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Active Galactic Nuclei population studies with the Cherenkov Telescope Array

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The Cherenkov Telescope Array (CTA) observatory is the next generation of ground-based imaging atmospheric Cherenkov telescopes (IACTs). Building on the strengths of current IACTs, CTA is designed to achieve an order of magnitude improvement in sensitivity, with unprecedented angular and energy resolution. CTA will also increase the energy reach of IACTs, observing photons in the energy range from 20 GeV to beyond 100 TeV. These advances in performance will see CTA heralding in a new era for high-energy astrophysics, with the emphasis shifting from source discovery, to population studies and precision measurements. In this talk we discuss CTA's ability to conduct source population studies of γ-ray bright active galactic nuclei and how this ability will enhance our understanding on the redshift evolution of this dominant γ-ray source class.

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1. Introduction

Over the last 15 years, the current generation of space and ground-based γ-ray telescopes has revolutionised our view of the high-energy non-thermal Universe. To build upon this success, the international community is now working towards the next generation of ground-based Imaging Atmospheric Cherenkov Telescope (IACT) instruments, the Cherenkov Telescope Array (CTA; [1]). CTA is designed to achieve an order of magnitude improvement in sensitivity with respect to the current generation of IACTs, with unprecedented angular and energy resolution over nearly 4 decades in energy, from 20 GeV to beyond 100 TeV.

The envisaged step-change in performance afforded by CTA will in part be due to CTA's sheer size, and the fact that it will be comprised of three telescope size classes, the Small-Sized-Telescopes (SST), Medium-Sized-Telescopes (MST) and Large-Sized-Telescopes (LST), with each size class optimised to observe a different γ-ray energy range. The SST component of CTA is primarily responsible for extending the high-energy reach of CTA, predominantly observing γ-rays with energies from a few TeV up to 100 TeV and beyond. At these extreme photon energies, the limiting factor is not the amount of Cherenkov radiation produced by air showers, but simply the number of γ-ray induced air showers to observe. As such, the SSTs will be modest in physical size, only 4 m diameter primary mirrors, but there will be a large number of SSTs spread over $\sim$ 4km^2 [2][1]. More than two thirds of CTA's southern array telescopes are foreseen to be SSTs. The MSTs will have a diameter of $\sim$ 12 m and will dominate the improvement in flux sensitivity in the core $0.2 \leq E_\gamma \leq 10$ TeV energy range. With a diameter of $\sim$ 23 m, the LSTs are designed to observe the low Cherenkov photon intensity associated with $20 \leq E_\gamma \leq 200$ GeV photon-induced air showers; however, unlike the SSTs, due to the expected γ-ray flux in this energy range, there will only be 4 LSTs at the centre of CTA. To allow all-sky coverage, the CTA observatory will consist of two different arrays, one in each hemisphere. The northern array is intended to contain $\sim$ 20 telescopes (LSTs and MSTs) spread over about 1 km^2, while the southern array is intended to contain $\sim$ 100 telescopes (LSTs, MSTs and SSTs) spread over an area of approximately four square kilometres. These improvements in telescope performance will see CTA heralding in a new era for ground-based γ-ray astronomy, with the emphasis shifting from source discovery, to population studies and precision measurements. During the initial phase of constructing CTA, first arrays of telescopes will enable early scientific observations, with 4 LSTs and 9 MSTs on the Northern site, and 14 MSTs and 37 SSTs on the Southern site, whilst a later construction phase will follow to complete the array. In the following study, this is referred as "alpha configuration", while the full-scope CTA arrays will be referred as "omega configuration".

These proceedings are dedicated to characterising CTA's ability to observe the population of γ-ray bright Active Galactic Nuclei (AGN). Considering sources in the fourth *Fermi*-LAT AGN (4LAC; [3]) catalogue with known redshifts, we use the GAMMAPY software suite [4, 5] with a variety of spectral extrapolation models to higher energies and exposure times, to estimate the number of AGN possibly detectable by both the Northern array and Southern array arrays when accounting for the extragalactic background light (EBL). Importantly, to highlight the impact that the full CTA arrays will have in the context of AGN population studies, we quantify the number

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[1] Also see Gueta et al. from these proceedings.

of AGN observed with the full CTA arrays, as well as the smaller total expected with CTA's initial alpha configuration.

