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What can *Fermi* tell us about CTA?

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Abstract

The Large Area Telescope (LAT) on board the *Fermi* Gamma-ray Space Telescope has surpassed previous gamma-ray missions with its greatly improved sensitivity, resolution, and energy range. The First Fermi-LAT catalog (1FGL), based on 11 months of data, contains 1451 sources detected characterized in the 100 MeV to 100 GeV energy range that represents the most complete map of sources in the GeV sky to date. We extrapolate source spectra and fluxes derived from the 1FGL to select potential targets for the Cherenkov Telescope Array (CTA) and estimate the number of sources that might be detected by this upcoming observatory.

1 Introduction

Our current knowledge of the high-energy non-thermal universe at TeV energies is mainly based on observations with ground-based instruments. Access to huge collection areas enable observation of relatively weak fluxes on the Earth's surface through the Cherenkov radiation generated in atmospheric electromagnetic cascades. The atmospheric Cherenkov technique was developed in the 80s and 90s [12]. The first reliable detections were obtained by the Whipple collaboration, which successfully detected the Crab nebula in 1989. Since then, results from the latest generations of telescopes have revealed a sky rich in diversity.

A curious fact is that the minimum energy that a gamma ray must have to be detectable from the ground just matches the maximum energy reachable by space telescopes such as *Fermi*. This fortunate coincidence enables nearly continuous coverage in the gamma-ray regime. It also naturally motivates the extrapolation of *Fermi* spectra to CTA energies. We take advantage of the vast *Fermi* catalog to introduce a method that might help us optimize the CTA layout and enable preliminary studies of the source population available to CTA in the future.

2 The Fermi satellite and the 1FGL catalog

Gamma rays with energies below 10 GeV can only be detected from space. Particles at such energies cannot be focused, so the collection area is only as large as (and often smaller than) the detector. Currently, the *Fermi* Gamma-ray Space Telescope, launched June 2008, is the most prolific space telescope in this energy regime. Its main instrument, the Large Area Telescope (LAT) detects photons from about 30 MeV to 300 GeV through pair-production with a field of view of about 20% of the sky and an effective area of ~ 8000 cm^2.

Recently, a first catalog (1FGL) has been presented by the *Fermi* team [1] consisting of all the high-energy gamma-ray sources detected by the LAT during the first 11 months of the science phase of the mission, which began on August 2008. The 1FGL catalog contains 1451 sources detected and characterized in the 100 MeV to 100 GeV range. Source detection was based on the average flux over the 11-month period, and the detection threshold corresponds to a significance of just over $4\,\sigma$. Care was taken to characterize the sensitivity of the results to the model of interstellar diffuse gamma-ray emission. Information in the 1FGL includes integrated flux from 100 MeV to 100 GeV, spectral index for best power-law fit in this energy range, curvature and variability indices. For individual LAT-detected sources, identifications or plausible associations with sources in other astronomical catalogs are also provided. With these criteria, a total of 690 of these sources are currently unassociated.

3 The Cherenkov Telescope Array (CTA)

CTA is a worldwide initiative to build the next generation ground-based gamma-ray observatory [11]. When compared to current facilities such as H.E.S.S., MAGIC or VERITAS, a factor of 5–10 improvement in sensitivity is expected in the 100 GeV to some tens of TeV energy domain, as well as an extension to both lower and higher energies. It will consist of two arrays, one in each hemisphere. The Southern hemisphere array will be mainly dedicated to Galactic sources and the central part of our Galaxy, whereas the Northern one will complement the observatory, and mainly be dedicated to northern extragalactic objects.

The CTA consortium is performing an exhaustive study concerning the Design Study through several work packages in order to optimize CTA's performance. Particularly, a number of possible configurations are being studied for both observatories. These are called *sub-arrays* or simply *arrays*, and their main performance parameters have been simulated internally by the Monte Carlo work package [4]. These arrays are composed principally of 3 types of telescopes: *large* (23 m diameter), *medium* (around 12 m) and *small* (6-7m). Apart from sizes, these telescope types also differ in other essential parameters, such as field of view or camera pixel diameter. Differences between arrays are due to the number of detectors of each kind that are used, and their spatial layout. Implementation of the first prototype telescopes will start after the current period of detailed design study and optimization, site

