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STUDY OF THE GALACTIC ANTICENTRE REGION AT 100 GEV WITH CELESTE

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Abstract. Located in the French Pyrénées, CELESTE was the first ground based detector with an energy threshold below 100 GeV. It took data between 1998 and 2004, and allowed flux measurements from the Crab nebula and from the blazars Mrk 421 and Mrk 501. Galactic diffuse gamma-ray emission is the most significant around the Galactic plane, [-5,+5] degrees of Galactic latitude. From the large samples on the Crab Nebula, we have selected Crab OFF data with different Galactic latitudes, in order to analyse the diffuse emission. After criteria applied on sky position, atmospheric conditions and detector stability, we obtain 108 min of data in the Galactic anticentre region, providing a new limit on the diffuse emission with ACT detectors.

1 Introduction

Galactic diffuse gamma-rays are produced by charged cosmic rays interacting with gas or photons of the interstellar medium. Most of these interactions occur in the Galactic plane: high energy gamma-rays have very weak attenuation and because of their neutrality, they propagate without deviation from their production regions. These gamma-rays can therefore be used to study indirectly the spatial distribution, propagation and spectrum of charged cosmic rays.

In the Galactic plane away from the Galactic centre region, previous measurements of the Galactic diffuse emission were done by the EGRET detector between 30 MeV and $\sim$50 GeV, leading to the localisation of this emission between -5 and +5 degrees of Galactic latitude (Hunter et al. 1997). Ground based detectors WHIPPLE (LeBohec et al 2000), HEGRA (Aharonian et al 2001) and TIBET (Amenomori 2006) gave upper limits at energies higher than 500 GeV. Milagro detected a signal at TeV energies with a significance of 4.5 σ between 40° and 100° of Galactic longitude (Atkins et al 2005). CELESTE did observations in the Galactic anticentre region, around the Crab Nebula. We consider for our study the two models of Strong, Moskalenko & Reimer (2000, 2004) which fit EGRET data and lead, after normalization with the Galactic anticentre flux at 10 GeV, to the following flux:

$$\frac{d\phi}{dS\ \ dt\ \ d\Omega\ \ dE} = 8.3 \times 10^{-4} \times \left(\frac{E}{10\,GeV}\right)^{-DI} m^{-2}s^{-1}sr^{-1}GeV^{-1}, \tag{1.1}$$

where DI is the differential index value, respectively 2.0 and 2.5 according to the two considered models between $\sim$50 and 400 GeV.

2 The CELESTE experiment

Located in the French Pyrénées (1650 m above sea level, latitude: 42.50° N, longitude: 1.97° E), CELESTE (for "C(h)Erenkov Low Energy Sampling and Timing Experiment") used 40 to 53 of the 54 m^2 mirrors (called heliostats) of the former solar plant of Themis between 1998 and 2004 (Paré et al. 2002). Secondary optics and photomultipliers equiped with Winston cones (one per heliostat), set at the top of the 100 m tower, gave a field of view of 10 mrad to the telescope. The large collection area combined with a fast acquisition electronics at 1 GHz for the sampling of the Cherenkov pulse allowed CELESTE to be the first ground based Cherenkov telescope with a threshold below 100 GeV (De Naurois, Holder et al. 2002).

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Because of the very strong hadronic isotropic background coming from the showers induced by cosmic protons and ions, point source data was taken in ON/OFF pairs, *ie* by pointing the telescope on the source direction (ON) and away from the source sky region (OFF). Most often OFF data are associated with gamma-ray source data acquisitions by shifting them by +20 or -20 min in hour angle. Data analysis is then based on geometric and timing properties of the Cherenkov wavefront. This allows discrimination between electromagnetic and hadronic showers. An significant excess in the ON-OFF substraction can then be interpreted as a gamma-ray signal.

