First Detection of Gamma Rays from the Crab Nebula with the CELESTE "Solar Farm" Cherenkov Detector

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We have converted the THEMIS solar array (French Pyrennees) into an atmospheric Cherenkov telescope, called CELESTE, sensitive to astrophysical gamma rays above 30 GeV ($7\text{x}10^{24}$ Hz). In early 1998 the Crab nebula was detected at 80 GeV with a preliminary 18 heliostat setup. The full 40 heliostat array has since been commissioned. The STACEE experiment using the same technique in New Mexico is also analysing their first data. Thus, the window between the EGRET instrument and the Cherenkov imagers has been opened. We describe the CELESTE detector and the data analysis, and discuss the prospects for studying AGN (specifically, blazars) and galactic sources in this energy range.

1. INTRODUCTION

Around 1990 two breakthroughs revolutionized very high energy astrophysics. First, ground-based atmospheric Cherenkov detectors became sensitive, reliable gamma ray detectors above a few hundred GeV, led by the Whipple imager [1] and followed by the Themistocle and ASGAT wavefront samplers [2, 3]. Second, 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 [4]. Since then, a number of Whipple-class imagers have begun operation [5–7], and imager arrays with increased sensitivity are being planned [8, 9]. GLAST will be a high performance successor to EGRET when launched in 2005 [10].

An energy gap existed between the Cherenkov telescopes and EGRET. The former "turn on" above 250 GeV; the latter have a significant counting rate only below 10 GeV. The ground devices have good flux sensitivity: the sources detected on the ground are amongst the weakest seen by EGRET (*e.g.* Mrk 421), or were undetectable by EGRET (*e.g.* Mrk 501). And so it is quite striking that the large majority of EGRET sources have *not* been seen by the Cherenkov imagers. Two possible explanations, both of great physical interest, are : the acceleration mechanisms in the sources suffer cut-offs between the EGRET and Cherenkov ranges; and/or gamma ray absorption by the diffuse infrared background in the intergalactic medium comes into play.

The motivation to explore the intermediate energy region, $30 < E_\gamma < 300$ GeV, is thus strong. For the CELESTE experiment, we transformed the Electricité de France central receiver solar

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power plant at Thémis (N. 42.50°, E. 1.97°, 1650 m. a.s.l.) into a gamma ray telescope [15–17]. We adapted the atmospheric cherenkov wavefront sampling technique to the geometry imposed by the power plant, in order to proceed rapidly and economically. The presence of the CAT imager on the same site, as well as the Themistocle and ASGAT experiments, also speeded this project.

After a discussion of the scientific goals of CELESTE, we will describe the experimental apparatus and we present the first detection of the Crab nebula in this new energy range. References [13, 14] are comprehensive reviews of very high-energy gamma-ray astronomy.

2. SCIENCE

2.1. Extragalactic gamma rays: Blazars

Figure 1 shows a remarkable result obtained in 1997. A flare of the blazar Mrk 501 was detected simultaneously by the BeppoSAX x-ray satellite and the Cherenkov imagers Whipple, HEGRA, and CAT [18]. During the flare, the peak positions shifted to higher energies by two orders of magnitude. The dark curves are from a Synchrotron Self-Compton model (SSC) for gamma ray production. This result alone nearly suffices to reject hadronic models of high energy phenomena in Active Galactic Nuclei.

The answer to the question raised above, why have so few EGRET blazars been seen by the Cherenkov imagers, lies partially in the figure: EGRET detects preferentially those blazars, such as Mrk 421, for which the inverse compton peak is near 10^{23} Hz (400 MeV). The sensitivity range of the Cherenkov imagers is then beyond the peak, in the region where SSC gamma ray production decreases rapidly with increasing energy. Inversely, Mrk 501 (and 1ES2344+514, the third Whipple blazar [19]) has its peak in the range accessible by the Cherenkov imagers, and EGRET finds itself “in the hole”.

To constrain the blazar models further, and thus AGN models in general, requires further detections beyond the EGRET energy range. This is the goal of the CELESTE experiment: peak sensitivity is near 40 GeV (10^{25} Hz) allowing detection of many EGRET blazars (mainly radio-selected BL Lac objects) as well as x-ray selected BL Lac objects as have been seen by the Cherenkov imagers. Once the SSC spectra (or variants invoking external photon sources to reproduce the inverse compton peak) have been measured for a larger variety of blazars, a major step towards understanding AGN in general will have been made.

