamma-rays, turns it into a potential source to be observed with the ANTARES neutrino telescope, located in the Mediterranean sea.

In order to the derive the rate of neutrino events in ANTARES from the gamma ray flux, we follow the procedure developed by Halzen and Hooper [1]

2 Estimating the neutrino flux

If we assume that the TeV gamma-rays come from the the decay of pions produced by the interaction of protons in the jet of the blazar, we can derive a flux of neutrinos associated with the gamma emission from energy conservation considerations:

[1] From http://tevcat.uchicago.edu

$$\int_{E_\gamma^{\min}}^{E_\gamma^{\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu, \tag{1}$$

where the factor K depends on whether the pions are generated on proton-proton ($K = 1$) , or in proton-photon interactions ($K = 4$). If we take as input the spectrum observed in gamma-rays by a Cherenkov telescope to be:

$$\frac{dN_\gamma}{dE_\gamma} = A_\gamma E_\gamma^{-\alpha}. \tag{2}$$

and if we assume the neutrino spectrum to follow that of the protons that have undergone Fermi acceleration (i.e. with an spectral index of 2)

$$\frac{dN_\nu}{dE_\nu} = A_\nu E_\nu^{-2}. \tag{3}$$

Then, we can relate the parameters of both spectra following the procedure explained in [1], where the normalization for the neutrino spectrum is given by:

$$A_\nu \approx \frac{A_\gamma E_{\gamma,\min}^{-\alpha+2}}{(\alpha - 2) K \ln\left(E_{\nu,\max}/E_{\nu,\min}\right)}, \tag{4}$$

Usually, the low energy limit of the neutrino spectrum will be determined by the fast decrease of effective area at low energies. For the proton-proton case, the maximum energy of neutrinos and gammas is related to the maximum energy of protons accelerated in the jet by the energy relation derived in [1], as follows:

$$E_\gamma^{\max} = \frac{E_p^{\max}}{6}, \;\; E_\nu^{\max} = \frac{E_p^{\max}}{12} \tag{5}$$

Which means that:

$$E_\gamma^{\max} \approx 2 E_\nu^{\max} \tag{6}$$

where this relation also holds for the pγ scenario. There is an extra factor of $1/3$ that goes into the normalization, that comes from the fact that we are only interested in the muon neutrino channel, and it has been assumed that the neutrinos have oscillated into equal fractions since their emission at the blazar.

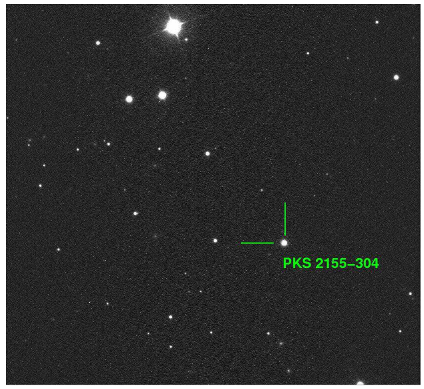

Figure 1: The blazar PKS 2155-304 as seen by ATOM, a 0.75 m optical telescope dedicated to the monitoring of TeV sources operated by the HESS collaboration.

3 The source: PKS 2155-304

The blazar PKS 2155-304 is an interesting source for both Cherenkov and neutrino telescopes. It has been routinely monitored in the TeV range by the HESS telescopes since its first detection in 2002 [6].

During this time, several periods of intense flaring activity have been observed. During the largest of this recorded flares, ocurred in 2006, the gamma-ray flux went from its quiescent value of 10-60% of the flux of the Crab nebula [2], to 7 times the flux of the Crab [3] at energies greater than 200 GeV.

The neutrino flux will be calculated for two different regimes: the "quiescent" state, an a "flaring" state. For the quiescent state, the two parameters that characterize the gamma-ray spectrum are obtained from the global values in Table 1, available in [6], with a cutoff energy of 200 GeV.

