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First Results & Future Prospects for 30 GeV Gamma Rays from CELESTE

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Abstract

The CELESTE solar farm gamma-ray telescope detected the Crab Nebula at 80 GeV (2×10^{25} Hz) using 18 heliostats in 1998. In March 1999, observations began with a setup extended to 40 heliostats, and with upgraded electronics.

Technical delays and bad weather only permitted a very small data set for the Crab nebula. 1.2 hours of data were taken simultaneously with the CAT imaging telescope showing evidence for a gamma signal. In this talk the analysis method of these data is described.

CELESTE has passed major milestones and the groundwork is laid for the blazar and pulsar studies presented elsewhere in this conference (OG 2.1.20, OG 2.2.31).

DEDICATION : *CELESTE is the brainchild of Eric Paré, who died at the age of 39 in an automobile accident, two weeks after finding our first gamma ray signal. Eric also played a major role in the conception and design of CAT. We dedicate this work to his memory.*

1 Introduction:

The motivation to bridge the energy gap between the current Cherenkov imagers and EGRET on the Compton Gamma Ray observatory has been emphasized elsewhere - see for example (Smith 1999). CELESTE and STACEE (OG 2.2.07) are so far the first experiments to peek through this new window, using the large mirror surfaces of heliostat arrays.

During the construction phase, we used 18 heliostats to acquire data from the Crab Nebula, from which we extracted a gamma ray signal (de Naurois, 1998). The energy threshold after analysis was 80 GeV and the significance was 5.6σ after 3.5 hours of observation.

We then turned to the installation of the additional 22 heliostats. We made significant changes to the acquisition electronics and software, e.g., we installed 1 GHz Flash ADC's (*FADC*) developed for CELESTE, and we added a network of secondary computers to enhance our data quality monitoring (phototube currents, etc) and thus facilitate the control of all systematics.

CELESTE has the unique advantage of sharing its site with the CAT imaging telescope (OG 2.1.08, OG 2.1.09, OG 2.2.03, OG 2.2.05). In February 1999, CAT and CELESTE tracked the Crab simultaneously, then used GPS time stamps to identify those air showers which triggered both detectors. This paper describes the data analysis method being developed for the 40 heliostat array, and describes the first efforts to understand the properties of the common CAT/CELESTE showers with a view towards improving the sensitivity of both telescopes.

2 Data Sample:

By the end of the Crab observation season, due to technical problems and unusually bad weather, we had a very small data sample. We had 3 hours of ON data and 3 hours of OFF data, including 1.2 hours of ON data acquired at the same time as CAT. The average number of operational heliostats for this data is 24.

In addition to Crab data, we have started accumulating data while tracking the blazars Mrk 421, Mrk 501, and 1ES 1426+428 (see OG 2.1.20). So far this data has served mainly to refine the analysis technique.

2.1 Analysis method: The first step in the analysis is to find peaks in the FADC data, and thereby to estimate the Cherenkov light amplitude and wavefront arrival time for each heliostat, on a shower-per-shower basis.

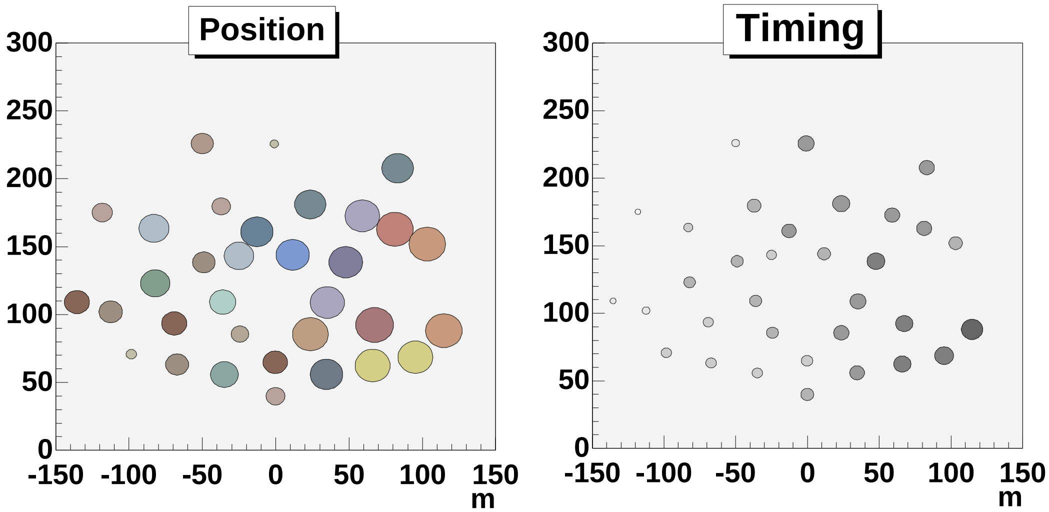

Figure 1: Typical event from CELESTE. Distribution of the light amplitude collected on each heliostat is shown on the left plot. The right plot shows the arrival time of the shower on each heliostat. Each circle corresponds to one heliostat, and distances are given in meters with the origin at the tower.