2.2. Diffuse infrared gamma absorption

Mrk 421 is the dimmest blazar seen by EGRET, while Mrk 501 and 1ES2344+514 are even fainter. Naive extrapolation of the other EGRET sources to imager energies suggests that many should have been seen, and the gamma-ray production arguments outlined above don't suffice to explain the shortfall. It happens that Mrk 421, Mrk 501, and 1ES2344+514 are the closest known blazars (redshifts from $z = 0.031$ to 0.044). The most probable explanation is then that gamma rays are absorbed via $\gamma\gamma \rightarrow e^+e^-$ in the intergalactic medium, where the target photons are from the diffuse infrared background [12]. The threshold energy of the target photons is m^2/E_γ (m is the electron mass). The density of diffuse extragalactic light is a power law decreasing with increasing energy, from 3° K to UV frequencies and beyond. For TeV photons (and thus infrared target photons), one optical depth corresponds to a redshift of about $z = 0.1$, as shown in figure 2. At EGRET energies the effect is negligible. The intermediate energy region covered by CELESTE should permit observation of the spectral cut-off due to infrared absorption.

Distinguishing intrinsic spectral cut-offs from intergalactic absorption will be tricky, at best. And CELESTE, with coverage of a single decade in energy, will need information from the adjacent energy ranges as well as a larger sample of sources than has presently been observed from the ground. Nevertheless, the scientific gain could be considerable: galaxy formation theory predicts that the extragalactic *IR* density is a good estimator of the epoch of galaxy formation. Galactic *IR* foregrounds render direct measurements of the extragalactic *IR* density difficult. The CELESTE energy range is thus critical.

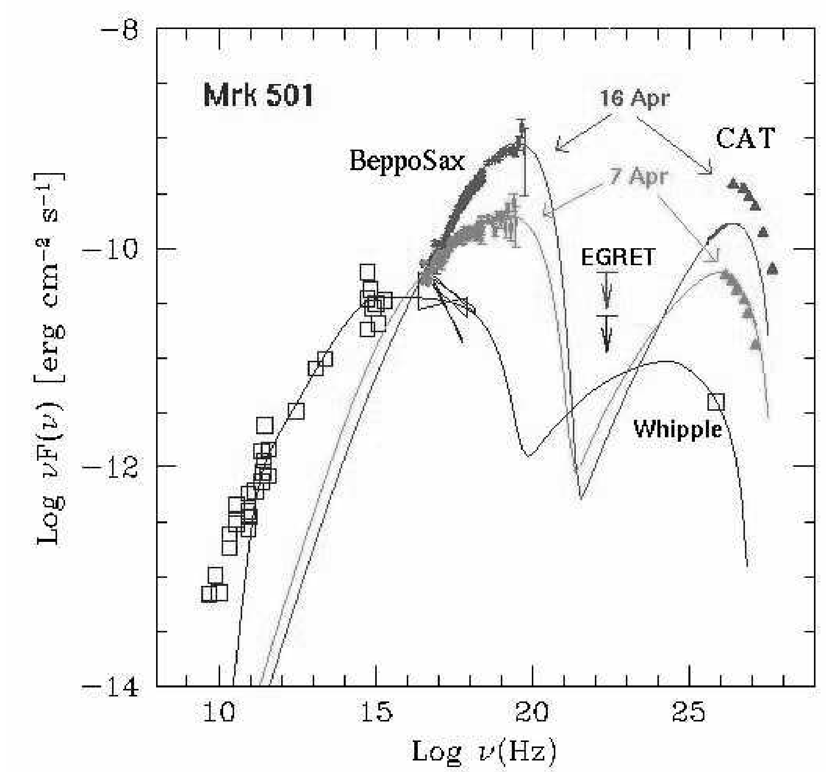

Figure 1. Spectrum of the blazar Mrk 501. The CAT Cherenkov imager (inverse compton peak, to the right) and the X-ray satellite SAX (synchrotron peak, to the left) both saw large changes in the spectral shape and intensity during a flare in April 1997. CELESTE, under construction at the time, covers the decade in energy just below CAT. The model is from Pian *et al.*

2.3. Galactic sources - Supernova remnants, and perhaps pulsars

Supernova explosions are the most plausible sites for the acceleration of charged particles to the energies observed in the cosmic radiation: the observed spectrum is a power law up to the "knee" near 10^{15} eV. (The steeper power law beyond the knee could emanate from extragalactic acceleration sites. The blazar studies discussed above should cast light on this problem.)