For the "flaring" state, we'll use the spectrum reported by the HESS collaboration [3], which was fitted with a broken power-law function:

$$E < E_{\rm B} : \frac{\rm dN}{\rm dE} = I_\circ \left(\frac{E}{1\,\rm TeV}\right)^{-\Gamma_1} \tag{7}$$

$$E > E_{\rm B} : \frac{\rm dN}{\rm dE} = I_\circ \left(\frac{E_{\rm B}}{1\,\rm TeV}\right)^{(\Gamma_2-\Gamma_1)} \left(\frac{E}{1\,\rm TeV}\right)^{-\Gamma_2} \tag{8}$$

where $I_\circ = (2.06 \pm 0.16 \pm 0.41) \times 10^{-10}$ cm^{-2} s^{-1} TeV^{-1}, $E_{\rm B} = 430 \pm 22 \pm 80$ GeV, $\Gamma_1 = 2.71 \pm 0.06 \pm 0.10$, and $\Gamma_2 = 3.53 \pm 0.05 \pm 0.10$. In this case, we're in-

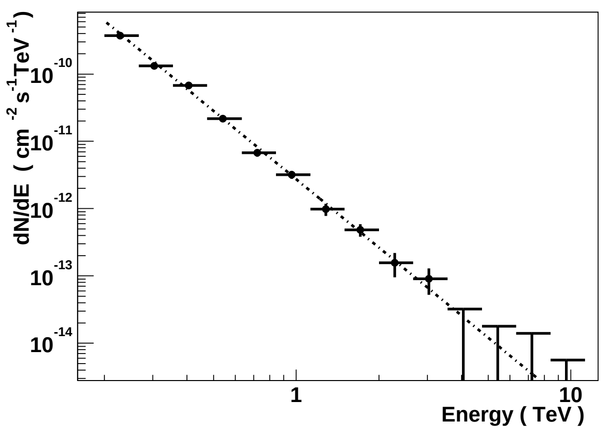

Figure 2: Time averaged spectrum derived from the October and November 2003 H.E.S.S. data along with a fit to a power law.

terested in the higher energy part of the spectrum (i.e. above the break) so we can use the break as a cutoff at 430 GeV.

4 The ANTARES neutrino telescope

The ANTARES neutrino telescope consists on an array of twelve 350m-long vertical strings, each one equipped with 75 optical modules. These strings have been deployed at depths of about 2.5 km in the Mediterranean Sea off the coast of Toulon, France.

The first string was deployed in February 2006, and the installation was completed on May 2008. The telescope has been running in its complete configuration since then.

To calculate the rate of neutrinos from an specific source, we are interested in the effective area of the telescope for the detection of muon neutrinos. This value is obtained from the plot in Fig. 3, which gives the effective are as a function of the sine of the declination for different spectral indices. The effective area has been already convoluted with spectra of the indicated index, so the area will enter the calculation of the rate just as a multiplicative factor.

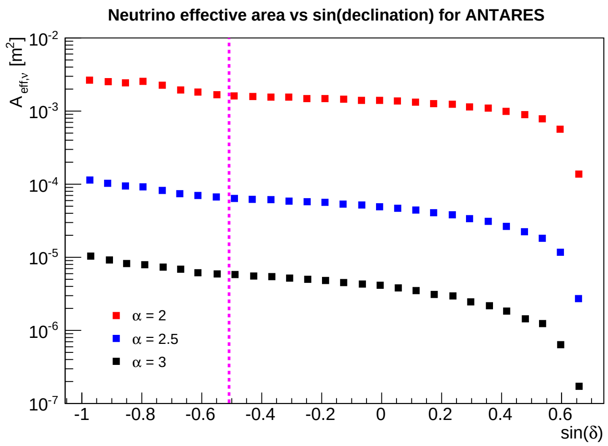

Figure 3: The effective area of ANTARES as a function of sin(declination) for different spectral indices of the muon neutrino spectrum.

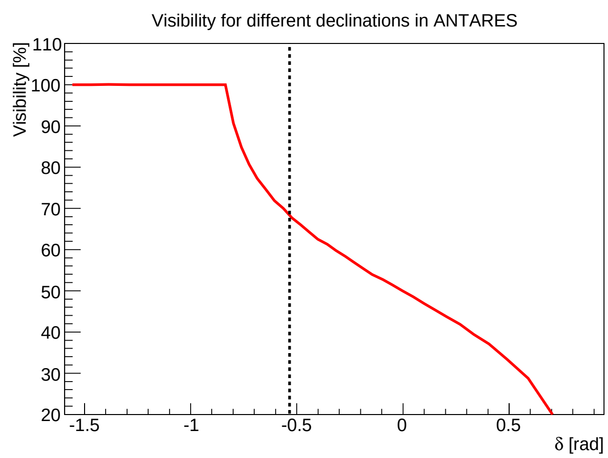

Figure 4: The visibility for different sources as a function of their declination for the ANTARES telescope. The dashed line at a declination of -30.4° indicates a visibility of ∼68% for PKS 2155-304

