Astroparticle Physics 61 (2015) 12–16

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Searching for tau neutrinos with Cherenkov telescopes

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ARTICLE INFO

Article history:
Received 6 March 2014
Received in revised form 13 June 2014
Accepted 16 June 2014
Available online 23 June 2014

Keywords:
Cherenkov telescopes
Tau neutrinos
Extensive air showers

ABSTRACT

Cherenkov telescopes have the capability of detecting high energy tau neutrinos in the energy range of 1–1000 PeV by searching for very inclined showers. If a tau lepton, produced by a tau neutrino, escapes from the Earth or a mountain, it will decay and initiate a shower in the air which can be detected by an air shower fluorescence or Cherenkov telescope. In this paper, we present detailed Monte Carlo simulations of corresponding event rates for the VERITAS and two proposed Cherenkov Telescope Array sites: Meteor Crater and Yavapai Ranch, which use representative AGN neutrino flux models and take into account topographic conditions of the detector sites. The calculated neutrino sensitivities depend on the observation time and the shape of the energy spectrum, but in some cases are comparable or even better than corresponding neutrino sensitivities of the IceCube detector. For VERITAS and the considered Cherenkov Telescope Array sites the expected neutrino sensitivities are up to factor 3 higher than for the MAGIC site because of the presence of surrounding mountains.

1. Introduction

Neutrinos have long been anticipated to help answering some fundamental questions in astrophysics like the mystery of the source of the cosmic rays (for a general discussion see [1]). For neutrinos in the TeV range, prime source candidates are Galactic supernova remnants [2]. Neutrinos in the PeV range and above are suspected to be produced by Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB) with many AGN models predicting a significant neutrino flux [3–5]. Recently, the IceCube Collaboration has reported the very first observation of a cosmic diffuse neutrino flux which lies in the 100 TeV to PeV range [6]. Individual sources, however, could not be identified up to now. While many astrophysical sources of origin have been suggested [7], there is yet not enough information to narrow down the possibilities to any particular source.

Due to the low interaction probability of neutrinos, a large amount of matter is needed in order to detect them. One of the detection techniques is based on the observation of inclined extensive air showers (EAS) induced by taus from tau neutrino interactions deep in the atmosphere. As these showers are initiated close to the surface of the Earth, they are still very young when reaching the detector and hence have a significant electromagnetic component leading to a broad time structure of the detected signal. In contrast, showers from cosmic-ray nuclei are induced in the upper atmosphere and therefore have a strongly reduced electromagnetic component when reaching the detector. However, because of its low density, neutrino interactions are not very likely to happen inside the atmosphere. A solution to this problem is to look for so-called Earth skimming (up-going) tau neutrinos [8–14] which interact within the Earth or a mountain and produce a tau. For neutrino energies of about a EeV, the charged leptons have a range of a few kilometers and hence may emerge from the Earth or mountain, decay shortly above the ground and produce EAS detectable by a surface detector. In some cases, two consecutive EASs might be observable, one coming from a tau neutrino interaction close to the surface and one from the decay of the resulting tau lepton. These two showers, coming from the same direction in a time interval corresponding to the tau decay time, can generate a unique signature in the detector called a Double-Bang event [15]. The detection of such a Double-Bang event would be very important both from the astrophysical and the particle physics point of view, as it would be an unambiguous sign for an ultra-high energy (UHE) tau-neutrino. Up to now, there has been no clear identification of tau neutrinos at high energies.

The detection of PeV tau neutrinos through optical signals also seems possible. A combination of fluorescence and Cherenkov light detectors in the shadow of steep cliffs could achieve this goal [8,9,16]. Recently, it has also been shown by the All-sky Survey High Resolution Air-shower detector (Ashra) experiment, that such

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http://dx.doi.org/10.1016/j.astropartphys.2014.06.005
0927-6505/

kind of experiments could be sensitive to tau neutrinos from fast transient objects such as nearby GRBs [17].We note, that the recent IceCube results do not show any neutrino events at or above the Glashow resonance at 6.3 PeV [6]. This likely means that there is either a cutoff in the astrophysical neutrino flux below ~ 6 PeV or the neutrino spectrum is steeper than the usually assumed E^{-2} spectrum.

In principle also existing Imaging Air Cherenkov Telescopes (IACTs) such as MAGIC [18], VERITAS [19] and H.E.S.S. [20] have the capability to detect PeV tau neutrinos by searching for very inclined showers [21]. In order to do that, the Cherenkov telescopes need to be pointed in the direction of the taus escaping from the Earth crust, i.e. at or a few degree below the horizon. This is because the trajectory of the tau lepton has to be parallel to the pointing direction of the telescope within a few degrees as the Cherenkov light is very much beamed in the forward direction. For example, the MAGIC telescope is placed on top of a mountain on La Palma at an altitude of about 2200 m a.s.l. Thus, it can look down to the Sea and monitor a large volume within its field of view (FOV). In [22], the effective area for up-going tau neutrino observations with the MAGIC telescope was calculated analytically with the maximum sensitivity in the range from 100 TeV to $\sim$1 EeV. However, the calculated sensitivity for diffuse neutrinos was very low because of the limited FOV, the short observation time and the low expected neutrino flux.

On the other hand, if flaring or disrupting point sources such as GRBs are observed, one can expect an observable number of events even from a single GRB if close by. In the case of MAGIC, however, the topographic conditions allow only for a small window of about 1° width in zenith and azimuth to point the telescope downhill. In case of other IACT sites with different topographic conditions, the acceptance for up-going tau neutrinos will be increased by the presence of mountains. Mountains can work as an additional target and will lead to an enhancement in the flux of emerging tau leptons. A target mountain can also shield against cosmic rays and star light.