Nevertheless, almost a century after the discovery of cosmic rays, only scant direct evidence pinpoints supernova remants as cosmic ray accelerators. It's a tough business - for the high-energy charged particle "beam" to produce a bright secondary gamma ray source requires a dense target (*e.g.* a molecular cloud)properly placed with respect to a terrestial observer. The number of candidate SNR's is thus small. The intensity is near the limits of EGRET's sensitivity; the Cherenkov imagers energy range may be higher than the spectral cut-off. Furthermore, SNR's tend to be extended spatially and all Cherenkov telescopes have highest performance for point sources. CELESTE operates in an energy region where non-observations may sufficiently constrain models, but it is unlikely at this time that it will be the richest field of study for this telescope.

(The Crab nebula is a special case: it is a nearly constant gamma ray source, well-measured at most wavelengths, and is studied more as a standard candle than for its scientific merit.)

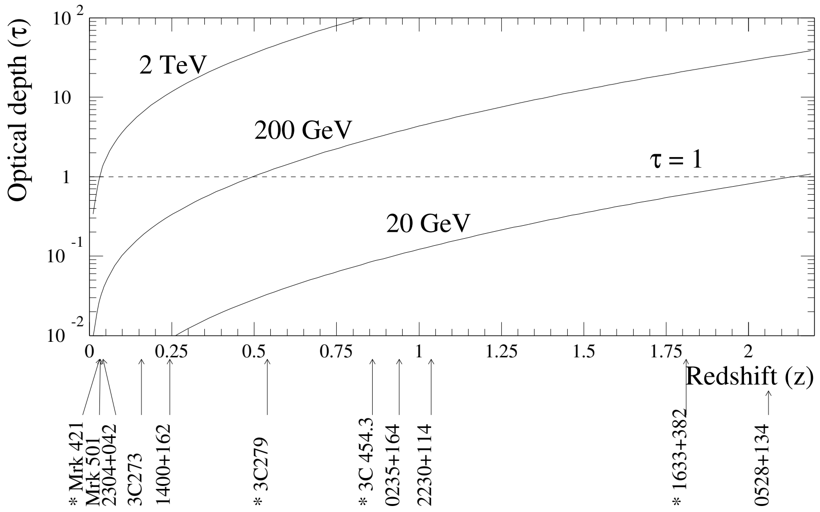

Figure 2. *The optical depth τ for gamma ray absorption by $\gamma\gamma \rightarrow e^+e^-$ pair production, as a function of the redshift of the source, for three gamma ray energies. The curves are calculated using a power law approximation of the diffuse extragalactic infrared photon density wavelength dependence. Absorption become appreciable in the energy range in which CELESTE is sensitive.*

3. THE ATMOSPHERIC CHERENKOV TECHNIQUE

An energetic particle incident on the atmosphere initiates a particle cascade. Below a few tens of TeV the only part of the shower reaching the ground is the Cherenkov light emitted by the ultrarelativstic charged shower particles. Photomultiplier tubes mounted in the focal plane of one or several mirrors sample a fraction of this Cherenkov light, from which the energy and direction of the primary particle is deduced. Primary particle identification is sufficient to enhance the gamma ray signal above the hadron background on a statistical basis.

Two major classes of Cherenkov telescopes exist. "Wavefront samplers" use several mirrors distributed over a field of the size illuminated by a shower (about 200 meters). Each mirror has one to several phototubes, to sample the spatial distribution and arrival time of the Cherenkov light on the ground. The only wavefront samplers to have seen a gamma ray source (the Crab nebula) are ASGAT and Themistocle, both at the Themis site.

"Imagers" use many phototubes mounted on a single mirror, and thereby sample the angular distribution of the Cherenkov light at one point in the field. (A variant is to use additional imagers for stereoscopic vision). Whipple remains the premier imager, but the CAT telescope at Themis has comparable flux sensitivity and energy threshold, compensating for a smaller mirror (16 m^2 vs. 75 m^2) with a smaller pixel size (2.2 mr vs. 4 mr) and faster optics and electronics [5].