At Themistocle energies (above 2 TeV) (Baillon, 1993), the showers are long enough (several kilometers) to generate a conical wavefront. Wavefront reconstruction using arrival times then suffices to estimate the shower direction. But at much lower energies, showers are much shorter and the wavefront, according to simulations, appears to be essentially spherical. The CELESTE timing thus only gives one point, which is the point of emission of the Cerenkov light, at about 11km above the ground.

We use the pulse times to reconstruct a spherical wavefront of radius $(11\ \mathrm{km})/\cos\theta$ where θ is the zenith angle. Using a parabolic approximation, the *shower maximum* can be reconstructed analytically. The time dispersion (FWHM) of the emitted light at the reconstructed shower maximum is observed to be less than 1ns. This result validates the timing control of the whole experiment at the nanosecond level.

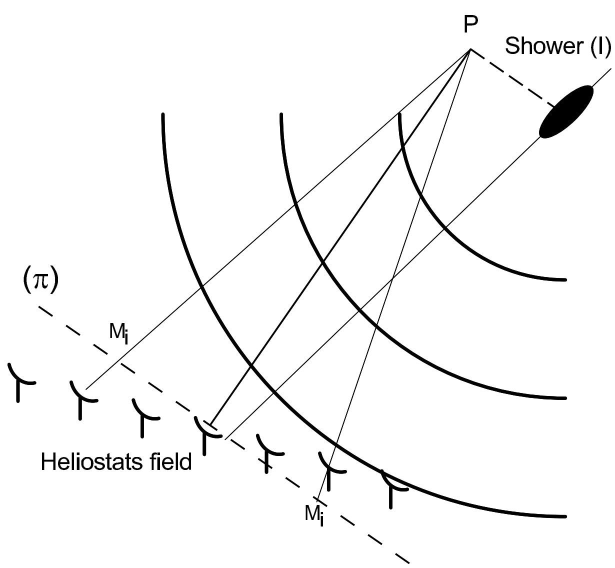

Figure 2: Shower Maximum reconstruction.

Small changes in the night sky light between the ON and OFF data change the timing resolution and hence distort the distributions of variables such as the number of peaks above a given amplitude in an event, the timing dispersion (or χ^2), and the reconstructed shower position. We estimate the amplitude-dependent timing resolution by injecting software pulses very similar to the Cherenkov signal into data taken with a random trigger, and then reconstructing them. We have also begun exploring software “padding” to equalize the noise in the ON and OFF data, in a spirit similar to that described by Cawley (1993).

The reconstruction of the shower maximum only provides one point of the shower axis. Direction reconstruction requires a second point. The region generating the collected light depends on the altitude of the convergent pointing. A method under study is to divide the heliostats into two subgroups, one of which aims towards the beginning of the shower and the other towards the tail. Timing reconstruction of the lateral position at these two heights would then provide the direction.

A different approach uses the pulseheight on each heliostat to estimate the shower impact point. Ideally, the light distribution is a two-dimensional disk of about the diameter of the Themis heliostat field. In practice, light collection efficiency depends both on the heliostat orientation and on shower impact parameter. A maximum-likelihood approach based on detector simulation results is being investigated.

3 CAT and CELESTE common events:

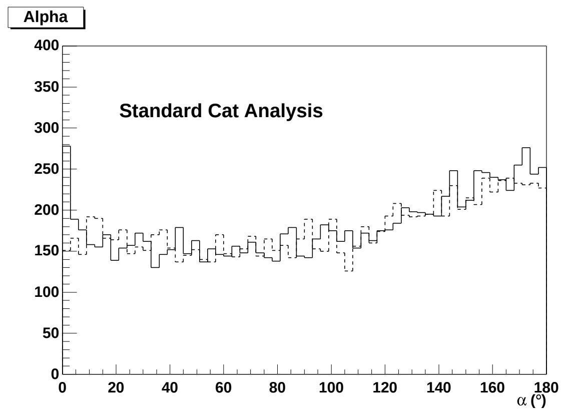

Figure 3: *Distribution of pointing angle* α *for Crab showers seen by the CAT telescope with standard analysis. This set of data corresponds to 1.5 hours observation On and Off source.*

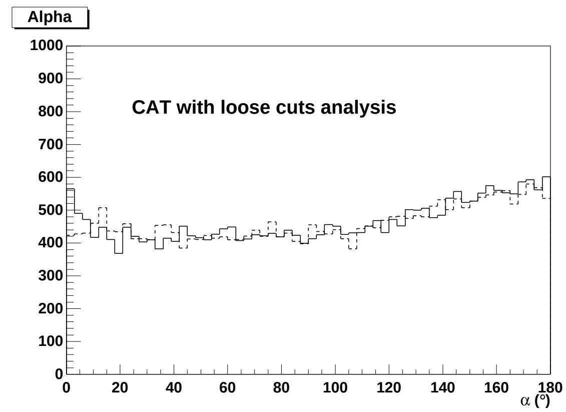

Figure 4: *Distribution of pointing angle* α *for Crab showers seen by CAT with loose analysis cuts.*

