Abstract: Cherenkov telescopes could have the capability of detecting high energy tau neutrinos by searching for very inclined showers. If a tau lepton, produced by a tau neutrino, escapes from the Earth crust, it will decay and initiate an air shower which can be detected by a fluorescence/Cherenkov telescope. Here we present a detailed Monte Carlo simulation of event rates induced by tau neutrinos in the energy range from 1 PeV to 1 EeV. Topographic conditions are taken into account for a set of example locations. As expected, we find a neutrino sensitivity which depends on the shape of the energy spectrum from astrophysical sources. We compare our findings with the sensitivity of the dedicated IceCube neutrino telescope under different conditions. We also find that a difference of several factors can be observed depending on the topographic conditions of the sites sampled.

Keywords: Cherenkov telescopes, Tau Neutrinos.

1 Introduction

Many models which try to explain the origin of the ultra high energy cosmic rays (UHECR) claim that their might be produced by Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB). Most of these models also predict a significant flux of high energy neutrinos from decay of charged pions. The chance of discovering extraterrestrial signals (neutrinos) from these objects largely varies with source classes and model predictions. For what concerns Blazars for example [1] Flat Spectrum Radio Quasars (FSRQ) are more promising, than BL-Lac objects, whereas in [2] the opposite is predicted. The proton blazar model [3] predicts that the Low synchrotron peaked BL-Lacs (LBL) are more likely to produce a significant neutrino emission than the High synchrotron peaked BL-Lacs (HBL). On the other hand in [1] the considered p-γ model leads to the conclusion that FSRQs bright in the GeV range are promising neutrino sources without any assumption on the spectral index.

From this point of view, detection of individual flares from AGNs, on the time scale of days or weeks can be more or less feasible for cubic-km scale neutrino telescopes like IceCube, based on different predictions for the mechanism yielding the observed electromagnetic emission at high energies.

The highest energy neutrinos are expected to be born as muon and electron neutrinos, but due to vacuum oscillations a flux of high energy cosmic neutrinos at Earth is expected to be almost equally distributed among the three neutrino flavors. Due to their low interaction probability, neutrinos need to interact with a large amount of matter in order to be possibly detected. The atmosphere and the Earth offer such a target. Since the Earth is not transparent for neutrinos at the highest energies, one of the detection techniques is based on the development of extensive air showers (EAS) in the atmosphere. In air, very inclined EAS can be detected only by instruments observing a large volume. Propagating through the Earth only the so-called Earth skimming tau neutrinos may initiate detectable air showers above the ground. A successful detection of such showers requires a ground array detector having a large acceptance, of the order of one km$^2$ and a great sensitivity to horizontal showers such as the Pierre Auger Observatory, which is sensitive to tau neutrinos in the EeV energy range [4]. However, the detection of PeV tau neutrinos (expected to be produced by AGNs and GRBs) through optical signals would also seem to be possible. A combination of fluorescence light and Cherenkov light detector in the shadow of steep cliff could achieve this goal [5]. Recently, it was also shown, that such kind of experiments could be sensitive to tau neutrinos from fast transient objects like nearby GRBs [6].

In this work we investigate the detection of high energy tau neutrinos in the energy range from PeVs to EeVs by searching for very inclined showers using Cherenkov telescopes. We have performed detailed Monte Carlo (MC) simulations of expected tau neutrino event rates, including local topographic conditions, for La Palma, i.e. the location of the MAGIC telescopes [7] and sample selection of few sites proposed for the Cherenkov Telescope Array (CTA) [8]. Results are shown for a few representative neutrino fluxes expected for giant flares from AGNs.

2 Method

The propagation of a given neutrino flux through the Earth and the atmosphere is simulated using an extended version of the code ANIS [9].