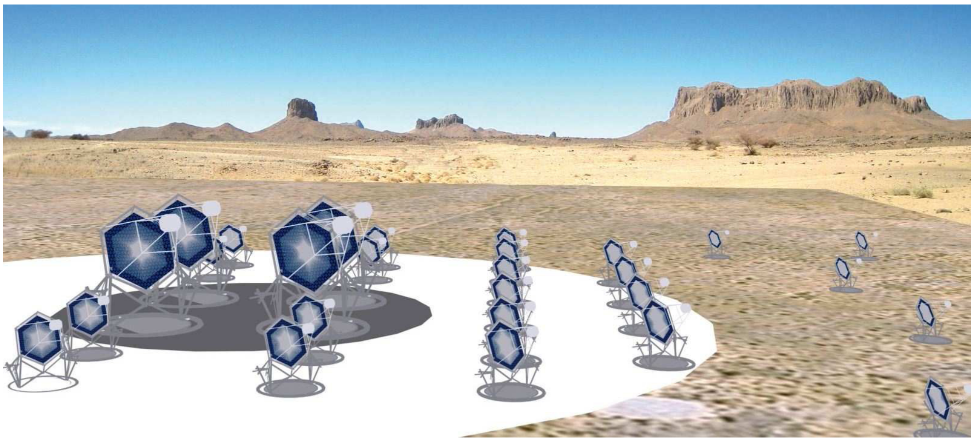

Figure 1: Conceptual layout of a possible CTA [11].

evaluation and production of industrial prototypes of components. An artist's view of the array can be seen in Fig. 1.

4 Forecasting model

The main purpose of this work is to establish a realistic estimation of the number of astrophysical sources listed in the 1FGL catalog that would be detectable with the future Cherenkov Telescope Array. For practical purposes, we divide the 1FGL sample in Galactic and Extragalactic. The specific steps taken in determining the number of detectable sources are summarized in the following subsections:

4.1 Galactic sources

(A) Sources with associations to known Galactic objects were selected, excluding pulsars and adding unidentified sources with characteristics that make them good candidates to be galactic objects: low Galactic latitude ($|b| < 15°$), and low variability index (in order to exclude AGN). We also imposed a low curvature index, to exclude pulsars, which cannot be treated as power law spectrum objects in our region of interest due to their exponential cutoff. We were left us with a total of 305 sources of this category.

(B) The power law spectrum and flux listed in the 1FGL catalog were then used and extrapolated to CTA energies.

(C) In order to avoid unrealistic results, sources with hard spectra (spectral index, $\Gamma <$ 2.0) in the *Fermi* band were softened through an artificial broken power law, which introduced a spectral index $\Gamma = 2.5$ starting at 100 GeV.

4.2 Extragalactic sources

(A) Source selection from the *Fermi* AGN catalog [2]. Sources with counterparts from any of the AGN catalogs (CRATES, CGRaBS [7] and Roma-BZCAT [9]) were included. From the 671 sources of this type, only objects with a known redshift have been selected, in order to be able to apply the corresponding absorption factor, which is distance and energy dependent. This left us with a total of 432 sources. Objects with a high curvature index were then discarded, which left us with a final sample of 400 extragalactic sources.

(B) Hard spectra ($\Gamma < 2$) in the Fermi region were softened through an artificial broken power law, which introduced a spectral index $\Gamma = 2.5$ starting at 100 GeV, in agreement with available AGN statistics.

(C) Attenuation due to optical and the infrared photons constitute a major cause of energy loss in the propagation of high energy particles through space [6]. When extrapolating extragalactic spectra into higher energies, the absorption of the gamma rays through interaction with background photons must be taken into account. This process is almost unique to the astrophysical situation as it requires unusual combinations of high energy photons and a high density of lower-energy photons. In the case of our study, Franceschini's attenuation model was used [5]. The observed Fermi spectra were taken as the non-absorbed spectra (as absorption by EBL hardly affects flux below 30 GeV), and the extrapolated spectra were weighed with the corresponding absorption factors, which are energy and distance dependent.

4.3 Significance estimate

Once the expected flux at the Earth's surface is obtained, it is weighed with the simulated CTA effective area for different telescope layouts. Figure 2 shows how different layouts produce different sensitivities according to the number of telescopes of each type [11]. This result, multiplied by the observation time (which is typically taken as 50 hours) gives the predicted number of detected photons for a certain source, layout and exposure time. The total background rates for the different configurations were also computed, using the results provided in the MC simulations [4].

