Astroparticle Physics 100 (2018) 69–79

Contents lists available at ScienceDirect

Astroparticle Physics

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

On the potential of Cherenkov Telescope Arrays and KM3 Neutrino Telescopes for the detection of extended sources

L. Ambrogi [a,c], S. Celli [a,*], F. Aharonian [a,b,c]

[a] Gran Sasso Science Institute, viale Francesco Crispi, L'Aquila (AQ) 7 67100, Italy
[b] Dublin Institute of Advanced Studies, 10 Burlington Road, Dublin 4, Ireland
[c] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, Heidelberg D-69117, Germany

ARTICLE INFO

Article history:
Received 19 October 2017
Revised 14 February 2018
Accepted 8 March 2018
Available online 9 March 2018

Keywords:
Neutrino telescopes: general
Cherenkov telescopes
Gamma-ray telescopes: general
Extended sources: RX J1713.7-3946 Galactic Center Ridge
2HWC catalog

ABSTRACT

We discuss the discovery potential of extended Very-High-Energy (VHE) neutrino sources by the future KM3 Neutrino Telescope (KM3NeT) in the context of the constraining power of the Cherenkov Telescope Array (CTA), designed for deep surveys of the sky in VHE gamma rays. The study is based on a comparative analysis of sensitivities of KM3NeT and CTA. We show that a minimum gamma-ray energy flux of $E^2\phi_\gamma(10\text{ TeV}) > 1 \times 10^{-12}$ TeV cm^{-2} s^{-1} is required to identify a possible neutrino counterpart with a 3σ significance and 10 years of KM3NeT observations with upgoing muons, if the source has an angular size of $R_{src} = 0.1^\circ$ and emits gamma rays with an E^{-2} energy spectrum through a full hadronic mechanism. This minimum gamma-ray flux is increased to the level of $E^2\phi_\gamma(10\text{ TeV}) > 2 \times 10^{-11}$ TeV cm^{-2} s^{-1} in case of sources with radial extension of $R_{src} = 2.0^\circ$. The analysis methods are applied to the supernova remnant RX J1713.7-3946 and the Galactic Center Ridge, as well as to the recent HAWC catalog of multi-TeV gamma-ray sources.

© 2018 Elsevier B.V. All rights reserved.

1. Introduction

The progress made in ground-based gamma-ray astronomy over the last two decades has lead to the detection of more than 200 very-high-energy ($E \geq 200$ GeV) sources reported by the H.E.S.S. [1], MAGIC [2], VERITAS [3] and HAWC [4] collaborations. Recently, success has been reported also in neutrino astronomy by the detection of a diffuse flux of multi-TeV neutrinos of extraterrestial origin by the IceCube collaboration [5]. In the feasible future, the upgraded IceCube and the planned KM3NeT neutrino telescopes will serve as the major tools of VHE neutrinos. Apparently, the identification of objects contributing to the reported diffuse neutrino flux, as well as the discovery of discrete sources of VHE neutrinos is the major objective of neutrino astronomy for the coming years. So far, no clear association between any class of astrophysical sources and cosmic neutrinos has been identified. Despite the broad class of potential neutrino sources and the different possible scenarios of neutrino production in astrophysical environments, the production mechanisms of VHE neutrinos are connected to the hadronic interactions of ultra-relativistic protons with the ambient gas and radiation. Namely, the major production channels of VHE neutrinos are the decays of charged $\pi^\pm$-mesons, the secondary products of hadronic pp and $p\gamma$ interactions. Since these processes are accompanied by the production and decay of π^0-mesons, the VHE gamma-rays and neutrinos are produced at comparable rates. Consequently, one would expect similar fluxes of gamma-rays and neutrinos. On the other hand, the ground-based gamma-ray detectors, in particular the current arrays of Imaging Atmospheric Cherenkov Telescopes (IACT), H.E.S.S., MAGIC and VERITAS, provide lower flux sensitivities for point-like sources around 1 TeV, compared to the sensitivities of the present IceCube and the forthcoming KM3NeT neutrino detectors. This circumstance reduces the chances of detection of discrete VHE neutrino sources, except for compact objects or sources located at cosmological distances. TeV gamma-ray fluxes from these objects are indeed expected to be suppressed because of both internal and intergalactic absorption, through photon-photon pair production interactions. In this regard, hidden sources constitute an interesting possibility for the explanation of the measured IceCube neutrino flux: these cosmic-ray accelerators, being surrounded by very dense environments, cannot be probed by gamma rays, while transparent to neutrinos. Among them, choked GRBs and supermassive black hole cores have widely been discussed in literature [6–8]: in these cases, neutrinos constitute crucial probes in shedding light on the central engine activity. Otherwise, the VHE gamma-ray fluxes should be taken as a robust criterion regarding the expectations of discovery of discrete VHE

