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Constraining the Possible Neutrino Spectra of High-Fluence Blazars with ANTARES

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The IceCube collaboration has detected an extraterrestrial neutrino flux with the most significant signal in the southern sky at PeV energies. In spite of its smaller volume, the ANTARES telescope provides comparable sensitivity and superior angular resolution at the given southern declinations and energies below ~ 100 TeV and is thus the ideal instrument to constrain the neutrino spectrum of candidate sources. We report on an analysis of the spectral energy distributions of a sample of blazars in positional agreement with PeV neutrinos detected by IceCube. Within the framework of the TANAMI program, we showed that the integrated calorimetric output of these blazars is high enough to explain a neutrino fluence in agreement with the observed IceCube events. For the two blazars with the highest predicted neutrino fluence in the fields of the IC 14 and IC 20 PeV neutrino events, Swift J1656.3$-$3302 and TXS 1714$-$336, ANTARES detects two signal-like TeV neutrino events, in agreement both with the blazar-origin hypothesis and with an atmospheric origin. In the absence of any signal-like neutrino events, ANTARES constrains the possible neutrino spectra of four other candidate sources to spectral indices flatter than -2.4. The 2 PeV neutrino event IC 35 is in positional agreement with the TANAMI blazar PKS B1424$-$418, which has shown a dramatic outburst over several months around the time of the neutrino event detection. It dominated the γ-ray output in this field and provided a fluence high enough to explain the observed event. A preliminary 406-day ANTARES point-source analysis around the event-detection time does not find any excess signal at the position of PKS B1424$-$418, excluding the possibility of a very steep neutrino spectrum associated with the blazar outburst.

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1. Introduction

It has long been suggested that blazars, i.e active galactic nuclei (AGN) with jets pointed at small angles to the line of sight, yield a cumulative flux of high-energy neutrinos in excess of the atmospheric background at high energies[17, 18]. These models have been motivated by the need to explain the observed variable γ-ray spectra of blazars and assume that both the neutrinos and the γ-ray photons are produced by accelerated protons in a relativistic jet, which interact with optical/UV photons to produce pions [16]. The dense UV photon fields associated with accretion disks in flat-spectrum radio quasars (FSRQs) are attractive candidate seed-photon sources for this process. The decaying pions cascade down in energy and produce γ-rays and neutrinos. While alternative scenarios involving purely leptonic processes can in general also explain most observed broadband spectral energy distributions (SEDs) in blazars, the discovery of extraterrestrial very-high energy neutrinos by the IceCube collaboration [1, 11] has stirred new interest in hadronic blazar emission models.

While there is a clear statistical excess over the expected atmospheric background, it is generally not possible to tell, which individual events are of real extraterrestrial origin. Because of the steep spectrum of the atmospheric neutrinos, they cannot contribute to the set of events observed at PeV energies. Thus, the three events IC 14, IC 20, and IC 35 provide the best opportunity to search for astrophysical sources of the IceCube signal. Unfortunately, the positional information of these three events is rather poor – 13.2°, 10.7°, and 15.9°, respectively. The IceCube team has published this information in terms of the median angular errors R_{50}, i.e., for each event there is a 50 % probability to find the real astrophysical source inside the angular radius given by R_{50}. The blazar sources inside the R_{50} radii of IceCube events have been listed and discussed based on the all-sky γ-ray information provided by the *Fermi Gamma-Ray Observatory* with its Large Area Telescope (LAT; [7]). Most of these studies (e.g., [20, 14, 9]) so far were based on the 2-year *Fermi*/LAT catalogs of γ-ray point sources (2FGL; [21]) and active galactic nuclei (2LAC; [2]).

Based on multiwavelength data collected within the framework of the TANAMI program [12, 13], it was shown by Krauß et al. [14] that the six radio- and γ-ray brightest AGN in the R_{50} fields of IC 14 and IC 20 have a high enough integrated flux to account for these two observed PeV events via photopion production from UV blue-bump photons. A direct association of a PeV-neutrino with an individual γ-ray blazar would have the important implication that a sizeable fraction of the observed γ-rays is due to hadronic decays and that the jets are sources of the observed ultrahigh-energy cosmic rays [10]. In the TANAMI study of the IC 14 and IC 20 R_{50} fields, no individual source could be found whose maximum possible neutrino output is high enough to make an individual association. Especially in the case of IC 20, the Poisson probabilities for a neutrino detection from an individual blazar in the R_{50} field are low and it is likely that a substantial contribution of faint unresolved blazars from the diffuse extragalactic γ-ray background has to be considered (cf. [15]).

