Flux Measurement at 110 GeV of the Blazar Mrk 501 with CELESTE

Elisabeth Brion for the CELESTE Collaboration
Centre d’études nucléaires de Bordeaux-Gradignan (CENBG)
Chemis du Solarium – Le Haut-Vigneau – BP 120
33175 Gradignan Cedex, France

The new analysis variable $\xi$, shown to be powerful on the data taken with the final configuration of CELESTE, has been applied to data taken with previous detector configurations. First, the analysis is validated on Crab observations, and then the cuts for the blazar Mrk 501 are optimized using Mrk 421 data since the sources have similar declinations. Data from Mrk 501 was recorded in 2000 and 2001. The old analysis gave a $2.5 \sigma$ excess. We obtain an excess of $2.9 \sigma$ during this time and of $4.9 \sigma$ during May and June 2000 that we interpret as a $\gamma$-ray signal from Mrk 501, for which we calculate a flux of $(6.9 \pm 2.2) \times 10^{-7}$ photons m$^{-2}$ s$^{-1}$. An upper limit from the other data with no signal is determined.

1 Introduction

CELESTE (Cherenkov Low Energy Sampling and Timing Experiment) was a Cherenkov experiment using the heliostats of the former Électricité de France solar plant in the French Pyrenees at the Thémis site. It detected Cherenkov light from showers produced in the atmosphere by cosmic rays and the $\gamma$-rays coming from high energy astrophysical sources. The light is reflected to secondary optics and photomultipliers installed at the top of the tower. Finally it is sampled to be analysed.

Two states of the experiment have to be distinguished to classify CELESTE data. During the first one (between September 1999 and June 2001), 40 heliostats were used with two types of pointing (single pointing: all heliostats at 11 km, double pointing: half at 11 km, half at 25 km), and during the second one (between September 2001 and June 2004), 53 heliostats pointing at 11 km were used (of which 12 veto heliostats aimed wide for proton rejection). An analysis improvement was made using 53 heliostat data for the Crab Nebula, a bright and stable source, the new analysis variable provided a sensitivity of $5.7 \sigma/\sqrt{h}$ on 4.7 h data, whereas the old data analysis gave 2.0 and 3.4 $\sigma/\sqrt{h}$ for single and double pointing. The new analysis has been tested on 40 heliostat Crab data and gives better sensitivity as will be shown.

CELESTE has taken 40 heliostat data on the blazar Mrk 501. The old analysis gave $2.5 \sigma$. We present here the results obtained with the new analysis after optimizing cuts on the blazar Mrk 421 which has nearly the same declination as Mrk 501.
2 New Analysis applied to 40 Heliostat Crab Data

After data selection based on stability criteria, a software trigger is applied to the data in order to remove trigger bias. The data can then be analysed with the new variable $\xi$ which is a normalised sum of the Cherenkov pulses from each heliostat, optimised by finding the shower position that gives the narrowest sum (i.e. the most gamma-like) \[3, 1\]. $\xi$ has been developed on Crab data taken with 53 heliostats. The 40 heliostats data sets have been analysed with new cuts on $\xi$, determined from simulations and data. The study confirmed the dependence of $\xi$ on configuration (heliostat number, trigger) and pointing (hour angle). Different cuts were chosen depending on these parameters, yielding a sensitivity of $4.0 \sigma/\sqrt{t}$ and $5.2 \sigma/\sqrt{t}$ for single and double pointing with 40 heliostats.

The acceptances of the detector were calculated to determine a flux. They depend on many parameters: atmosphere, optical simulation (heliostats, secondary mirrors), electronic simulation, and pointing (configuration, declination, hour angle). The simulations have been improved to better fit the data, taking into account variations of the trigger rates between different data sets (two different atmospheres) and degradation of the optical chain of the detector. The lightcurve for the Crab nebula was determined for the 40 heliostat data with a spectral hypothesis of $E^{\alpha + \beta \log E}$ with $E$ in TeV, $\alpha = -2.74$ and $\beta = -0.50$ \[4\]. It is shown in figure 1 where the calculated flux is stable, within the statistical error bars.

![Figure 1: Crab nebula lightcurve seen by CELESTE above 100 GeV with statistical error bars (monthly averages centred on New Moon). The dashed line represents the mean integral flux for all the data: $\bar{\sigma}(E \geq 100 \text{ GeV}) = (3.6 \pm 0.2) \times 10^{-6} \text{ photons m}^{-2} \text{ s}^{-1}$, MJD (Modified Julian Date) 51450 and 51900 correspond to 09/29/1999 and 12/22/2000.](image-url)
Mrk 501 Flux Determination after Cut Optimisation using Mrk 421 Observations

The blazar Mrk 421 has the double advantage of having about the same declination as Mrk 501 and of being well observed with CELESTE. So cuts were optimized on Mrk 421 data. (In fact, both the simulation and the data lead to very nearby the same cuts.) We obtained a final significance for all Mrk 421 data of $29.4\sigma$ during 38.9 h. The integral flux is $\Phi(E \geq 100 \text{ GeV}) = (2.3 \pm 0.1) \times 10^{-6}$ photons m$^{-2}$ s$^{-1}$ for an $E^{-2}$ spectral hypothesis.

The number of events and significance for Mrk 501 after the same cuts are shown in table 1. A $2.9\sigma$ excess is obtained for the 2000-2001 period. The lightcurve of Mrk 501 (figure 2 left top), determined for an $E^{-2}$ spectral hypothesis, presents an excess of activity during May and June 2000 (between MJD 51660 and 51700). For this period, the significance of the excess is 4.9 $\sigma$ which is interpreted as a $\gamma$-ray signal from Mrk 501, since the blazar is already well-known in low- and high-energy $\gamma$-rays. Thus, a differential flux is calculated for this period and an upper limit is determined for the rest of the data which contains no signal.

| Cut            | $N_{\text{ON}}$ | $N_{\text{OFF}}$ | $N_{\text{ON}} - N_{\text{OFF}}$ | $N_\sigma$ | Signal to noise ratio $\frac{N_{\text{ON}} - N_{\text{OFF}}}{N_{\text{OFF}}} \times \%$ |
|----------------|-----------------|------------------|-------------------------------|-------------|------------------------------------------------------------------------|
| Raw trigger    | 815,924         | 813,641          | 2,284                         | 1.5         | 0.3                                                                    |
| Software trigger| 472,450         | 469,569          | 2,881                         | 2.5         | 0.6                                                                    |
| Final cuts     | 10,565          | 10,096           | 469                           | 2.9         | 4.6                                                                    |

Table 1: Number of events for the blazar Mrk 501 after cuts for the final data set (11.5 h).

4 Discussion

The differential flux and the upper limit, obtained for a counting maximum at 110 GeV, are drawn on figure 2 right. The different states of activity of Mrk 501 in $\gamma$-rays are not correlated to variations in X-rays: in figure 2 left bottom, the ASM flux is $40 \pm 10$ % higher in May and June 2000 than the low baseline of the rest of the studied period (figure 2 right shows a $\times 20$ and $\times 100$ increases during historical flares. These observations suggest that for May and June 2000, the emission population was different between synchrotron emission in X-rays and $\gamma$-ray emission. If the $\gamma$-ray emission is due to an inverse Compton process, it can not be explained with a SSC (Synchrotron Self-Compton) model for this particular case. Further observations of Mrk 501 with
new generation detectors (GLAST, HESS) and simultaneous to other wavelength observations will help to understand the emission processes of Mrk 501.

References

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