2. The 4LAC catalogue

Since 2008 August 4, the vast majority of data taken by the Large Area Telescope (LAT) on board the *Fermi* satellite has been performed in all-sky-survey mode, whereby the *Fermi*-LAT detector points away from the Earth and rocks north and south of its orbital plane, on subsequent orbits. This rocking motion, coupled with *Fermi*-LAT's large effective area, allows the LAT instrument to scan the entire γ-ray sky in about a few hours. This observational characteristic, coupled with *Fermi*-LAT's long mission lifetime, allows us to construct a deep exposure of the γ-ray sky in the 0.1 – 100 GeV photon energy range.

The 4LAC catalogue lists all γ-ray bright AGN detected by the LAT during the first 8 years of the *Fermi* mission. In particular, the 4LAC reports the position and best-fit spectral parameters for 2863 γ-ray bright AGN derived from integrating over the entire 8-year data set. The vast majority of the 4LAC AGN are of the blazar class ($\sim$ 98%). Of this 4LAC blazar population, 38% are BL Lac-type objects (BL Lacs), 24% are Flat Spectrum Radio Quasars (FSRQs) and 38% blazar candidates of unknown types (BCUs). Importantly, all AGN currently detected by IACTs are present in 4LAC. As such, the 4LAC catalogue represents a natural starting point from which to quantify the potential of CTA to observe the γ-ray bright AGN population. For this study, we use a subset of the 4LAC catalog revised to only contain sources with a well-known redshift [6]. This target AGN list is then extrapolated to the TeV regime, and prospects of CTA detectability are calculated by using GAMMAPY. A total of 1551 AGN were considered over the whole sky.

3. Extrapolation and computing sensitivity of CTA to the AGN population

3.1 Extrapolating from the 4LAC

Starting with the 4LAC, to quantify CTA's potential to observe the γ-ray bright AGN population we must extrapolate the 4LAC spectra up across the entire observable energy range expected for CTA. During this extrapolation process, there are several key aspects that need to be considered:

- **Extrapolation scheme:** the functional form of the extrapolation from *Fermi*-LAT to CTA energies influences the total number of AGN detected. Given our lack of a-priori knowledge of the most appropriate functional form for extrapolation, we use a bracketing approach by assuming both (i) power-law (optimistic) extrapolation (PL) (ii) log-parabola (pessimistic) extrapolation (LP). We note however the LP fits should be taken with caution as existing TeV observations disfavour such an extrapolation of LAT spectra.

- **Extragalactic Background Light:** during propagation from source to Earth, the γ-rays emitted by AGN can interact with the diffuse flux of the Extragalactic Background Light (EBL) creating a positron-electron pair. This interaction will result in an attenuation of the observed γ-ray flux, with the probability of this attenuation being redshift and γ-ray energy dependent. Throughout this study, we describe this probability with the Dominguez 2011

EBL model [7]. Furthermore, due to the redshift dependence of the EBL-attentuation, this study only considered 4LAC AGN with a well-known redshift[2].

As such, taking these two aspects into consideration, for each AGN, we apply two different extrapolation schemes: (i) Power-law + EBL and (ii) log-parabola + EBL. Given the MeV-GeV energy range over which the the 4LAC detects AGN and the fact that the EBL has a minimal impact on γ-rays in the 4LAC energy range, these two extrapolation schemes were applied to the observed 4LAC spectra rather than their EBL-corrected counterparts.

3.2 GAMMAPY simulations

For this study, GAMMAPY v0.17 was used with a standard ON-OFF (or aperture photometry) approach. The instrument response functions (IRFs) utilised by GAMMAPY were the final omega array configuration and the proposed initial alpha array configuration, for both Northern sites and Southern sites, from the so-called `prod3b-v2` production version[3] [9]. As each of these IRF configurations were simulated for three different sets of zenith distances, depending on each source culmination altitude at each site, the correct IRF was used: 20°, 40° and 60° in zenith IRFs were used for sources culminating below 25°, between 25° to 45° and between 45° to 65° from zenith respectively. Those sources culminating above 65° from zenith on a site were considered un-observable. For each of these array configurations, a 5 hour and 20 hour exposure per source was considered along with five different energy thresholds: 30 GeV, 50 GeV, 100 GeV, 300 GeV, 500 GeV and 1 TeV.

Throughout the analysis, we employ detectability conditions as follows: (i) detection significance: $S > 5\sigma$ (eq. 17 from [10]); (ii) excess required to be larger than 5% the background rate (five times the systematic uncertainty on the background rate) and (iii) excess required to be larger than 10 events. For each AGN, once the two different extrapolations were applied, for each array configuration, exposure time and energy threshold configurations, 100 separate GAMMAPY simulations were performed. Any AGN for which the average of these 100 simulations satisfied the detection criteria, were considered to be detectable by CTA.

