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Initial Blazar Studies with the CELESTE Cherenkov Telescope

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Abstract

CELESTE began systematic blazar observations in March 1999 with a 40-heliostat array at the site of the solar array at Themis in the French Pyrenees. Data is recorded using 1 GHz Flash ADC's which allow faint Cherenkov pulses to be measured. The hybrid analog-logic trigger scheme provides good hadron rejection and high efficiency for low-energy showers. A trigger threshold below 50 GeV allows CELESTE to probe the region near the peak of the inverse compton spectrum observed in many blazars. In this first observation campaign we are concentrating on Mrk 421, Mrk 501, and 1ES 1426+428.

1 Introduction

At the beginning of this decade two breakthroughs revolutionized very high energy astrophysics. Ground-based atmospheric Cherenkov detectors became sensitive, reliable gamma ray detectors above a few hundred GeV, led by the Whipple imager [Quinn, 1996]. Also, the EGRET instrument on the Compton satellite measured the spectra of over 150 point sources in the energy range $0.1 < E_\gamma < 10$ GeV [Thompson, 1995]. Since then, a number of Whipple-class imagers have begun operation.

However, an energy gap existed between data from satellites and Cherenkov detectors. The former are limited by a quite small detecting area, the latter by night-sky noise that pushes their thresholds above 250 GeV. A large light collecting surface is needed to overcome this problem. A really striking question is why very few of the EGRET sources were detected on the ground. For the extragalactic sources, one of the possible explanations is that the cut-off comes from the absorption of the gamma rays by the diffuse infrared background in the intergalactic medium [Biller, 1998]. The other explanation concerns directly the acceleration mechanism in active galactic nuclei and thus is even more appealing for the extragalactic astronomers.

In the blazar category, the νF_ν representation of the spectral energy distribution exhibits a two-peak structure. The lower-energy peak is believed to originate from the synchrotron radiation of a population of energetic electrons in a magnetic field, while the same electrons produce a peak at high energies via inverse Compton scattering of photons either from the synchrotron radiation (SSC models) or of external origin (EC). Observations of Mrk 501 by the CAT imager at Thémis are described in [Djannati, 1999]. In the case that the inverse Compton peak is well-bellow the imager energy threshold, ground observation of such blazars is not possible without new instruments allowing either increased flux sensitivity or a lower energy threshold.

The exploration of the highly interesting energy region $30 < E_\gamma < 300$ GeV is the goal of the CELESTE detector [Paré, 1993. We adapted the wavefront-sampling technique pioneered by the Themistocle [Baillon, 1993] and ASGAT [Goret, 1993] experiments to the geometry of the central-receiver solar power plant built by Electricité de France at Thémis in the Eastern Pyrenees (N. 42.50°, E. 1.97°, 1650 m. a.s.l.). Below 100 GeV, the advantages of the imaging technique for hadron rejection are less compelling because in this energy range hadron showers emit relatively less Cherenkov light than gamma showers.

CELESTE is approaching its final form. In this paper we describe its current state with 40 heliostats. Details of the data analysis and description of gamma-ray events recorded simultaneously by both CELESTE and the CAT imager are presented in OG 4.3.06. OG 2.2.31 describes work underway to search for pulsed emission.

2 Detector status

For this stage of the experiment we use 40 of the 160 heliostats still available on the site (see figure 1). Each of these quasi-spherical back-silvered mirrors wit 54 m^2 surface area with an alt-azimuth mount is guided from the control room situated at the top of the 100-meter tall central tower.

Our secondary optics has replaced the 30-ton heat receiver in the five-by-five meter opening at the top of the tower. The reflecting surface is composed of 50 cm mirrors arranged into six sections in order to optimize light collection: one section views the farthest heliostats; two view the intermediate heliostats; and three view the heliostats at the foot of the tower.

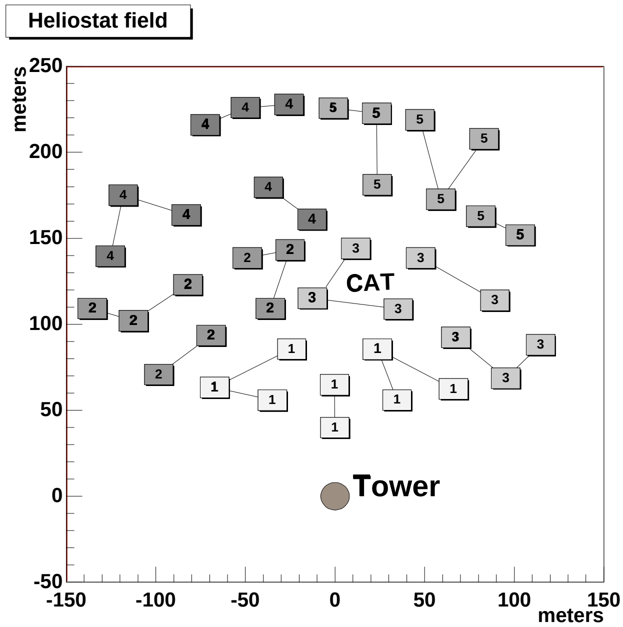

Figure 1: *Field of heliostats in use. Numbers indicate division into the trigger groups, thin lines join the subgroups.*

