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Cherenkov telescope array extragalactic survey discovery potential and the impact of axion-like particles and secondary gamma rays☆

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ABSTRACT

The Cherenkov Telescope Array (CTA) is about to enter construction phase and one of its main key science projects is to perform an unbiased survey in search of extragalactic sources. We make use of both the latest blazar gamma–ray luminosity function and spectral energy distribution to derive the expected number of detectable sources for both the planned Northern and Southern arrays of the CTA observatory. We find that a shallow, wide survey of about 0.5 hour per field of view would lead to the highest number of blazar detections. Furthermore, we investigate the effect of axion-like particles and secondary gamma rays from propagating cosmic rays on the source count distribution, since these processes predict different spectral shape from standard extragalactic background light attenuation. We can generally expect more distant objects in the secondary gamma-ray scenario, while axion-like particles do not significantly alter the expected distribution. Yet, we find that, these results strongly depend on the assumed magnetic field strength during the propagation. We also provide source count predictions for the High Altitude Water Cherenkov observatory (HAWC), the Large High Altitude Air Shower Observatory (LHAASO) and a novel proposal of a hybrid detector.

1. Introduction

Current generation instruments detected a few hundred objects in the very high energy (VHE) gamma–ray band above 50 GeV during the past decade, a good fraction of which also come with a distance measurement from multi–wavelength campaigns and optical observations [1][1–5]. The Cherenkov telescope array (CTA) is expected to come online within the next few years and outperform current imaging atmospheric Cherenkov telescopes (IACTs). Its improved flux sensitivity and larger field of view (FoV) will enable the detection of many new sources and will allow for population oriented studies at VHE [6]. An up-to-date estimate of detectable sources is needed in order to devise the best CTA survey strategies.

Blazars, a class of active galactic nuclei (AGNs), are the dominant population in the VHE gamma–ray sky. Currently, ∼ 200 VHE blazars have been reported [7] out to redshift $z \sim 1$ [8–10]. The number of VHE blazars is expected to dramatically increase in an improved IACT sensitivity. Indeed, it would be possible to perform a statistical study of VHE blazars in the CTA era (see, e.g., Inoue & Tanaka 2016 using current IACT blazar samples [11]), which would provide the key to understand AGN populations in the VHE end and high-energy phenomena in the vicinity of supermassive black holes.

The expected potential of this upcoming VHE blazar CTA survey has been studied in the literature (Inoue, Totani, & Mori 2010 [12], Dubus et al. 2013 [6], Inoue, Kalashev, & Kusenko 2014 [13], and more). Very recently, Ajello et al. [14] reported an improved model of the spectral energy distributions (SEDs) and evolution (gamma-ray luminosity function, GLF) of blazars based on the latest catalog from the Large Area Telescope [15] on board the NASA *Fermi* gamma–ray satellite. Utilizing these latest models, in this work we will show the expected source count distribution and redshift distribution at the energy bands covered by the CTA sensitivity. We will also consider the cases for the high altitude water Cherenkov (HAWC) [16] and the large high altitude air shower observatory (LHAASO) [17–19]. We include consideration for a recent proposal of a hybrid detector composed of a carpet of resistive plate cham-

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bers on top of an array of water Cherenkov detectors dubbed Hybrid in this work [20].

VHE gamma rays propagating in intergalactic space are known to be attenuated by the extragalactic background light (EBL) [21–24]. EBL attenuation would affect the expected number of extragalactic source detections in a future survey. Recent studies have detected attenuation of gamma rays on EBL [25–27], using a dataset dominated mostly by optical depth of the order of unity. However, distant VHE blazars appear to have harder intrinsic spectra than simple gamma-ray emission models [28], as well as a redshift dependence of the observed spectral index that is different from what was expected [29–32], although a large uncertainty remains in the measured redshifts and spectral indices [33,34].

To explain such intrinsically hard spectra, several scenarios have been proposed in the literature such as secondary cascade components generated by very high energy cosmic rays [35–37], emission from stochastically accelerated particles in the jet [38], axion-like particles (ALPs) [39–45] and Lorentz invariance violation [39]. Except for the stochastic acceleration scenarios, that also suffer from EBL attenuation, the other mentioned processes would affect gamma–ray propagation in intergalactic space, potentially hardening the observed blazar spectrum as compared to the pure gamma-ray absorption on standard EBL scenario. This would be particularly true for sources located at high redshifts. In this paper, we also study implications of ALPs and secondary gamma rays on the source count distribution and whether the number of detected sources with an extragalactic survey with CTA could provide enough statistical significance of one of this effects at work.

This paper is organized as follows. In Section 2, we describe the model used to compute the cumulative source count distribution under the above mentioned scenarios. Discussion of the results is presented in Section 3. Conclusions are given in Section 4. Throughout the paper we consider the cosmological parameters: H_0 = 67 km s^{-1} Mpc^{-1}, Ω_M = 1 - Ω_Λ = 0.3.