2. ANTARES study of IC 14 and IC 20 candidate blazars

The most promising candidate blazars in the TANAMI study were found in the R_{50} field of IC 14. The sources Swift J1656.3−3302 (1653−329) and PMN J1717−3342 (1714−336) showed the highest integrated γ-ray flux of $F_{1\,\mathrm{keV}-5\,\mathrm{GeV}} = 4.5^{+0.5}_{-0.5} \cdot 10^{-10}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ and $F_{1\,\mathrm{keV}-5\,\mathrm{GeV}} =$

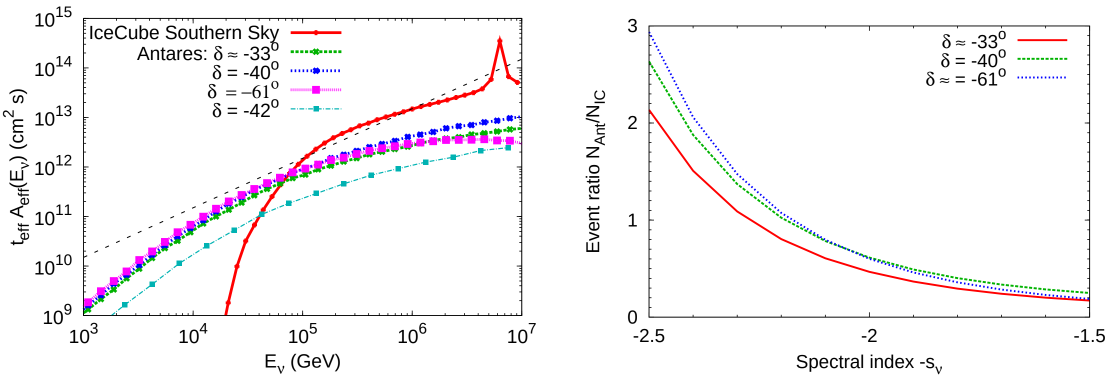

Figure 1: Left: Exposures (effective area times integration time) for the recently published ANTARES 1338-day analysis [3] of the six blazars in the IC 14 and IC 20 fields and the preliminary 406-day analysis of PKS B1424−418 reported here. The red line shows the exposure for the recent IceCube analysis [11, 8] and the black dashed line indicates an exposure proportional to E_ν for comparison. Right: Expected number of ANTARES events per detected IceCube event as a function of the neutrino spectral index $-s_\nu$ (defined via $\Phi_\nu \propto E_\nu^{-s_\nu}$). Adapted from [6].

$2.4^{+0.5}_{-0.6} \cdot 10^{-10}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, respectively. In 662 days of IceCube observations, this yielded predicted maximum possible neutrino values of $0.86^{+0.10}_{-0.10}$ and $0.46^{+0.10}_{-0.12}$ events, respectively. If all of their observed γ-ray emission would originate from high-energy protons interacting with UV disk photons, the Poisson probabilities for the detection of one or more additional 1 PeV neutrinos in the third year of the IceCube analysis would be 48 %. The non-detection of additional events and the non-detection of PeV events from most other sources of comparable or higher γ-ray fluence strongly suggests that a substantial scaling factor has to be applied, accounting for other (non-hadronic) components in the γ-ray emission or a wider distribution of the output neutrino energies (e.g., if accretion tori with virial temperatures of $\sim 10^9$ K are assumed rather than optically thick accretion disks or if proton-proton collisions dominate over photo-pion production). Distributing the neutrinos of these southern-hemisphere sources over a broader range of energies increases their detection potential for the ANTARES telescope [5], which is optimized to detect neutrinos below ~ 100 TeV from the southern sky (see Fig. 1).