At the focus of the secondary mirrors is one Philips XP2282 photomultiplier for each of the heliostats (also divided into six cameras, reducing thus the shadowing effects). A solid Winston cone glued to each phototube defines a field-of-view of 10 milliradians, their openings corresponding to the sizes of the heliostat images in the focal plane of the secondary optics (to minimize the albedo photons entering the PM). The small field-of-view requires us to aim the telescope not at the gamma-ray source itself, but at the region in the atmosphere where the Cherenkov light is generated (about 10 km above the site when tracking a source near the zenith).

The heliostats have been aligned by maximizing phototube currents while scanning bright stars. The combined phototube and electronic gains are set to give 15 mV per photoelectron in the control room. The average anode current due to night-sky light is typically 12 μA.

The trigger is designed to reach the lowest possible energy threshold: the signals of photons originating from the pointing region reflected on different heliostats should sum up to a single peak well above the night-sky noise. Programmable analog delays are set to compensate for the differences of the optical paths of Cherenkov photons following the celestial track of the source. We assume a spherical wavefront of the shower, most justified in this range of energies — many less-regular hadronic showers are thus rejected at the trigger level. With the distances up to a few hundred meters and analog delays limited to 255 ns, the field of the heliostats has to be divided into smaller groups triggering individually with the threshold proportional to the number of heliostats available in each group. The trigger signal of all groups is put in time using programmable logic delays, and the final trigger is a coincidence of a given number of groups (three at present).

A larger number of groups makes a larger part of the sky accessible with a given range of analog delays but fewer heliostats per group also means a reduced signal-to-noise ratio in the analog sum, thus imposing a higher threshold. We have chosen the minimum number of 5 groups of 8 heliostats (as shown in figure 1) — our delay modules allow up to 9 channels per group divided into 3 subgroups (indicated by thin lines), the delays between channels in one subgroup are limited to 127 ns. With a number of fixed delays (roughly compensating the differences in the distances from the tower of the heliostats of one group) we are able to observe targets up to 30 degrees from the zenith, i.e. sources with declinations from 15 to 70 degrees (however, for northern directions beyond $\delta = 55°$, the projected collecting surface of heliostats becomes too low).

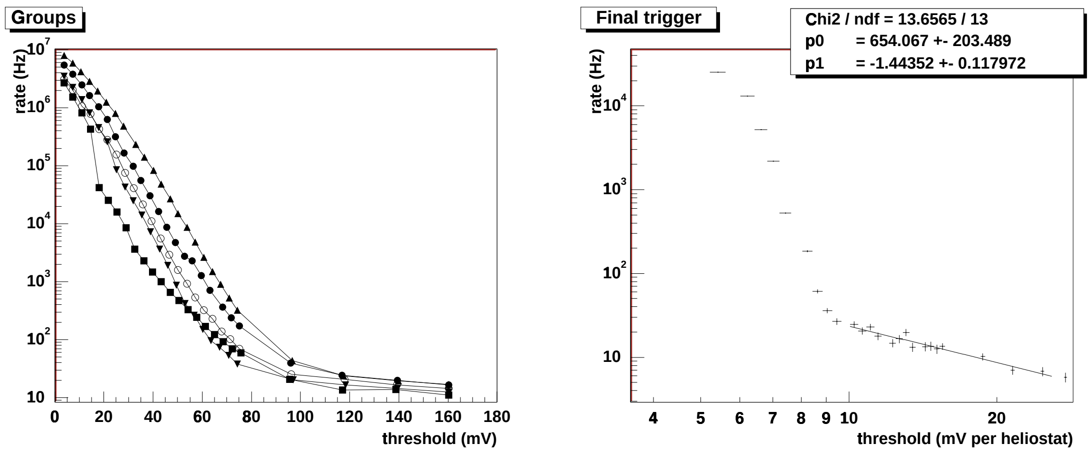

Figure 2: *Trigger rate versus threshold for each of the five groups of 8 heliostats (left) and the three-fold coincidence trigger (right). The breakpoint between night sky light induced accidentals and air showers is below 3 photoelectrons per heliostat. The upper part of the graph is fitted with a function* $r = p_0 * T^{p_1}$ *(the explanation of a difference of the exponent from that of the power-law spectrum of infalling hadrons is given in (Giebels, Dumora)).*