3 CELESTE sensitivity to diffuse gamma-rays

Accurate Monte Carlo simulations (MC) are necessary for detector calibration. MC/data tuning is provided by comparing the distributions of the four variables used in our calibrating analysis. These variables are $\sigma_{\rm grp}$, θ^2, $T_{\rm Width}$ and $\sigma_{\rm t}$, and represent respectively the uniformity of the Cherenkov pool on the ground, the reconstructed direction of the shower, the width of the wavefront and the signal arrival time dispersion. Point source gamma MC reproduces ON-OFF data for each discriminating variable, as seen on Fig. 1 *(left)*, but hadronic MC are not accurate with the OFF data. On Fig. 1 *(right)*, we see diffuse gamma-ray MC distributions to be discriminant with OFF data. The distributions in both these previous figures are obtained after preliminary analysis cuts, when OFF data are mostly constituted by protons and helium nuclei.

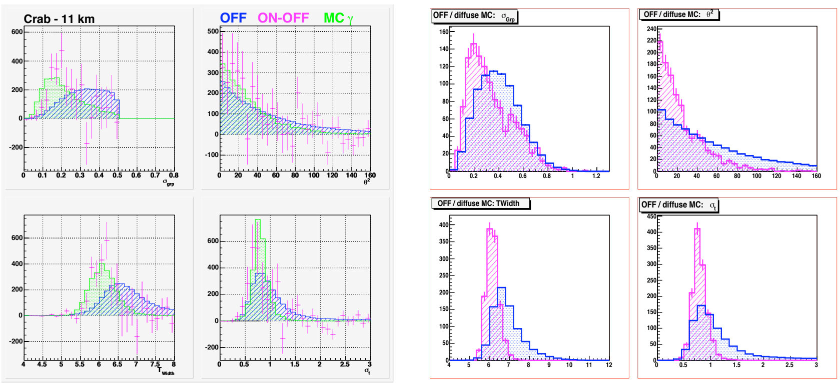

Fig. 1. Normalized distributions of the four discriminating variables. *Left:* gamma MC/data comparisons. MC/data tuning is verified. *Right*: OFF/diffuse gamma MC comparison. Discrimination between hadrons and diffuse gamma-rays is possible.

In order to improve the sensitivity of gamma-ray identification, a composed discriminating variable ("$x_{\rm eff}$") is used. It is built from probability density functions (*pdf*) of the 3 discriminating variables σ_{grp}, θ_2 and T_{Width} for gamma MC simulations and OFF data to represent respectively diffuse gamma-ray signal and hadronic background as:

$$x_{\rm eff} = \frac{\eta \times \prod_{i=1}^{n} g_{bckg}(x_i)}{(1-\eta) \times \prod_{i=1}^{n} g_{signal}(x_i) + \eta \times \prod_{i=1}^{n} g_{bckg(x_i)}}, \tag{3.1}$$

where η is a weight factor, x_i the discriminating variable i, and g_{bckg} & g_{signal} are the pdf. As visible in Fig. 2, $x_{\rm eff}$ distributions allows gamma candidates to be located at $x_{\rm eff}$ values close to 0, while hadron candidates are located at $x_{\rm eff}$ values close to 1.

The search for Galactic diffuse gamma-rays mostly located at low Galactic latitudes with CELESTE is done by OFF source data analysis, comparing data taken near the Galactic plane with data taken away from the Galactic plane, based on the ON-OFF method presented in section 2, where "ON" is now replaced by the OFF region the nearest to the Galactic equator, and "OFF" by the OFF region the farthest, in order to complete OFF-OFF pair analysis (Britto 2006). Data used in this study was selected with criteria based on atmospheric and acquisition stabilities. We also imposed source following at the same altitudes and a similar path on the sky for the two OFF members of a same pair, which is only possible if they have the same declination. The use of Crab OFF-source data give a large sample of data where some OFF are near the Galactic plane (OFF 1) since some other OFF are in the periphery of the Galactic plane (OFF 2).

The sensitivity of our analysis is characterised by the quality factor Q as a function of the efficiencies of the diffuse signal (ϵ_γ, computed with diffuse gamma MC) and backgroud ($\epsilon_{\rm OFF}$), after analysis cuts on $x_{\rm eff}$, as $Q = \frac{\epsilon_\gamma}{\sqrt{\epsilon_{\rm OFF}}}$. The significance of the expected diffuse signal is then:

$$N_\sigma \simeq Q \times \frac{n_\gamma}{\sqrt{2\, n_{\rm OFF}}} \times \sqrt{T_{\rm obs}}, \tag{3.2}$$

where n_γ is the diffuse gamma-ray rate, $n_{\rm OFF}$ ~25 Hz is the hadron rate, and T_{obs} the observation time.