For Cherenkov telescope sites, very often nights with high clouds prevent the observation of gamma-ray sources. In such conditions, pointing the telescopes to the horizon could significantly increase the observation time and the acceptance for up-going tau neutrinos. Next-generation Cherenkov telescopes, i.e. the Cherenkov Telescope Array (CTA) [23], can in addition exploit their much larger FOV (in extended observation mode), a higher effective area and a lower energy threshold.

In this work, we present an update of the work in [24], where a detailed Monte Carlo simulation of event rates induced by Earth skimming tau neutrinos was performed for an ideal Cherenkov detector. Neutrino and lepton propagation was simulated taking into account the local topographic conditions at the MAGIC site and at four possible locations of Cherenkov instruments: two in Argentina (San Antonio, El Leoncito), one in Namibia (Kuibis) and one on the Canary Islands (Tenerife). In this work, similar simulations have been performed for the location of the VERITAS telescopes and for two sites located close to VERITAS: Meteor Crater and Yavapai Ranch. These two sites were recently also considered as possible locations for CTA. Results are shown for a few representative neutrino fluxes expected from giant AGN flares. We would like to stress that in this work we are exploring the effect of different topographic conditions rather than providing a comprehensive survey of potential sites.

2. Method

The propagation of a given neutrino flux through the Earth and the atmosphere is simulated using an extended version of the ANIS code [25]. For fixed neutrino energies, 10^6 events are generated on top of the atmosphere with zenith angles (θ) in the range 90–105° (up-going showers) and with azimuth angles in the range 0–360°. Neutrinos are propagated along their trajectories of length ΔL from the generation point on top of the atmosphere to the interaction volume, defined as the volume which can contribute to the expected event rate, in steps of $\Delta L/1000$ ($\Delta L/1000 \geqslant 6$ km). At each step of propagation, the ν-nucleon interaction probability is calculated according to parametrization of its cross section based on the chosen parton distribution function (PDF). In particular, the propagation of tau leptons through the Earth is simulated. All computations are done using digital elevation maps (DEM) [26] to model the surrounding mass distribution of each site under consideration. The flux of the leptons emerging from the ground as well as their energy and the decay vertex positions are calculated inside an interaction volume, modeled by a cylinder with radius of 35 km and height 10 km. The detector acceptance for an initial neutrino energy E_{ν_τ} is given by:

$$A(E_{\nu_\tau}) = N_{\mathrm{gen}}^{-1} \times \sum_{i=1}^{N_k} P_i(E_{\nu_\tau}, E_\tau, \theta) \times T_{\mathrm{eff},i}(E_\tau, x, y, h, \theta) \times A_i(\theta) \times \Delta\Omega, \tag{1}$$

where N_{gen} is the number of generated neutrino events. N_k is the number of τ leptons with energies E_τ larger than the threshold energy $E_{\mathrm{th}} = 1$ PeV and a decay vertex position inside the interaction volume. $P(E_{\nu_\tau}, E_\tau, \theta)$ is the probability that a neutrino with energy E_{ν_τ} and zenith angle θ produces a lepton with energy E_τ (this probability was used as “weight” of the event). $A_i(\theta)$ is the physical cross-section of the interaction volume seen by the neutrino and $\Delta\Omega$ is the solid angle. $T_{\mathrm{eff}}(E_\tau, x, y, h, \theta)$ is the trigger efficiency for tau-lepton induced showers with the decay vertex position at (x, y) and height h above the ground. The trigger efficiency depends on the response of a given detector and is usually estimated based on Monte-Carlo simulations. In this work, we used an average trigger efficiency extracted from [17], namely $\langle T_{\mathrm{eff}} \rangle = 10\%$, which is comparable to what was calculated for up-going tau neutrino showers studied in [16]. This is a qualitative estimation and as such it is the major source of uncertainty on the results presented hereafter. Eq. (1) gives the acceptance for diffuse neutrinos. The acceptance for a point source can be estimated as the ratio between the diffuse acceptance, defined in Eq. (1), and the solid angle covered by the diffuse analysis, multiplied by the fraction of time the source is visible $f_{\mathrm{vis}}(\delta_s, \phi_{\mathrm{site}})$. This fraction depends on the source

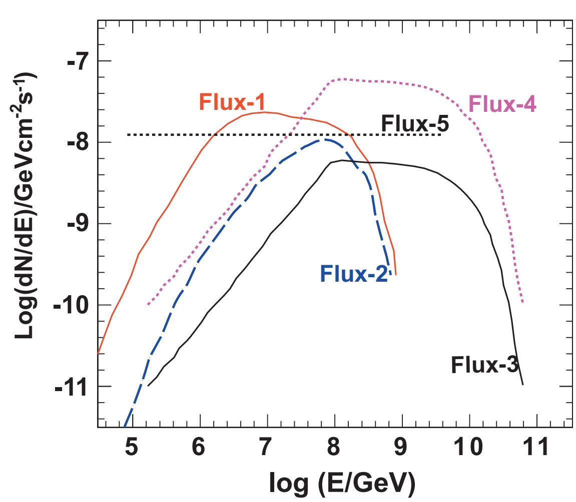

Fig. 1. A sample of representative neutrino fluxes from photo-hadronic interactions in AGNs. See text for more details. Flux-1 and Flux-2 are calculations for γ-ray flare of 3C 279 [27]. Flux-3 and Flux-4 represent predictions for PKS 2155-304 [28]. Flux-5 corresponds to a prediction for 3C 279 calculated in [29].