In the beginning of 1998, CELESTE made its first observation of the Crab Nebula [de Naurois, 1998], validating the principle of its trigger by measuring the knee in the threshold-rate function. Since then, the detector has not only doubled its size, but has also much improved in timing of the trigger and heliostat alignement. As seen in figure 2, the knee position now corresponds to threshold of $9-10$ mV per heliostat and rate 25 Hz. With a conservative threshold 13 mV per heliostat, we are well above the noise and obtain a rate of Cherenkov events of about 20 Hz. This rate in the current configuration results in an acquisition deadtime of around 25% due mainly to the readout time of FADC described below (this will be reduced to less than 10% in the coming months). The attenuation in the analog delay modules being almost independent of the set delay, a threshold of 13 mV per heliostat corresponds to approximately 3 photoelectrons per hel. Assuming the peaks are perfectly summed in each group, i.e. for a gamma shower falling in the center of the field, we get an energy threshold of about 30 GeV.

The phototube signals are sampled using 1 GHz flash ADC's. In 1998 the Struck DL515 were gradually replaced with 2-channel Etep model 301c (see reference). Since January 1999, we are recording all 40 channels by summing pairs of PM signals. This, however, increases the night-sky light fluctuations in the data by the factor of $\sqrt{2}$, (by the Fall we will have installed 10 more cards and thus will abandon the summing).

The data acquisition system is rather elaborate. A HP workstation orchestrates tasks amongst secondary computers: heliostat tracking, measurement of phototube anode currents and weather monitoring are each on a separate PC. Three VME crates are controlled by Motorola processors running the Lynx variant of real-time Unix. All exchanges amongst the computers use standard TCP/IP protocol and the data files are stored on the central HP. The data is transferred daily to central computer facilities in Lyon for subsequent analysis.

3 Data sample

Out of our three principal blazar targets, two, Mrk 421 and Mrk 501, are well established sources, detected by EGRET and followed regularly by ground based Cherenkov detectors. The choice of the last one, 1ES 1426+428, is an attempt to probe extreme blazars, with synchrotron peaks in the hard X-ray range. We follow the strategy that was succesful for Whipple in their discovery of 1ES 2344+514 [Catanese *et al*, 1998], namely, to favour X-ray selected BL Lacs [see the ROSAT catalog by Perlman et al, 1996]. Moreover, with a redshift of 0.129 its (non) detection would be a strong argument in probing the extragalactic infrared background. Finally, at our lattitude, 1ES 1426+428 passes near Zenith (allowing the longest observation times) and its Right Ascension falls between those of Mrk 421 and Mrk 501, filling thus the gap in our observation schedule.

The observation strategy insists on rigorous following of ON-OFF pairs, usually 30 minutes long. Tracking the same part of the sky, we thus assure equal light-collecting efficiency in both runs. However, underlying stars and changes in meteorological conditions may still cause the variation of the night sky noise, that has strong influence on event reconstruction and χ^2 of the wavefront fit (for details on the analysis, see OG 4.3.06). A more sophisticated analysis procedure has to be developed, including probably software padding to equalize the noise background.

Our current data sample for blazars can be summarized as follows:

- ⊙ **Mrk 421 :** Since January 1999 we have spent almost 36 hours observing this source, getting about 15 hours of ON-OFF pairs. Putting aside the data form January, when only 18 channels were recorded, and February, when about 7 to 10 heliostats of 40 had tracking problems, there remains about 9 hours of ON-OFF data. About one third of these runs suffers from instabilities in the current, so we are left with about 13 pairs of good data. About 5 of the has been analysed so far, giving generally a small negative signal, that can be attributed to the insufficient treatment of the night sky noise excess in ON data (a star of 6^{th} magnitude near Mrk 421).
- ⊙ **Mrk 501 :** For this source, which became observable in March, we have so far collected 13 hours of raw data, forming 9 pairs ON-OFF (250 minutes). Only about 100 min have sufficiently stable conditions, but observation of this source will continue intensively during May and June, preferably in common runs with the CAT telescope, for which Mrk 501 is also a source of a high interest.
- ⊙ **1ES 1426+428 :** During March and April we have been observing this source for about 12 hours i.e. 11 ON-OFF pairs, 6 of them of a sufficient quality (moreover, in the first half of May we have another 5 pairs, partly in common runs with CAT).

4 Conclusions:

The CELESTE detector has started to collect data of good stability and quality. The trigger efficiently selects Cherenkov events with intrisic hadron rejection. A large amount of observational time has already been spent on the blazar sources. More time will be needed to make the analysis a reliable tool offering good variables for the hadron rejection insensitive to the variation of the night-sky light. The results of this effort will be presented at the conference.

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