We therefore conducted a standard ANTARES candidate list search (CLS) analysis as described in [3] to constrain the neutrino emission of the TANAMI candidate blazars in the IC 14 and IC 20 R_{50} fields. The results are reported in a joint paper of the ANTARES & TANAMI Collaborations [6] and summarized here. We used six years of data (1338 days effective livetime; 5516 events, cf. [4]) and considered only upgoing muons (i.e., those originating from below the horizon). About 10 % of the events in the CLS analysis are expected to be due to atmospheric muons, the rest being due to atmospheric and extraterrestrial neutrinos. As can be seen from Fig. 1, the predicted number of neutrinos for the six TANAMI candidate blazars in the IC 14 and IC 20 R_{50} fields depend strongly on the neutrino spectrum. For steep spectra ($-s_\nu < -2.5$), one would expect more than 2 events from each individual blazar. For flat spectra in the range of $-s_\nu > -2$, the expectation values fall below 0.6 even for the southernmost sources.

For all three blazars in the IC 14 field, the maximum-likelihood fitting method did not associate any neutrino event with the sources. This puts strong limits on their flux: e.g., for an assumed E_ν^{-2} neutrino spectrum, the flux at 1 GeV is constrained to $< 1.3 \cdot 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ at 90 % confidence. From the non-detection of any of these blazars with ANTARES, we can constrain the minimum allowed spectral index to be $-s_\nu > -2.4$. In other words, if IC 20 does originate from the brightest blazars in this field, their neutrino spectral index must be flatter than -2.4. Similar constraints can be derived for the blazar PMN J1802−3940 (1759−396) in the IC 14 field (see Fig. 2).

Approximately one ANTARES neutrino event[1] was associated with each of the two blazars with the highest predicted PeV neutrino output in the TANAMI study [14], 1653−329 and 1714−336. This result is fully compatible with the hypothesis that one of these sources was responsible for the IceCube PeV neutrino IC 14 for the full range of spectral indices considered (e.g., for a flat spectrum with $s_\nu = -2$, the Poisson probabilities for a detection of one event is of the order of 40 %). However, it is also still fully compatible with the background hypothesis.

3. A high-fluence blazar in the IC 35 field

Recently, the IceCube collaboration released results from a third year of observations, including a third neutrino event at PeV energies (~ 2 PeV; [8]) and with the coordinates $R.A. = 208.4^\circ$, $Dec = -55.8^\circ$ and a median angular error of $R_{50} = 15.9^\circ$. In this larger field and given the higher neutrino energy and longer IceCube integration time of 988 days, the methods outlined in the Krauß et al. study of the IC 14 and IC 20 R_{50} fields lead to higher integrated γ-ray fluxes of the blazars inside the R_{50} field. A detailed multiwavelength study of the field (Kadler et al., in prep.) shows that the maximum neutrino output in the blazar scenario is of the order of 15. In fact, the detection of only 1 such event (and the detection of zero events in the first two years in this field) constrains the scaling factor to be likely well below 0.2. The unique new aspect of IC 35 is that a major outburst of a single source, the blazar PKS B1424−418, occurred inside the R_{50} field[2] and dominated the predicted integrated neutrino flux of the field between mid July 2012 through the end of the IceCube data analysis period in April 2013. During the 9-month period of this outburst and around the time of the IC 35 neutrino event, the Poisson probability to detect a neutrino from PKS B1424−418 was about three times higher than the corresponding probability to detect an event from the integrated emission of all other known γ-ray blazars in the field. PKS B1424−418 is the only known source found inside any of the reported PeV IceCube event R_{50} fields so far, whose energy output of PKS B1424−418 has risen high enough to solely explain the observed PeV event, even if a substantial scaling factor is assumed. High-fluence outbursts of this magnitude are extremely rare and have been observed at GeV γ-ray energies by *Fermi*/LAT only eight times over the whole sky in six years of operation. The Poisson probability for a chance coincidence with one of the three observed PeV neutrino events can be estimated to be about 5%. In addition to IC 35, PKS B1424−418 is positionally consistent within $2 \times R_{50}$ with two additional IceCube neutrino events: IC 16 ($30.6^{+3.6}_{-3.5}$ TeV at an offset of $1.5R_{50}$) and IC 25 ($33.5^{+4.9}_{-5.0}$ TeV, $1.4R_{50}$). Thus, while

[1] The maximum-likelihood procedure estimates a continuous variable, as discussed in [6].

