PROCEEDINGS OF SCIENCE

AGN Forecasts for the Cherenkov Telescope Array

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The First Fermi-LAT catalog (1FGL) represents the most complete list of sources in the GeV sky to date. We use the reported 1FGL spectral parameters to extrapolate *Fermi* AGN spectra to the very-high energy (VHE) range (15 GeV – 300 TeV). The extrapolated VHE spectra are then attenuated using current estimations of the extragalactic background light (EBL) absorption as a function of redshift. Using the expected effective areas and background rates of the Cherenkov Telescope Array (CTA) from Monte Carlo simulations, we make a first order prediction of the AGN population accessible to CTA in the VHE sky. We find that CTA should easily triple the AGN detection rate of current ground-based Cherenkov telescopes. In addition, CTA should allow unprecedented access to high-redshift blazars out to $z \approx 2$, and hence will start to reveal the EBL shape with gamma-ray observations.

AGN Physics in the CTA Era - AGN2011,
May 16-17, 2011
Toulouse, France

 http://pos.sissa.it/

PoS(AGN 2011)024

1. Introduction

The future Cherenkov Telescope Array (CTA) represents the next generation of ground-based Cherenkov detectors [1]. When completed, CTA is expected to improve the sensitivity of present observatories such as H.E.S.S., MAGIC or VERITAS by an order of magnitude. It will also expand the energy range coverage from some tens of GeV to hundreds of TeV, opening a new window in the Very High Energy (VHE) domain never reached with such exquisite detail. Furthermore, the synergy between the Large Area Telescope (LAT) on board of the *Fermi* Gamma-ray Space Telescope and CTA will allow nearly seamless coverage from MeV to TeV.

The CTA Observatory will consist of two arrays, one in each hemisphere. The Southern hemisphere array is expected to be mainly dedicated to Galactic sources and bright active galactic nuclei (AGN), whereas the Northern one will complement the Southern one, focusing on northern extragalactic objects including AGN, galaxy clusters, gamma-ray bursts, and starburst galaxies. CTA is a complex project; as a result understanding its capabilities and limitations is not a simple task. One possible way to evaluate its science impact is to simulated a population study using real data from known gamma-ray sources expected to emit in the VHE range.

Specifically, the *Fermi* Gamma-ray Space Telescope provides an ideal set of candidates for this study through the First Fermi-LAT catalog (1FGL). With 11 months of accumulated data, the 1FGL catalog contains 1451 sources characterized in the 100 MeV to 100 GeV energy range [2]. Here, we exploit the overlap of the high energy end of *Fermi* with the low energy range of CTA to attempt a first order approximation of the extragalactic CTA sky. It is likely that many of the 1FGL catalog sources have no yet been discovered in VHE due to a lack of sensitivity of existing instruments, but could be accessible to CTA. In fact, 39 out of the 45 VHE AGN detected by ground-based Cherenkov observatories are found in the 1FGL (B. Lott, priv. comm.). Therefore an extrapolation of the 1FGL data to higher energies seems a sensible step to build a mock catalog of CTA sources. In this work we present this approximation to forecast the AGN population for CTA.

Throughout this work, we rely on the CTA design concepts summarized in [1], where a number of of possible array configurations including their effective areas and predicted cosmic ray backgrounds are presented [3]. The proposed configurations are composed mainly of 3 types of telescopes: *large* (23 m diameter), *medium* (around 12 m) and *small* (6-7m). Apart from number of telescopes, the individual configurations differ in other parameters such as the field of view or pixel size [1]. For simplicity, in this paper we only consider candidate array E, that achieves a well balanced sensitivity over the full energy range of CTA.

2. Forecasting model

The motivation for this work is to provide a method for estimating the number of AGN accessible to CTA, based on the sources listed in the 1FGL catalog. The specific steps taken in determining the significance of each source are summarized in the following subsections.

2.1 Selection criteria

From the *Fermi* AGN catalog [4], we first selected sources with counterparts in at least one