* Corresponding author.
E-mail addresses: lucia.ambrogi@gssi.infn.it (L. Ambrogi), silvia.celli@gssi.infn.it (S. Celli).

https://doi.org/10.1016/j.astropartphys.2018.03.001
0927-6505/© 2018 Elsevier B.V. All rights reserved.

neutrino sources. Given the difference in the TeV flux sensitivities of IACT arrays and KM3-scale neutrino detectors, the gamma-ray fluxes are especially constraining for point-like sources. In this paper, a point-like source is called an astronomical object with angular extension less than the typical angular resolution of IACT arrays ($\sim 0.1°$). For mildly-extended sources with an angular size $\sim 1°$, which is one order of magnitude larger than the Point Spread Function (PSF) of IACTs but still comparable to the PSF of VHE neutrino detectors, the gamma-ray flux sensitivity degrades, while the flux sensitivity of neutrino detectors does not change significantly. Presently, this leaves room for the discovery of extended neutrino sources in our Galaxy, given also the fact that the Galactic Disk has not been homogeneously covered by the current IACT arrays. On the other hand, in-depth surveys of the Galactic Disk in coming years by CTA could significantly improve this situation. Alternatively, in a more optimistic scenario, CTA could reveal on the sky bright extended regions of multi-TeV gamma-rays, and thus indicate the sites of potential detectable sources of VHE neutrinos. Here, we study this question based on the comparative analysis of the sensitivities of CTA and KM3NeT for extended sources. For this purpose, we have developed a common approach for calculations of sensitivities of CTA and KM3NeT. The method is based on the analytical parametrization of the main quantities (as functions of energy) characterizing the process of detection of gamma rays and neutrinos: the effective detection area, the point spread function, the energy resolution and the background rates. These functions for CTA have been provided in our previous work [9] using the results of the publicly available simulations performed by the CTA consortium. In this paper we present similar parametrizations for the neutrino detector based on the simulation results published by the KM3NeT collaboration [10]. Similar results are expected to hold for the IceCube-Gen2 detector [11], whose performances however are not yet publicly available. Hence, we will focus on KM3NeT only here.

The paper is structured as follows: in Section 2 we discuss the performances of CTA and KM3NeT, in particular their angular resolution, effective area and expected background rates. Then, in Section 3 we describe the procedure defined to compute the instrument sensitivity, considering different sizes of the sources and analyzing the different impact they have on the sensitivity of these instruments. As an application of this study, in Section 4 we consider the case of two galactic objects, for which the gamma-ray and neutrino connection has been widely discussed in literature [12–15]. The young supernova remnant (SNR) RX J1713-3946 is presented in Section 4.1, while the region of the Galactic Center Ridge is investigated in Section 4.2, being both realistic candidate neutrino sources [16–20]. In addition to these scenarios, the second HAWC catalog of TeV sources is considered in Section 5, where potential sources for a neutrino detection are highlighted. Eventually, conclusions are derived in Section 6.