4. Results

The results of these simulations for the Northern site alpha and omega configurations can be seen in Table 1, whilst the Southern site alpha and omega configuration results can be seen in Table 2. For both arrays, there are significant differences in the number of AGN detected by the predicted sensitivity of the two different array configurations. As expected, the omega configuration performs better than the initial smaller alpha array, showing that we will be able to expand science reach as more telescopes are installed. In some cases, the final omega array detects over double the number of AGN compared to the initial alpha array. This is most notable in the lower energy threshold analysis of the Southern array arrays where the lack of LSTs in the Southern array alpha array has a

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[2] CTA has a dedicated 'redshift working group' that validates 4LAC redshifts where necessary, as well as organizes observational campaigns to determine the redshifts for CTA AGN candidates that currently do not have a known redshift [e.g. 8]; for example, see also Kasai et al. from these proceedings.

[3] See `https://www.cta-observatory.org/science/cta-performance/`.

Northern omega array	30 GeV	50 GeV	100 GeV	300 GeV	500 GeV	1 TeV
5 hour - PL	51	84	114	98	83	65
20 hour - PL	93	171	209	164	135	103
5 hour - LP	30	50	73	62	54	41
20 hour - LP	51	101	131	107	87	64
Northern alpha array	30 GeV	50 GeV	100 GeV	300 GeV	500 GeV	1 TeV
5 hour - PL	30	53	76	73	63	49
20 hour - PL	60	117	154	131	105	84
5 hour - LP	19	35	45	45	40	27
20 hour - LP	33	64	96	86	68	56

Table 1: Number of AGN detected for Northern array alpha and omega configurations for the different extrapolation schemes, exposures and energy thresholds considered in this study.

Southern omega array	100 GeV	300 GeV	500 GeV	1 TeV
5 hour - PL	117	112	90	71
20 hour - PL	209	173	147	116
5 hour - LP	68	66	52	45
20 hour - LP	122	108	92	73
Southern alpha array	100 GeV	300 GeV	500 GeV	1 TeV
5 hour - PL	50	72	72	53
20 hour - PL	100	124	125	96
5 hour - LP	30	45	46	39
20 hour - LP	57	78	74	56

Table 2: Number of AGN detected for Southern array alpha and omega configurations for the different extrapolation schemes, exposures and energy thresholds considered in this study.

significant impact in the number of AGN detected. It should be highlighted that in both Table 1 & 2, the number of AGN detected doesn't simply decrease as the energy threshold increases; rather, the number of AGN detected by CTA varies due to the fact that, at the lowest energies there is a large background, whilst at the highest energy, the signal from the AGN becomes statistics limited.

To achieve some of its key science goals [11], CTA needs to expand the cosmic distances at which blazars are studied. Figure 1 shows the redshift distributions of the simulated and detected AGN for both the alpha and omega configurations of the Northern array and Southern array, for 20 h exposures considering a power-law extrapolation scheme. In both cases, the omega array detects significantly more AGN at large redshifts compared to the alpha configuration. It should be stressed that in this study, we only consider the average 4LAC spectra for extrapolation, integrated over 8 years of the *Fermi*-LAT data. AGN undergoing γ-ray flares often exhibit 'harder-when-brighter' spectral characteristics (see e.g. [12, 13]), which can facilitate CTA detecting AGN at higher redshifts than those reported here.

The difference in performance of the alpha and omega configurations will also result in differences in the spectral characteristics that CTA will be able to detect from this AGN population.

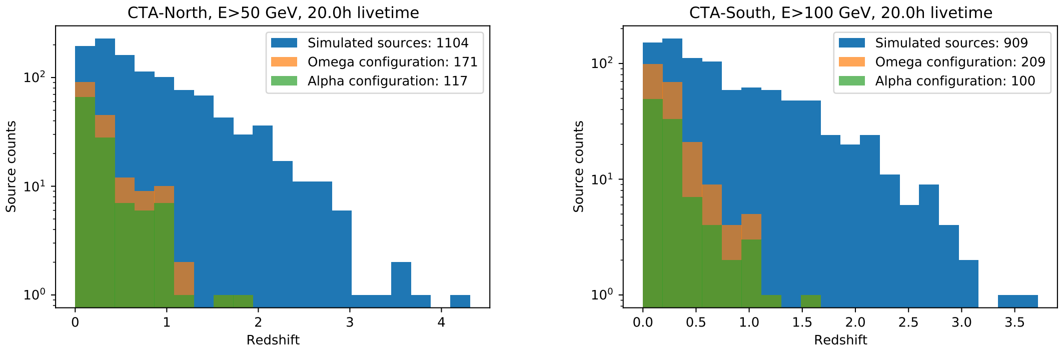

Figure 1: Redshift distributions of AGN detected by CTA-North (left) and Southern array (right) with 20 h exposures considering a power-law extrapolation scheme. In both cases, the increased sensitivity of the omega array significantly increases the number of AGN detected at larger redshift of the further detected AGN, compared to the alpha configuration. It should be noted that the Southern array comparison considers an energy threshold of 100 GeV, thus negating the major difference between the two array configurations due to the LSTs. As such, this comparison is a conservative one, and we would expect a greater difference.