For fixed neutrino energies, $10^6$ events are generated on top of the atmosphere with zenith angles ($\theta$) in the range $90^\circ$–$105^\circ$ (up-going showers) and with azimuth angles in the range $0^\circ$–$360^\circ$. Neutrinos are propagated along their trajectories of length $\Delta L$ from the generation point on top of the atmosphere to the backside of the detector in steps of $\Delta L/1000$ ($\geq 6$ km). At each step of propagation, the $\nu$–nucleon interaction probability is calculated according to different 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 with different energy loss models. All the computations are done using digital elevation maps (DEM) [10] to model the surrounding mass distribution of each consid-
Figure 1: (Left panel) Expected event rate as a function of azimuth and zenith in the case of tau leptons with energies between $10^{16}$ eV and $10^{17}$ eV; (Right panel) Topography of the La Palma Island according to CGIAR-CSI data. The center of the maps corresponds to the position of the MAGIC telescopes (latitude $\phi_{\text{MAGIC}} = 28^\circ 45' 34''$ N, longitude $\lambda_{\text{MAGIC}} = 17^\circ 53' 26''$ W, height 2200 m a.s.l.).

where the flux of the outgoing leptons as well as their energy and the decay vertex positions are calculated inside a defined detector volume (set to $35 \times 10^3$ km$^3$). The acceptance for a given initial neutrino energy $E_{\nu}$ is given by:

$$A(E_{\nu}) = N_{\text{gen}}^{-1} \times \sum_{i=1}^{N_t} P(E_{\nu}, E_{\tau}, \theta) \times T_{\text{eff}}(E_{\tau}, x, y, h, \delta, \phi_{\text{site}}) \times A_s(\theta) \times \Delta \Omega,$$

where $N_{\text{gen}}$ is the number of generated neutrino events and $N_t$ is the number of $\tau$ leptons with energy $E_{\tau}$ larger than the threshold $E_{\text{th}} > 1$ PeV and decay vertex position inside the detector volume. $P(E_{\nu}, E_{\tau}, \theta)$ is the probability that a neutrino with energy $E_{\nu}$ and crossing the distance $\Delta l$ would produce a particle with an energy $E_{\tau}$ (this probability was used as “weight” of the event), $A_s(\theta)$ is the cross-sectional area of the detector volume seen by the neutrino, $\Delta \Omega$ is the solid angle. The $T_{\text{eff}}(E_{\tau}, x, y, h, \delta, \phi_{\text{site}})$ is the trigger efficiency for tau lepton induced showers with first interaction position $(x, y)$ and height $(h)$ above the ground. The trigger efficiency depends on the response of a given detector, and is usually estimated based on MC simulations. In this work we used an average trigger efficiency extracted from [6], namely $\langle T_{\text{eff}} \rangle = 10\%$, which is comparable with what calculated for up-going tau neutrino showers studied in [5]. This is a qualitative estimation and as such it is the major source of uncertainties on the results presented hereafter.

Eq. (1) gives the acceptance for diffuse neutrinos. The acceptance for a given point source could be estimated as the ratio between the diffuse acceptance and the solid angle covered by the diffuse analysis, multiplied by the fraction of time the source is visible $f_{\text{vis}}(\delta, \phi_{\text{site}})$ with the aperture defined in the beginning. This fraction depends on source declination ($\delta$) and the latitude of the observing site ($\phi_{\text{site}}$). In this work the point source acceptance is calculated as: $A^{PS}(E_{\nu}) \approx A(E_{\nu}) \times f_{\text{vis}}(\delta, \phi_{\text{site}})$. In Figure 2, a compilation of fluxes expected from AGN flares are shown. Flux-1 and Flux-2 are calculations for the February 23, 2006 $\gamma$-ray flare of 3C 279 [11]. Flux-3 and Flux 4 predictions for PKS 2155-304 in low-state and high-state, respectively [12]. Flux-5 corresponds to a prediction for 3C 279 calculated in [13]. The flux labeled as GRB corresponds to the recent limit on the neutrino emission from GRBs reported by the IceCube Collaboration [14].

The total observable rates (number of expected events) were calculated as $N = \Delta T \times \int_{E_{\text{th}}}^{E_{\text{max}}} A^{PS}(E_{\nu}) \times \Phi(E_{\nu}) \times dE_{\nu}$, where $\Phi(E_{\nu})$ is the neutrino flux and $\Delta T$ an arbitrary observation time (3 hours in Table 1).