Taking into account the two models with the DI = 2.0 and 2.5 differential power laws in our simulations of diffuse gamma-rays, $x_{\rm eff}$ distributions of the Crab OFF data at the lowest latitudes b are compared with $x_{\rm eff}$ distributions of both these MC respectively. Optimization to 0.5 of the η parameter of Eq. 3.1 to maximize the quality factor Q give the results presented in Tab. 1 on the CELESTE sensitivity of the diffuse gamma-ray, in gamma / min, for $x_{\rm eff} \leq 0.35$. Fig. 2 *(left)* show the $x_{\rm eff}$ distributions for DI = 2.5.

ϕ_0 at 10 GeV ($m^{-2}s^{-1}sr^{-1}GeV^{-1}$)	DI	n_γ (min^{-1})	Q	T=1h	T=10h	T=50h
8.3 $\times 10^{-4}$	2.0	1.45 $\pm$ 0.03	1.39	0.3	0.9	2.1
8.3 $\times 10^{-4}$	2.5	0.36 $\pm$ 0.01	0.96	0.05	0.2	0.4

Table 1. CELESTE sensitivity of the diffuse signal for different observation times and the spectral models of Eq. 1.1

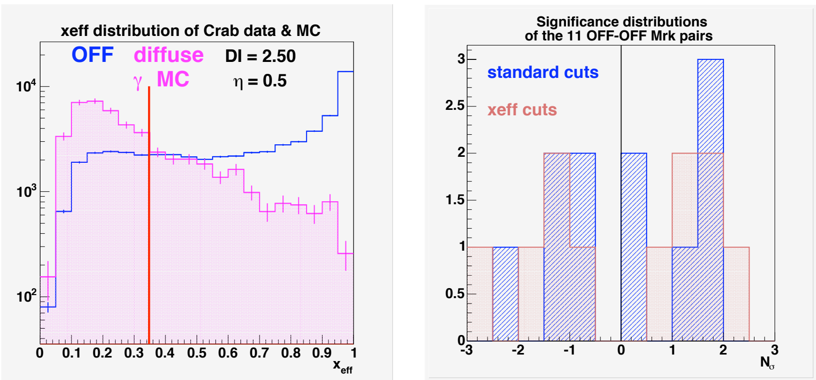

Fig. 2. *Left:* Normalized distributions of $x_{\rm eff}$ for OFF data and diffuse gamma MC for DI = 2.5. The red bar indicate the $x_{\rm eff}$ = 0.35 cut of our analysis. *Right:* Distributions of the significances of the 11 pairs of the Markarian 421 & 501 OFF-OFF selection. Comparison is done between our $x_{\rm eff}$ analysis and standard independant cuts on the discriminating variables.

4 Data analysis of diffuse gamma-rays

4.1 *OFF-OFF analysis: validation of the method*

A first step in the OFF-OFF analysis is to verify that there is no significant systematic effect in the OFF / OFF pair association of data taken at different dates but at the same local coordinates on the sky. We do for this the OFF-OFF analysis of data associated with the Mrk 421 and Mrk 501 blazar data, because we did not expect to find diffuse signal in these high Galactic latitude region. The OFF-OFF analysis around these two blazars with adapted hadron and MC gamma pdf shows the compatibility with zero of the significances of 11 selected pairs—corresponding to 150 min of data—(Fig. 2 *right*), which is a favorable issue for our analysis method.

4.2 *OFF-OFF analysis in the anticentre region*

A second step was to perform OFF-OFF analysis with other OFF acquisitions taken at different dates to search for an event excess from the data acquisitions the nearest to the Galactic equator. We have a large set of OFF data associated with Crab nebula observations, such as "OFF 1" data are near Galactic latitude $l = -2°$ since "OFF 2" data are near $l = -10°$, for a same declination. OFF 1-OFF 2 analysis is done in the view of detecting a gamma-ray excess expected to be the most intense in the data the nearest the Galactic equator. Fig. 3 *(left)* shows $x_{\rm eff}$ distributions after preliminary cuts. Diffuse gamma-ray pdf are done for both the DI = 2.0 and 2.5 indices. The $x_{\rm eff} \leq 0.35$ analysis of the 7 pairs of this data sample show no significant signal (Tab. 2).