In this study, we do not explore different possible improvements of the sensitivities of both detectors by applying dedicated tools for the background rejection and for the reconstruction of the gamma-ray and neutrino induced events from extended sources. Further details on these dedicated tools are given in Section 3. Therefore, we cannot exclude some deviations of our results from the upcoming, more detailed and sophisticated studies by the CTA and KM3NeT consortia. In this regard, the results presented in this work can be considered as conservative estimates of sensitivities of both CTA and KM3NeT.

2. Detector performances

In this Section we discuss the sensitivities of CTA and KM3NeT. Both instruments are based on the Cherenkov technique, detecting the light induced by the passage of an ultra-relativistic charged particle in a given medium: the air in the case of IACTs and the water or the ice in the case of neutrino detectors. Although the same physical principle is applied, the reconstruction of the signal parameters and the background rejection are quite different. Both telescopes operate in the TeV domain, reaching the best performance between 1 and 10 TeV in the case of CTA and 10 – 100 TeV in the case of KM3NeT.

2.1. The Cherenkov Telescope Array

Although the principle of detection of gamma-rays by CTA is almost identical to the operation of the current H.E.S.S., MAGIC and VERITAS stereoscopic systems of IACTs, the angular resolution of CTA will be reduced down to 1–2 arcminutes, and the flux sensitivity will be improved compared its predecessors, by one order of magnitude. In order to view the whole sky, CTA will consist of two arrays of IACTs, one in the Northern (La Palma, Canary Islands) and one in the Southern (Paranal, Chile) hemisphere. The Southern array is aimed to study the major fraction of the galactic plane including the Galactic Center region. One of the proposed layouts for the Southern observatory, the so-called *2-Q* layout, consists of 4 large size telescopes (LSTs; 23 m class, field of view (FoV) of the order of 4.5°) optimized for detections below 100 GeV, 24 medium size telescopes (MSTs; 12 m class, FoV of 7°), covering the core energy of CTA, i.e. 100 GeV to 10 TeV, and 72 small size telescopes (SSTs; 4 m class, FoV ranging from 9.1 to 9.6°), sensitive to energies above 10 TeV [21]. For this configuration, publicly available Instrument Response Functions (IRFs) have been released by the CTA Consortium[1], obtained through detailed Monte Carlo (MC) simulations of a point-like object placed at the center of the FoV and observed at a zenith angle of 20° (averaged between north/southwise in azimuth). In our previous work [9] we parametrized these IRFs by simple analytical functions of energy. The results are presented in Table 1 and Fig. 1. It should be noted that the IRFs released by the CTA Collaboration, and here considered, are the derived best responses which maximize at each energy bin the CTA differential sensitivity to point-like sources. Therefore, an improvement of the instrument performance is expected when using analysis cuts aimed to maximize the telescope potential to extended objects, which are the main topic of this paper.

2.2. The KM3 Neutrino Telescope

High-energy neutrino telescopes are three dimensional arrays of photomultipliers, where Cherenkov radiation produced by the neutrino interaction products are observed: the position, time and charge deposit are used to infer both the direction and the energy of the incoming neutrino. KM3NeT is an under-construction neutrino telescope [25], located deep in the Mediterranean sea. In its final configuration, the detector will consist of 6 building blocks, each instrumented with 115 vertical Detection Units (DU): a DU is composed of 18 digital optical modules, each containing 31 PMTs [10]. Although neutrino detectors are sensitive to all neutrino flavors, from the point of view of reconstruction of arrival directions of primary neutrinos, the best channel is represented by charged current interactions of muon neutrinos resulting in the production of a muon, which is experimentally visible as a track. The main background source for this event sample is then constituted by atmospheric muons and the accompanying atmospheric neutrinos. In order to reduce atmospheric muons, only events coming from below the detector horizon are selected (the so called upward going sample), as they are absorbed in their path through the Earth.

[1] The publicly available CTA performance files can be accessed at [22].

Download English Version:

https://daneshyari.com/en/article/8132704

Download Persian Version:

https://daneshyari.com/article/8132704

Daneshyari.com