[2] See [19]; cf. `http://fermi.gsfc.nasa.gov/FTP/glast/data/lat/catalogs/asp/current/lightcurves/PKS1424-41_604800.png`

the Krauß et al. [14] model predicts peaked neutrino spectra at PeV energies, the data are consistent with a rather broad and steep neutrino spectrum.

4. ANTARES constrains the possible neutrino spectra of PKS B1424−418

As for the blazars in the first two IceCube PeV neutrino R_{50} fields, we again applied a standard ANTARES CLS [3] analysis as described above to constrain the neutrino spectrum of the FSRQ PKS B1424−418. This analysis is only sensitive to muon neutrinos and has been optimised for an E^{-2} neutrino source spectrum. The median angular resolution has been estimated to 0.4° and the fraction of misreconstructed atmospheric muons in the selected neutrino candidate sample has been evaluated to about 10%. We have analyzed ANTARES data taken in the time range from July 12, 2012, when the γ-ray light curve indicates the begin of the blazar high-state through the end of 2013[3]. The effective livetime of this analysis was 406 days which yielded more than 1000 neutrino candidates and we therefore expect about 3 events within a 5-degree radius around the source position for a random background distribution of events following the declination dependent sky visibility of the detector. Our preliminary analysis found only one event in this field at about 4 degrees distance from PKS B1424−418 and with a low number of hits, which is thus very likely a background event. Consequently we derive a preliminary 90 % confidence upper limit of $E^{-2}\Phi = 4.2 \cdot 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ on the neutrino flux of PKS B1424−418 during this time range.

This situation is very similar to the case of 1759−396 in the IC 14 R_{50} field. The fact that ANTARES did not find any event close to the position of this source did allow us to constrain its possible neutrino spectra for different assumed numbers of associated IceCube events [6]. From the measured ANTARES flux limit, we can exclude the possibility that PKS B1424−418 was responsible for a large number of IceCube neutrinos over a wide range of realistic neutrino spectra. Under the hypothesis that PKS B1424−418 was the source of event IC 35 only, the final analysis will constrain its neutrino spectrum in a similar way as it was possible for 1759−396.

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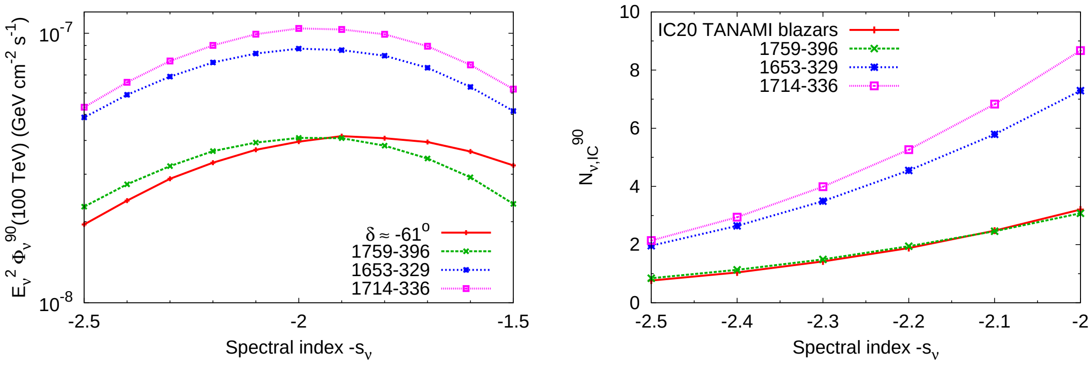

Figure 2: Left: ANTARES 90% confidence limits on a flavour-uniform neutrino flux ($\Phi_\nu \equiv \Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau} = 3\Phi_{\nu_\mu}$) from the six blazars in the IC 14 and IC 21 R_{50} fields[6] as a function of spectral index s_ν. Right: 90 % confidence limits on the expected number of IceCube events using the exposures from Fig. 1 and the limiting fluxes shown in the left panel of this figure. Taken from [6].

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