Table 2	raw data	after first cuts	standard cuts	$x_{\mathrm{eff}} \leq 0.35$ cuts ID = 2.0	DI = 2.5
$\mathrm{N_{OFF1}}$	169869	34863	3131	6763	7337
$\mathrm{N_{OFF2}}$	168499	34692	3147	6737	7383
$\mathrm{N_{OFF1}} - \mathrm{N_{OFF2}}$	-	-	-16 $\pm$ 71	26 $\pm$ 92	-46 $\pm$ 94
N_σ	-	-	-0.17	0.17	-0.32

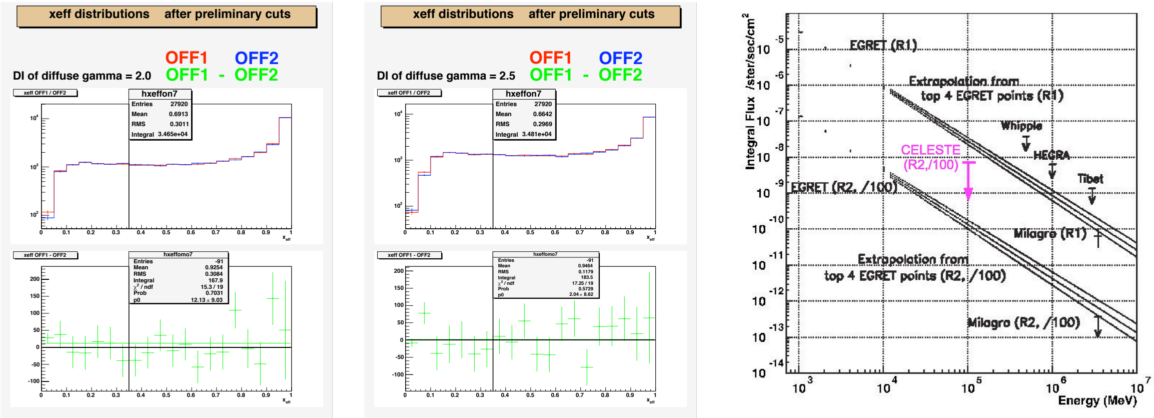

Fig. 3. *Left & centre:* x_{eff} Crab OFF and OFF-OFF distributions in the search of diffuse γ-rays in the anticentre region, with pdf of the 2.0 and 2.5 indices of the spectral models. *Right:* Upper limit of the CELESTE integral flux at 100 GeV. This limit is compared with the R2 region Milagro data, which is around the Galactic anticentre (Atkins et al 2005).

4.3 Upper limit on the diffuse gamma-ray emission

Taking account of secondary signal in the OFF regions the farthest the Galactic plane, an upper limit with 95 % C.L. on the gamma-ray flux from the Galactic anticentre region is provided (Fig. 3 *right*):

$$\phi_{int}^{UL}(E > 100\ GeV) \simeq 6.6 \times 10^{-7}\ \ cm^{-2}s^{-1}sr^{-1}. \quad (4.1)$$

5 Conclusions and prospects

CELESTE was the first ground based Cherenkov detector with an energy threshold around 50 GeV, and opening the unexplored 30-300 GeV window.

Although we had a lot of OFF data associated with acquisitions on the Crab nebula, the absence of dedicated observations to search for the diffuse emission allows us to analyse 108 min of data without significant signal. This work allows CELESTE to be currently the only experiment to have provided an upper limit on the diffuse gamma-ray emission in the Galactic anticentre region around 100 GeV.

Our result did not constrain any models, but the performed study shows a favorable perspective to go on searching for the diffuse emission with other Cherenkov atmospheric sampling and timing detectors such as STACEE and CACTUS. The next generation Cherenkov telescopes HESS II and MAGIC II are expected to be sensitive enough to detect diffuse gamma-ray emission with an energy threshold around 20 GeV, in complementarity with the AMS-02 and GLAST space detectors which will join the EGRET data to the VHE gamma-ray measurements.

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