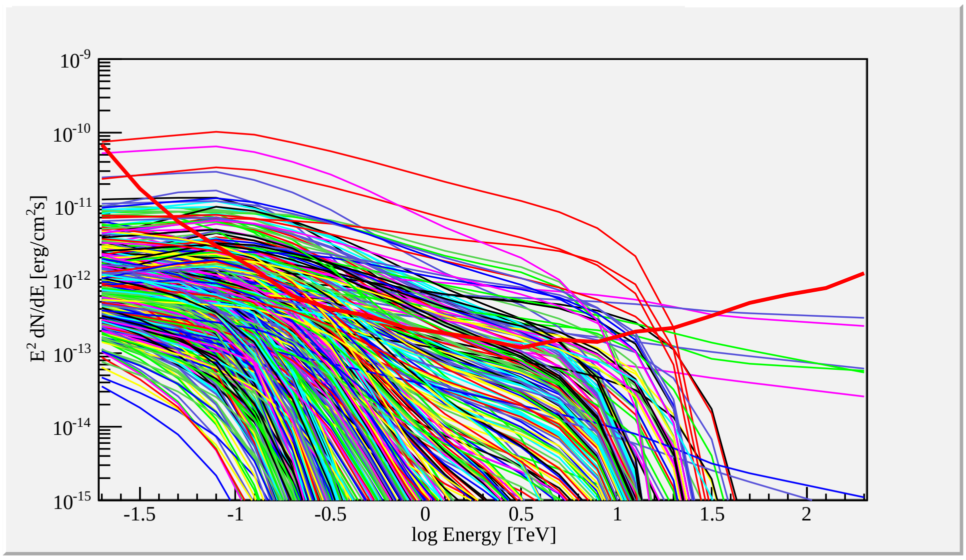

Figure 1: Extrapolated spectra from the 1FGL catalog attenuated with the EBL model by [9]. The thick red line marks the integral sensitivity for a Crab-like spectrum expected for 50 hours at a zenith angle of 20° with CTA candidate configuration E [1].

of the commonly used AGN catalogs (CRATES, CGRaBS [5] or Roma-BZCAT [6]). Out of 671 sources we only select AGN with a measured redshift, a condition needed to apply the corresponding extragalactic background light (EBL) absorption, which is critical for AGN flux estimation in the VHE range. This results in 432 sources. Finally, we discard sources whose spectra show a high curvature index $C > 11.34$ [2], ending with a subset of 400 *Fermi* AGN including 247 flat-spectrum radio quasars (FSRQs), 128 BL Lacs, and 25 of other/unknown type.

In order to extrapolate the AGN spectra to higher energies, we use the integral flux from 1 to 100 GeV in ph cm^{-2} s^{-1} units (F1000) and spectral index (Γ) furnished by the 1FGL catalog. For nearby hard sources $\Gamma < 2$, a straight extrapolation could create runaway integrations, therefore we apply an artificial broken power law with a $\Gamma = 2.5$ starting at 100 GeV to soften such spectra. The latter is in agreement with observed spectral properties [7].

As commented above, the flux attenuation due to infrared photons from the EBL is a critical factor that must be carefully taken into account for a precise and realistic flux calculation at energies above about 30 GeV. This effect produces a significant attenuation in photons with energies above tens of GeV through space [8]. The observed *Fermi* spectra are thought to be free of EBL attenuation. However, for a proper extrapolation we applied the EBL model by [9] through the whole range of CTA energies. The resulting set of attenuated differential spectra can be seen on Figure 1.

2.2 Significance Estimation

Using the final extrapolated AGN spectra, we integrate the flux per energy bin weighted with the effective areas at a zenith angle of 20° for CTA candidate array E, obtained by the CTA Monte Carlo Work Package. The expression is subsequently multiplied by the observation time (through-

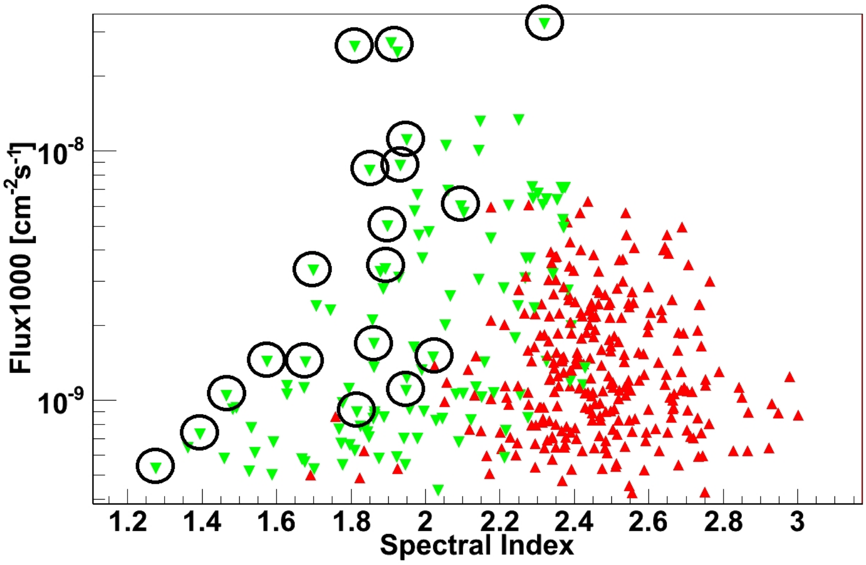

Figure 2: *Fermi* Spectral index and *Fermi* flux F1000 for AGN that would exceed the 5σ level in less than 50 hours with CTA. The points correspond to detections (green filled inverted triangles) and non-detections (red filled triangles) respectively. Large black empty circles denote AGN detected by current ground-based Cherenkov observatories. CTA candidate array E was used to produce this plot.

out this work we have assumed 50 hours) producing the total number of detected source photons. Total background rates for candidate array E are gathered from Monte Carlo simulations [3].

For each source, the significance was calculated using Equation 17 in [10] assuming N_{on} (on region) to be the number of source photons plus the number of photons from the background (BG), and N_{off} fixed at the BG rate (off-region). The number α is given by the ratio of the sizes of the two regions, the ratio of the exposure times and the respective acceptances. For simplicity, an energy threshold of 20 GeV, 5 off-regions for each on-region observations and a 5% systematic error were considered in this study [1]. A detection must exceed a significance above 5σ in 50 hours *and* a signal over 5% of the background.