In general, Cherenkov telescopes trigger when the signals from n phototubes exceed m photoelectrons, in a coincidence time gate τ. The phototubes are illuminated by the constant diffuse night sky light ϕ (photons per unit time, area, and solid angle), and the threshold m has to be high enough above the average light level so that fluctuations above the mean yield a rate of accidental coincidences much lower than the Cherenkov trigger rate. For a given phototube type (speed, dispersion, and dark current are the key parameters) the fluctuations scale as the square root of the mean light level per phototube, which is $\phi\tau\epsilon\Omega A$. Ω is the solid angle per pixel, ϵ is the photon collection efficiency, and A is the mirror area. The number of Cherenkov photons scales as $\epsilon E_\gamma A$, where E_γ is the primary gamma ray energy, and hence the energy threshold for a Cherenkov gamma ray telescope is

$$E_\gamma^{threshold} \propto \sqrt{\frac{\Omega\tau\phi}{A\epsilon}}. \quad (1)$$

The current generation of imagers have pushed τ and Ω to their practical limits. The CAT imager is an excellent example: an isochronous mirror and very fast phototubes and electronics match the detector response to the intrinsic time spread of the Cherenkov signal (a few nanoseconds). While waiting for technological progress to improve quantum efficiencies and hence ϵ, the race to lower energies amounts essentially to a search for larger mirror areas, A.

The MAGIC project is the most ambitious effort to extend the imaging technique to 30 GeV [20]. MAGIC should be operational in 2003. CELESTE and STACEE (see below) have already reached the new energy regime, exploiting solar plant infrastructures to obtain very large mirror areas. Two Cherenkov projects dominate the horizon : HESS is a franco-german imager array that will be built in Nambibia [8]; VERITAS is the American version [9]. Operation will begin in 2002.

4. IMAGERS AND WAVEFRONT SAMPLERS

The key parameters defining the performance of a gamma ray telescope are: flux sensitivity; angular resolution; and energy resolution. Flux sensitivity determines how long it takes to detect a signal from a source of a given strength, and depends on the collection area, background rejection, and angular resolution of the instrument. (The collection area here is not the mirror area sampling the shower but the area over which air showers trigger the telescope.) The angular resolution further determines the precision with which a source can be located. About half of the EGRET sources are unidentified, in part due to EGRET's $\sim 1^\circ$ resolution. The typical angular resolution of a Cherenkov telescope is about a tenth of that, and so Cherenkov telescopes should be able to contribute to the identification problem.

Imagers have worked best above 200 GeV, since the fine sampling of their cameras allows excellent hadron rejection. But below 100 GeV, hadron backgrounds are naturally suppressed because the Cherenkov yield of the hadron showers decreases faster than that of the gamma showers. Hence, the advantage of the imagers is less.

Below 100 GeV single cosmic ray muons replace hadron showers as the most important background for high precision Cherenkov imagers. A single muon passing near the mirror appears as a circle or an arc in the imager camera and can be easily rejected. But muons farther from the mirror produce arcs so short that some are indistinguishable from a gamma ray signature. Modern imagers thus incorporate subsystems to help measure this background, and the trend is towards multiple (e.g. stereo) imagers in part to decrease muon sensitivity. Wavefront imagers, and especially CELESTE, are inherently insensitive to muons. This is because the small field-of-view (10 mr) combined with the separation between heliostats makes it nearly impossible for a single Cherenkov cone to illuminate more than a few phototubes.

At low energies, the background due to cosmic ray electrons is also more important than above 200 GeV. Their energy spectrum is steeper than the hadron spectrum, and as stated, the efficiency for primary hadrons falls off rapidly below 100 GeV. Since electron induced showers are practically indistinguishable from gamma ray showers, angular resolution is the key to suppressing the electron background.

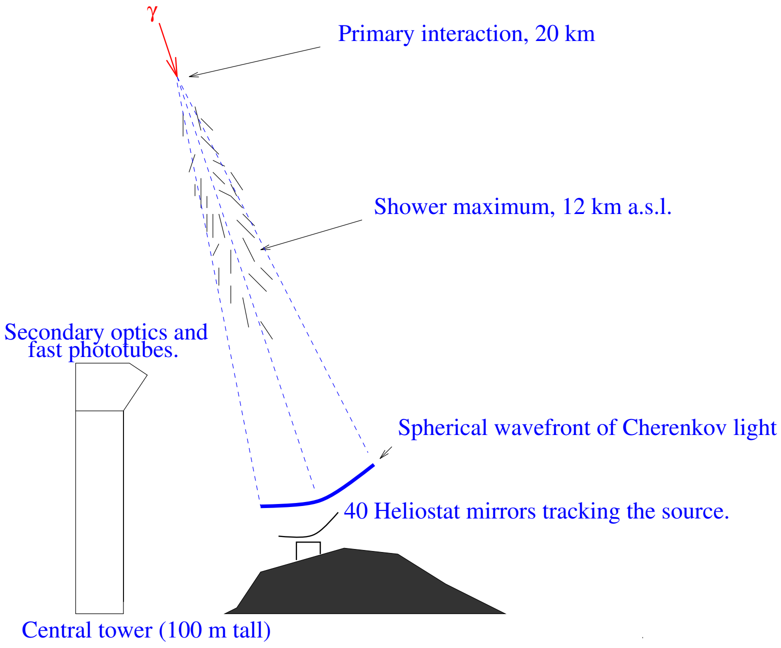

Figure 3. *Principle of a "solar farm" Čerenkov gamma ray telescope. Heliostats and secondary mirrors are not to scale. The tower is 100 meters tall.*