Both CAT and CELESTE record a GPS timestamp in their data streams (OG 2.2.31). We identify air showers that triggered both detectors by requiring the GPS times to match within 2 μs. Roughly 20% of the CELESTE events satisfy this requirement, which represents about 4Hz. Note that CAT & CELESTE acceptances are quite different. In particular CAT has poor sensitivity for showers with a small impact parameter, which corresponds to the region in the heliostat field where CELESTE has its best sensitivity. Above 300 GeV, the CELESTE acceptance is 4 times smaller than CAT's.

The number of accidental coincidences, estimated by adding a constant shift to the GPS time of one experiment, does not exceed 10 events in one hour for a 2 μs match. It is thus established that a single shower can trigger both detectors.

For each event, CAT provides a list of quantities such as the pointing angle α from their standard analysis procedure (Lebohec *et al*). CELESTE provides the

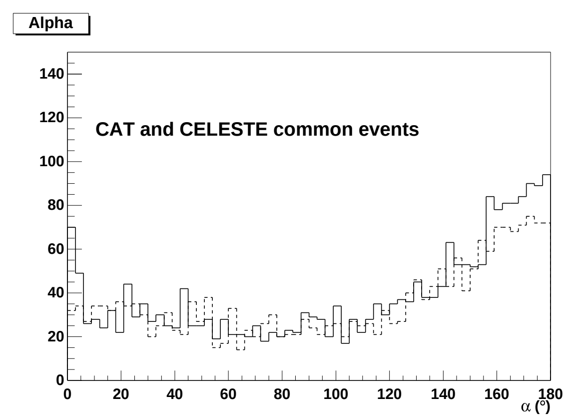

Figure 5: *Distribution of CAT pointing angle* α *for Crab showers seen both by the CAT and CELESTE telescopes. The data set corresponds to 1.2 hours On source and 1.2 hours Off source. This distribution exhibits a* 4σ *excess for* $\alpha < 6^o$*. The significant excess at high pointing angle (i.e.* $\alpha > 160^o$*) can be interpreted in term of low energy events that are not properly reconstructed by the CAT telescope.*

time and amplitude measured at each heliostat.

Figure 3 shows an α-plot for 1.5 hours observation on the Crab by CAT. The signal in the $\alpha < 6^o$ region has a significance of 4.3σ for an hour of observation. Standard cuts from the CAT analysis are applied to the data: total charge above 30 photoelectrons and reconstruction χ^2 probability above 0.35. Figure 4 shows the α-plot constructed from the same data set with looser cuts: no cut on the total charge, a cut on the χ^2 probability set to $P(\chi^2) > 0.2$ instead of 0.35. We use looser cuts to take low energy (badly reconstructed) events into account. This set of cuts lowers the significance of the signal to 3.8σ per hour. Figure 5 shows the same distributions for events that triggered both CELESTE and CAT. The time overlap between CAT and CELESTE data is only 1.2 hours out of the 1.5 hours from the CAT Data.

Some major points need to be emphasized:

- ⊙ In the medium α range, where no signal is expected, the CELESTE trigger condition reduces the number of hadronic showers by factor of 3 beyond the 20% event overlap. This is because the CELESTE trigger requires a shower to illuminate a wide area on the ground (more than 100m), and in particular rejects single muons, which are likely to be accepted by CAT operating alone.

- ⊙ Altogether, the signal/background ratio in the $\alpha < 6^o$ range is increased by a factor of more than 2, and reaches the value of 1 in the set of events seen by both CAT and CELESTE, whereas the standard CAT analysis gives a ratio of 0.5.

- ⊙ In the $\alpha > 160^o$ range, CELESTE selects a significant excess of about 2.8σ not seen by CAT alone. This excess is probably due to low energy γ events from the Crab whose orientation is reversed in the CAT analysis, as is more likely to occur for events with too few photons for the CAT reconstruction scheme.

4 Conclusions

We dispose of a detector sensitive to gamma rays below 50 GeV, using 40 heliostats of the Themis solar array. Timing of the experiment is now under control below the 1ns level, and reconstruction of the shower maximum can be performed with a precision estimated to be below 40m. Analysis techniques are now being refined to extract the direction of the shower from the data.

Air showers recorded by both the CAT imager and CELESTE contain a gamma-ray Crab signal that can be used to optimize the analysis, and the use of the CELESTE trigger in the CAT analysis increases the signal/background ratio by a factor of more than two.

We have begun accumulating data samples from other sources.

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