Dark period	Signif. $[\sigma]$	Avg flux A_γ $[10^{-12}cm^{-2}s^{-1}TeV^{-1}]$	Photon index α_γ
July 2002	13	15.6 $\pm$ 2.1	2.84 $\pm$ 0.24
Oct 2002	8.2	6.36 $\pm$ 1.75	3.10 $\pm$ 0.46
June 2003	21.1	2.42 $\pm$ 0.28	3.56 $\pm$ 0.17
July 2003	22.1	1.75 $\pm$ 0.18	3.26 $\pm$ 0.11
Aug 2003	27.7	1.84 $\pm$ 0.18	3.36 $\pm$ 0.09
Sept 2003	14.7	2.40 $\pm$ 0.41	3.42 $\pm$ 0.15
Oct-Nov 2003	34.3	2.73 $\pm$ 0.17	3.37 $\pm$ 0.07
July-Sept 2004	95.6	2.17 $\pm$ 0.08	3.58 $\pm$ 0.04
Global (median)		*2.41*	*3.37*

Table 1: Values of the average flux and the spectral index for the blazar over a time period of the order of one year, as reported by the HESS collaboration. The global values will be used in the calculation of neutrino rates when the source is in its quiescent state.

5 Event rate in ANTARES

5.1 Quiescent state

For the quiescent state, we have a $A_\gamma = 2.41\ 10^{-12}\ cm^{-2}\ s^{-1}\ TeV^{-1}$ and a spectral index of $\alpha_\gamma = 3.37$. For the spectral index of the neutrino spectrum (γ_ν), we obtain from the plot in Fig. 3 a small effective area of $A_{\rm eff} \approx 15cm^2$. The visibility η for the blazar, from Fig. 4, is $\sim 68\%$.

The normalization of the neutrino flux is obtained from Eq. 4, that can be rewritten as

$$A_\nu \approx \frac{A_\gamma E_{\gamma,\rm min}^{-\alpha+2}}{3(\alpha-2)K \ln \frac{E_{\gamma,\rm max}}{E_{\gamma,\rm min}}} \tag{9}$$

As we have mentioned, $A_\gamma = 2.41\ 10^{-12}\ \rm cm^{-2}s^{-1}\ TeV^{-1}$, $E_{\gamma,\rm min} = 0.2$ (normalized to TeV), $\alpha = 3.37$, $K = 1$ (pp interactions), and for a maximum energy $E_{\gamma,\rm max} = 10\ \rm TeV$. This yields a normalization of $A_\nu = 1.36\ 10^{-12}\ \rm cm^{-2}\ s^{-1}\ TeV^{-1}$.

The rate of events can be then calculated using:

$$\frac{dN_\nu}{dt} = \eta\ A_{eff}\ A_\nu \int_{E_{\nu,min}}^{E_{\nu,max}} \frac{dN_\nu}{dE_\nu} dE_\nu \tag{10}$$

$$= \eta\ A_{eff}\ A_\nu \left(\frac{1}{E_{\nu,min}} - \frac{1}{E_{\nu,max}} \right) = 6.80\ 10^{-11}\ \mathrm{s}^{-1} \tag{11}$$

Which means that such signal is practically undetectable.

5.2 Flaring state

Given the low rate of events calculated for the blazar in its quiescent state, there's still a possibility for a detection using a time-dependent search for events when the blazar is bursting in gamma-rays. For the flaring case, we use a gamma-ray spectrum with parameters given in Eq. 3, with a cutfoff of 0.43 TeV, and $A_\gamma = 1.03\ 10^{-10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ \mathrm{TeV}^{-1}$. We use the same value for the effective area as in the previous case of $A_{\mathrm{eff}} = 15\ \mathrm{cm}^2$. In this case, the spectral index is $\alpha_\gamma = 3.53$.

For these parameters, the normalization constant for the neutrino spectrum is $A_\nu = 2.59\ 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{TeV}^{-1}$, which also gives a low event rate of $1.29\ 10^{-9}\ \mathrm{s}^{-1}$ (roughly 1 event every 24 years).

6 Conclusions

Neutrino event rates associated with the blazar PKS 2155-304 have been calculated for the ANTARES neutrino telescope. The calculated rate is $6.80\ 10^{-11}\ \mathrm{s}^{-1}$ for the blazar in its quiescent state, and $1.29\ 10^{-9}\ \mathrm{s}^{-1}$ under intense flaring activity.

In order to derive this rates, we used spectra of the blazar in TeV gamma-rays as reported by the HESS collaboration.

The extremely low rates indicate the unlikeliness of the observation of neutrinos from this blazar during the normal operational life of ANTARES.

References

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