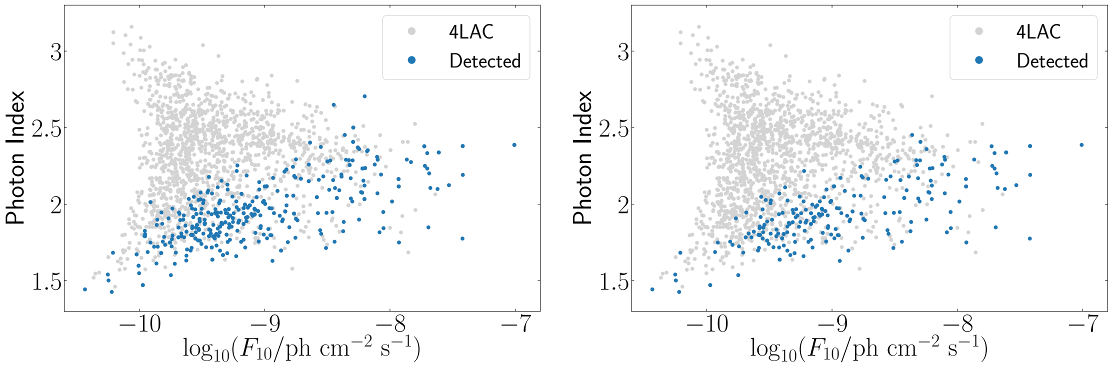

Figure 2: Flux vs index parameter space for the AGN considered in this study. The grey symbols indicate all AGN simulated, whilst the blue symbols represent the AGN detected by CTA (by either the Northern or Southern array). From left to right, the panels depict the results for the omega and alpha configurations, respectively.

This is best seen in Figure 2, which shows the photon index versus integrated flux of all AGN considered in this study. Figure 2 clearly indicates that the omega configuration will increase CTA's reach across the 'photon index versus integrated flux' parameter space compared to the alpha configuration, with CTA being able to detect fainter and/or softer AGN than is possible in its smaller initial alpha configuration.

The results highlight that the CTA will not only multiply the number of sources detected, but also expand the horizons to which we can observe the gamma-ray sky. As described in [14], the detection of high-redshift blazars will enable scientists to explore a range of topics in astronomy, cosmology and fundamental physics. These include the measurement of the gamma-ray absorption by the EBL, investigations of intergalactic magnetic fields, searches for evidence of axion-like particles and multiple tests for Lorentz invariance violation. The increased number of sources will also provide a basis for a robust reliable estimate of the luminosity function of blazars and help investigate the evolution of the different source populations in this energy regime.

5. Conclusions

With its improved sensitivity, we find that in all analysis configurations considered in this study, the omega configuration performs better that the initial alpha configuration, which shows that we will be able to expand science reach of CTA as more telescopes are installed. In some cases, specifically the Southern array low threshold energy analysis, the difference in the number of AGN detected between the Southern array omega and alpha configurations is greater than 100%. Furthermore, CTA's omega configuration will detect more AGN at higher redshifts compared to current IACTs, as well as detecting a larger number of fainter and softer AGN compared to the alpha configuration. In addition, multiple propagation studies will already be possible due to the alpha configuration being able to detect sources up to a redshift of $\simeq 1.8$.

This study shows that even during the construction phase, CTA will already be able to double the number of extragalactic sources detected in the VHE regime, even taking into account that these predictions are most likely conservative, given *Fermi*-LAT 8-year-averaged spectra are dominated by AGN in low-activity states.

Unfortunately, other γ-ray cosmology studies which require the detection of numerous AGN across a large redshift range, such as attempting to measure the evolution of the EBL across different cosmological epochs or Lorentz invariance violation [14], would greatly profit from the LST component of the omega configuration for the Southern array. This benefit relating to the lower energy threshold is afforded to us by the LSTs, which allow for additional AGN to be detected at large redshifts.

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