Significance was calculated using equation [17] in [8], which, in its simple form, can be expressed as

$$S_{\mathrm{LM}} = \frac{N_{\mathrm{on}} - \alpha N_{\mathrm{off}}}{\sqrt{N_{\mathrm{on}} + \alpha^2 N_{\mathrm{off}}}} \quad , \tag{1}$$

where N_{on} is the count number originated in the so-called on-region and N_{off} is the count number in a certain background region considered to contain no sources. 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, 5 off-regions for each on-region observations and a 5% systematic error were considered in this study. Sources that yielded a significance above $5\,\sigma$ in 50 hours and a signal over 5% of the background were considered as positive detections. It must be noted that zenith angles of 20° were considered for all sources.

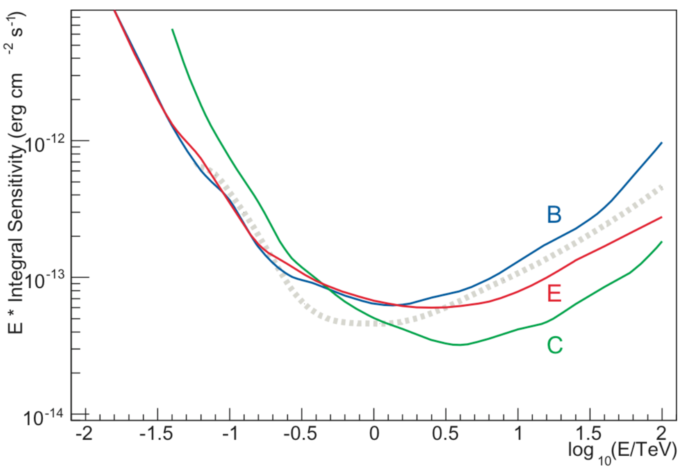

Figure 2: Integral sensitivity for candidate configurations B, C, and E, for point sources observed for 50 hours at a zenith angle of 20° [11].

5 Results

The performance of several candidate CTA configurations was computed following the method outlined above. Using the full CTA energy range, a minimum of 200 sources were predicted as positive detections, with certain configurations producing up to 300 detections. In general, about two thirds of these sources are Galactic objects. It is important to note that by imposing energy cuts in the analysis, the number of detected sources increases significantly. For most Galactic objects, there is an actual gain in the number of detected sources when imposing a lower limit to observation energy, as the amount of background events decreases more rapidly with increasing energy than the flux from most of the sources.

Cuts in extragalactic observations give raise to very different results depending on the telescope layout. Due to attenuation due to the EBL, spectra in general are softer than in the Galactic case. Layouts with an important number of large telescopes can benefit from low energy cuts. Optimizing energy cuts to maximize source detection increases the total number to approximately 400 sources (in general two thirds are Galactic). We should clarify at this point that the advantages that can be derived from imposing energy cuts largely depend on the observation mode that is to be used. We have assumed that the array is always used as a whole, not divided in subsets following different soruces.

6 Conclusions

Overall, our results show that regardless of the particular CTA layout there will be significant overall gains over current ground-based Cherenkov instruments. A combination of pointed observations and sky surveys should easily produce in excess of 400 sources above 30 GeV.

This should also be considered a conservative lower limit as we have limited our estimates to extragalactic sources with known redshifts and we have no way of assessing potential unexpected populations of sources in said energy range. However, there are important caveats to consider: uncertainties in the *Fermi* parameters, limitations in the Monte Carlo simulations, and our limited knowledge of the actual EBL.

But even under the most pessimistic scenario, CTA has the potential for revealing a very populated VHE sky. In the future, we plan to expand these models to evaluate the actual breakdown of source type/redshift per configuration. We also plan to explore what arrays are better suited for variability studies of individual sources. These will be critical for choosing the final layout that best meets the core science goals set by the CTA Consortium. Once the layout is chosen, we hope the forecasting model will lay the foundation for a set of planning tools that helps rank the order of pointed observations within the CTA Collaboration. As well as, a set of external observer tools that can be fully available to plan new observations.

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