2. Method

Cumulative source counts above a certain flux limit F is given as

$$N(>F) = \int_{z_{\rm min}}^{z_{\rm max}} \int_{\Gamma_{\rm min}}^{\Gamma_{\rm max}} \int_{L_{min}(F,z,\Gamma)}^{L_{\rm max}} \Phi(L_\gamma, z, \Gamma) \frac{dV}{dzd\Omega} dLd\Gamma dz, \qquad (1)$$

where z is the redshift of the source, Γ is a photon index (see Eq. (3)), L_γ is the intrinsic source gamma–ray luminosity in the energy band 0.1 – 100 GeV. Φ is the blazar GLF and V is the comoving volume [46]. For the GLF, we use the luminosity dependent density evolution (LDDE) model in [14]. We set $z_{\rm min} = 0.001$, $z_{\rm max} = 4$, $\Gamma_{\rm min} = 1$, $\Gamma_{\rm max} = 3.5$, $L_{\rm max} = 10^{52}$ erg s^{-1} as in [14]. L_{min} is the intrinsic source luminosity corresponding to the flux detected at Earth. We constrain L_{min} to be greater than 10^{42} erg s^{-1} following [14]. To relate L_{min} to a certain flux limit, we make use of an average blazar SED template presented in [14]:

$$\frac{dN_\gamma}{dE}(E, \Gamma, z) \propto \left[\left(\frac{E}{E_b}\right)^{1.7} + \left(\frac{E}{E_b}\right)^{2.6}\right]^{-1} e^{-\tau(E,z)}, \qquad (2)$$

where the dependency from measured Γ derives from:

$$\log E_b(\mathrm{GeV}) = 9.25 - 4.11\Gamma \qquad (3)$$

For the opacity coefficient τ due to absorption of gamma-ray photons on the EBL, we adopt the model of [47] as our reference one. We verified that there is no significant disagreement in results computed with other EBL models [48–50]. Below, we explore the effect of two different scenarios on the cumulative source count distribution.

2.1. Axion-like particles

ALPs are pseudo-scalar bosons similar in properties to standard QCD axions [51,52] but with a coupling constant which is independent of their mass. They are predicted by several extensions of the Standard Model and can constitute all or part of the dark matter density (see, e.g., [53] for a recent review). Photons couple with ALPs in the presence of external magnetic fields, therefore should such kind of particles exist, VHE gamma rays would oscillate back and forth to ALP in astrophysical magnetic fields during their propagation.

ALPs would not interact with the EBL, possibly resulting in a less opaque universe to VHE gamma rays. As a result, CTA could observe spectral hardening [54] of distant sources due to this effect.

In Ref. [44] the authors explore different intergalactic magnetic field (IGMF) strength values and conclude that the effect is evident for an IGMF strength of $B = 10^{-10}$ G and 10^{-11} G, uniform in 1 Mpc domains but whose orientation randomly varies from one domain to another. The probability of photon/ALP conversion increases with the component of the magnetic field along the polarization vector of the photon [55], but the overall effect on the observed spectra also depends on the distance travelled and the precise structure of the magnetic field (direction, strength, size of coherent domains). For example, in cases where the photon/ALP conversion probability is very high, ALPs would not travel long distances before oscillating back to photons, thus not efficiently preventing absorption on EBL. On the other hand, if the mixing effect is not efficient enough, very few photons can oscillate to ALPs, leading to a negligible overall effect on the observed spectra. For simplicity, we adopt uniform IGMF strengths of $B = 10^{-10}$ G and 10^{-11} G for ALPs in this paper, following the values adopted in Ref. [44]. We note that these values are allowed by current observational constraints on the IGMF strength [56], although they lie close to the existing upper limits coming from the cosmic microwave background (CMB). The spectral distortions induced by photon/ALP mixing on top of the EBL-absorbed source spectrum are computed following [44]. The general effect is a hardening of the spectrum for sources at $z \gtrsim 0.2$, yet as said this result largely depends on the properties of the IGMF, to a large extent unconstrained at present [57–64].

It is important to emphasize that the ALP scenario presented in [44] for the intergalactic case only represents an average case over a large number of realizations of the IGMF configuration (strength and orientation). It has been shown that this average typically leads to a less opaque universe to gamma rays as due to ALPs; however the actual range of possibilities is expected to be much larger and, indeed, may lead to a more opaque universe [65]. We also note that ALPs/photons oscillation in our Galaxy is not taken into account in this work, though it could also contribute to alter the spectra significantly [66–69].

2.2. Secondary gamma rays

The origin of high and ultra-high-energy cosmic rays (UHECR) has not yet been uniquely identified, and AGN could contribute to it up to the EeV energies or even higher [70] (but see also [71]). Energetic protons propagating in the intergalactic space interact with the intergalactic photon fields via photo-pion production ($p\gamma \rightarrow p\pi^0/n\pi^+$) and electron/positron pair production ($p\gamma \rightarrow pe^-e^+$). Both channels lead to cascades of particles and generate secondary gamma rays, which would be detected along the line of sight of the blazar [36,37,72–77], provided that the IGMF is less than ~1 nG [72,74].

Protons with energies around ~1 EeV, i.e. below the Greisen–Zatsepin–Kuzmin (GZK) [78,79] cutoff, would not be absorbed by