3 Results

Figure 1 shows the expected rate for a detector located at the La Palma site (with an average trigger efficiency of 10%) as a function of the incoming neutrino direction (defined by the zenith and azimuth angles). Correlations can

Figure 2: A sample of representative neutrino fluxes from photo-hadronic interactions in AGNs. See text for more details.
Table 1: Expected event rate, $N_{\text{LaPalma}}$ for a detector located at the La Palma Roque with a trigger efficiency of 10%, compared with what expected for IceCube (with realistic efficiency). The values are calculated with ALLM [16] tau energy loss model and GRV98lo [18] cross-section, with $f_{\text{vis}} = 100\%$, $\Delta \Omega = 2\pi (\cos(90^\circ) - \cos(105^\circ)) = 1.6262$ and $\Delta T = 3$ hours. The rate are calculated with the point source acceptances shown in Figure 3.

<table>
<thead>
<tr>
<th>Flux</th>
<th>Flux-1</th>
<th>Flux-2</th>
<th>Flux-3</th>
<th>Flux-4</th>
<th>Flux-5</th>
<th>GRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{LaPalma}}$</td>
<td>0.00028</td>
<td>0.00015</td>
<td>8.6 x 10^{-5}</td>
<td>0.00086</td>
<td>0.00026</td>
<td>5.0 x 10^{-5}</td>
</tr>
<tr>
<td>$N_{\text{Northern Sky}}$</td>
<td>0.00068</td>
<td>0.00025</td>
<td>4.6 x 10^{-5}</td>
<td>0.00046</td>
<td>0.00088</td>
<td>4.4 x 10^{-5}</td>
</tr>
<tr>
<td>$N_{\text{IceCube}}$</td>
<td>0.00110</td>
<td>0.00032</td>
<td>7.6 x 10^{-5}</td>
<td>0.00076</td>
<td>0.00088</td>
<td>3.4 x 10^{-5}</td>
</tr>
</tbody>
</table>

Figure 3: Acceptance, $A^{\text{PS}}(E_{\nu_e})$ to earth-skimming tau neutrinos as estimated for the La Palma site and a sample selection of few CTA sites (with a trigger efficiency of 10%) and IceCube (with correct efficiency, as extracted from [15]).

be observed between the expected rate and the local topography i.e. the expected number of events from South-East is usually larger than from other directions, due to largest amount of matter encountered by incoming neutrinos when coming from the South-East direction. For tau lepton energies between 10^{16} eV and 10^{17} eV the decay length is a few kilometers, so detectable events should mainly come from local hills from La Palma Island when considering the location of MAGIC. While for tau leptons energies between 10^{18} eV and 10^{19} eV the decay length is larger than 50 km, so that the matter distribution of other Canary Islands can also slightly contribute.

In Figure 3 we show the estimated point source acceptance for the La Palma site and other possible locations as a function of the neutrino energy together with the IceCube acceptance as extracted from [15]. We stress at this point that we aim at exploring the effect of different topographic conditions rather than providing a comprehensive survey of potential sites.

The IceCube acceptance shows an increase for energies between 10^{6} GeV and 10^{9} GeV, and is on average about 2 x 10^{-3} km^{2}. A potential detector located in La Palma with an average trigger efficiency of 10% can have an acceptance as large as a factor 5 greater than IceCube (Northern Sky) at energies larger than ~5 x 10^{7} GeV. Indeed, for neutrino fluxes covering the energy range below ~5 x 10^{7} GeV (Flux-1, Flux-2, Flux-5 and GRB) the number of expected events is smaller than what estimated for IceCube assuming 3 hours of observation time. However, even in this energy range (see Table 1) similar rates can be obtained with a trigger efficiency increased by a factor 2-3 compared to the rough estimate of 10%. For Flux-3 and Flux-4 the event rate is about a factor 2 larger than the realistic rate calculated for IceCube (Northern Sky). This indicates that Cherenkov telescopes could have a sensitivity comparable or even larger to neutrino telescopes such as IceCube in case of short neutrino flares (i.e. with a duration of about a few hours). For larger durations the advantage of neutrino telescopes as full sky no dead-time instruments will be relevant. An accurate simulation of the neutrino trigger efficiency for realistic Cherenkov telescopes is however needed. Table 1 also shows that for a GRB flux at the level of the current IceCube limit a trigger efficiency larger by at least a factor 10 compared to what we assumed here is needed.