3. Results

Using the outlined recipe, we analyzed the complete 400 sources in the AGN sample extracted from the *Fermi* 1FGL catalog. We obtain > 120 AGN detections, or approximately three times the current sample of VHE AGN at the time of this writing. In order to visualize our results in context of current detections, Figure 2 shows the *Fermi* flux (F1000) and spectral index for expected $> 5\sigma$ detections with CTA. Also shown are VHE AGN detected with the current generation of instruments. It is obvious that CTA will be most efficient for hard sources ($\Gamma < 2$) and will reveal the AGN population beyond the tip of the iceberg of current detections. For softer sources, CTA will allow us to detect quiescent sources that are currently only accessible during prominent flares.

It must be noted that the artificial break introduced at 100 GeV for hard sources might restrict the number of detections. Furthermore, we have left out nearly 200 BL Lacs with unknown redshift listed in the 1FGL. These are typically $\Gamma < 2$ sources where CTA is most efficient. As a result, 120 AGN must be considered a conservative lower limit for the AGN detection rate with CTA. Therefore, these forecasts are quite encouraging overall.

3.1 Redshift limits

Apart from increasing the actual number of AGN detected, CTA should increase dramatically the number of AGN visible at high redshifts. The most distant quiescent AGN predicted with our code is at $z = 1.8$. However, certain conditions could push that limit to even higher redshift. In particular, our estimations indicate that, certain flaring FSRQs with a gamma-ray flux increase of a factor of 10 and moderate spectral hardening $\Delta\Gamma = 0.3$ could produce a detection out to $z = 2.9$. Alternatively, a fraction of well-studied *Fermi* BL Lacs could be detected out to $z = 1.2$. The main difficulty in elucidating the BL Lac population will be actually obtaining direct redshift measurements from featureless optical/UV spectra. A possible redshift workaround might come from a direct measure of the EBL shape that could allow to set an upper limit for the redshift.

4. CTA Survey Capabilities

Even though CTA will not be able to match the *Fermi*-LAT in cadence, its wide field of view (FoV) capabilities should allow easy access to wide portions of the sky. Analyzing our results, we find that a dedicated pointed survey with the CTA Observatory should detect an excess of 120 sources in less than a year for sources observed for a maximum of 50 hours. Over a year and assuming a 5 degree effective FoV, the large number of pointings should produce an initial sky survey covering 5% to 7% of the sky by default. Although these pointings will not reach equivalent flux levels, there is a relative high probability of finding interesting sources from serendipitous detections (see for example [11]).

An alternative survey approach could select a continuous region of interest and image it deeply (at least 5 hours per pointing). Depending on the specific details such a wide field survey could cover 400 to 4000 square degree stripes per site per year. This deeper survey could aim for well-mapped areas in other wavelengths to allow for multifrequency analyses, and be oriented to both: a) probe the faint end of AGN population and b) guide the design of subsequent observations.

5. Conclusions

The work presented here illustrates the tremendous CTA capabilities compared to current ground-based Cherenkov instruments. An excess of 120 AGN is expected as a first order approximation. This number could swell to close to 300 AGN considering that at least 200 *Fermi* 1FGL BL Lacs without redshift have not been included in this analysis. Thus, our results should be considered as a conservative lower limit. Further increases are expected from the discovery of AGN that eluded *Fermi* detection with gamma-ray emission peaking in the CTA energy range.

The highest AGN redshift detected should be pushed from current $z = 0.5$ to approximately $z \approx 2$. It could even reach higher values if one takes into account flaring FSRQs or if ongoing surveys manage to constrain the redshifts of more distant *Fermi* BL Lacs. All the results presented are preliminary as further refinements to CTA array configurations and improvements to analysis tools

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are introduced. It is important to bear in mind that there are important caveats in our calculations: uncertainties in the spectral parameters, limitations in the CTA effective area calculations, and the EBL model. But regardless of the actual outcome, it is clear that we should look forward to a densely populated sky in the TeV range with CTA. This will open new opportunities to AGN studies including dedicated multiwavelength campaigns and studies of flares short time-scales. The next logical step for this work will come soon with the release of the Second *Fermi* LAT Catalog (2FGL). With improved spectral fitting and a larger number of sources, the 2FGL should allow us to better understand the CTA capabilities. Additional redshift constraints of BL Lac objects will help us to better account for the full AGN population. Finally, improvements on EBL absorption models should produce more detailed results.

6. Acknowledgments

We thank Catherine Boisson, Helene Sol and Andreas Zech for organizing a very interesting workshop. We are indebted to the CTA Monte Carlo Work Package for their exceptional work during the design study. We gratefully acknowledge support from the agencies and organizations listed in this page: http://www.cta-observatory.org/?q=node/22. The authors acknowledge the support of the Spanish MICINN under project codes FPA2009-0838 and FPA2010-22056-C06-06. N.M. gratefully acknowledges support from the Spanish MICINN through a Ramón y Cajal fellowship.

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