An other interesting possibility, for the detection of up-going tau neutrinos, is to built Cherenkov detectors at sites surrounded by mountains. Mountains can work as additional target and will lead to an enhancement of emerging tau leptons. A target mountain can also function as a shield to cosmic rays and star light.

In order to estimate the possible influence of mountains on the calculated event rate for up-going tau neutrinos, we performed a similar simulation as done for La Palma site for four sample locations: two in the Argentina (San Antonio, El Leoncito), one in Namibia (Kuibis) and one in the Canary Islands (Tenerife), see Table 2 and Figure 4. In case of sites surrounded by mountains (San Antonio, El Leoncito, Kuibis) results show an higher event rate (by at least a factor of 2) than for a site without surrounding mountains (La Palma and Tenerife).

Table 2: The ratio of event rates defined as: $k = N^{\text{site}}_{\nu_{\tau}} / N_{\text{LaPalma}}$ for the Flux-1 and Flux-3.

<table>
<thead>
<tr>
<th>Site</th>
<th>$k_{\text{Flux-1}}$</th>
<th>$k_{\text{Flux-3}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Antonio</td>
<td>4.6</td>
<td>2.6</td>
</tr>
<tr>
<td>El Leoncito</td>
<td>3.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Kuibis</td>
<td>2.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Tenerife</td>
<td>1.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>

We also studied the influence on the expected event rate arising from uncertainties on the tau lepton energy
loss. The average energy loss of taus per distance travelled (unit depth X in gcm$^{-2}$) can be described as $\langle dE/dX \rangle = \alpha(E) + \beta(E)/E$. The factor $\alpha(E)$, which is nearly constant, is due to ionization $\beta(E)$ is the sum of $e^{+}e^{-}$-pair production and bremsstrahlung, which are both well understood, and photonuclear scattering, which is not only the dominant contribution at high energies but at the same time subject to relatively large uncertainties. In this work the factor $\beta_{\tau}$ are calculated using the following models describing contribution of photonuclear scattering: ALLM [16], BB/BS [22] and CMKT [23]. and different neutrino-nucleon cross-sections: GRV98lo [18], CTEQ66c [17], HP [19], ASSS [20], ASW [21]. Results are listed in Table 2 for Flux-1 and Flux-3.

Table 3: Relative contributions to the systematic uncertainties on the up-going tau neutrino rate. As a reference value the expected event rate for La Palma site calculated for Flux-1 and Flux-3 (in brackets) was used.

<table>
<thead>
<tr>
<th>rate</th>
<th>PDF</th>
<th>$\beta_{\tau}$</th>
<th>sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.8 \times 10^{-4}$</td>
<td>+14% (+22%)</td>
<td>+2% (+7%)</td>
<td>+14% (+43%)</td>
</tr>
<tr>
<td>$(8.6 \times 10^{-5}$)</td>
<td>-2% (-7%)</td>
<td>-7% (-14%)</td>
<td>-7% (-16%)</td>
</tr>
</tbody>
</table>

4 Summary

In this paper detailed Monte Carlo simulation of event rate, including local topographic conditions of the detector, and using recent predictions for neutrino fluxes in AGN flares are presented for La Palma site and a few proposed CTA sites. The calculated neutrino rate is usually worse compared to what estimated for IceCube assuming realistic observation times spend by Cherenkov telescopes (a few hours). However for models which predict neutrino fluxes with energy above $\sim 5 \times 10^{17}$ eV, the sensitivity can be comparable to IceCube or even better. For the sites considered which have surrounding mountains the expected event rate is up to factor 5 higher compared to what expected for La Palma.

References