Angular resolution, especially at lower energies, tends to be limited by the shower development rather than by instrument response. Scattering in the first few generations of the shower, and deflection of low energy secondaries in the geomagnetic field, are the factors limiting angular precision. Hence, a high-granularity imager does not necessarily outperform a wavefront sampler. Both should achieve resolutions and pointing precisions around $0.1°$.

5. SOLAR FARMS

The central receiver solar power plants, built in the early 1980's in several countries and then abandoned, consist of thousands of square meters of mirrors designed to focus light from a celestial body onto the top of a central tower. The heliostats collect the Cherenkov light just as in the wavefront sampling detectors. Figure 3 sketches the basic idea. The major difference with the "classic" wavefront samplers is the focal length of the mirrors: the heliostats reflect the light to the top of the tower, rather than onto phototubes mounted directly on the mirrors. Correcting for path length differences which vary as a source is tracked, to permit fast coincidence electronics, requires secondary optics that image each heliostat onto a single photomultiplier tube.

Modern imagers have several hundred photomultipliers. The most ambitious solar farm projects foresee only one or two hundred channels, and we believe that good science can be done with as few as 40 channels. Hence, the cost is reduced.

The solar farm approach has weaknesses. For example, since the heliostat mirrors are oriented so as to reflect the Cherenkov light onto the tower, a source is in general off the heliostat axis, increasing light losses due to aberrations. The angles vary as the source crosses the sky. Thus, the dependence of the energy threshold and flux sensitivity on source position is complex. The relative low cost and speed with which a solar plant can be used to explore 30 GeV gamma rays outweigh the disadvantages.

6. THE CELESTE EXPERIMENT

At Themis we removed the 30-ton heat receiver from the top of the tower, thus liberating a five-by-five meter opening for the secondary optics. We installed a counting house in the tower, just below the focal area, with electronics and acquisition computers.

Fourty heliostats are in use (2000 m^2). Measurements of their optical properties using sun and moon images projected on the tower confirm that the mirror quality is adequate for our purposes. The heliostats have been aligned by recording the phototube currents while scanning bright stars.

The secondary mirrors are spherical, and are bigger than the $\sim$meter spot-size in order for the phototube camera to view the entire heliostat field with small aberrations. The mirror is divided into six subsections to decrease shadowing by the phototube camera: the lowest subsection views the farthest heliostats while the top three subsections view the heliostats at the foot of the tower. Each phototube sees a single heliostat. The field-of-view of 10 mr (total) is sharply defined using solid Winston cones on each phototube. The CAT and CELESTE mirrors as well as the CELESTE Winston cones were made by our collaborators in the Czech Republic. 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 phototube signals are recorded with 1 Ghz VME flash ADC's: in this way variable delay, charge measurement, and timing measurement are made by the same circuit. The Flash ADC's were developed specifically for CELESTE and provide an excellent compromise between cost and performance [21]. The trigger is conceived to reach the lowest possible energy threshold: programmable analog delays allow the Cherenkov signals to be summed in five groups of eight heliostats each. The resulting signal is discriminated, path length differences between the groups are compensated for using programmable logic delays, and the trigger is a threefold coincidence amongst the five groups. We trigger at 3 photoelectrons per heliostat, which according to detailed Monte Carlo simulations corresponds to a gamma ray primary energy near 30 GeV. The trigger rate is 16 Hz.

The data acquisition system is rather elaborate. An HP workstation orchestrates tasks amongst secondary computers: heliostat tracking; phototube anode currents; phototube high voltage; and weather monitoring are each on a separate PC. The 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 night's data is transferred each morning to major computer facilities in Lyon for subsequent analysis.

7. THE STACEE EXPERIMENT IN NEW MEXICO

The modern incarnation of the idea to recycle a heliostat farm into a Cherenkov gamma-ray telescope came from Tumay Tümar at U.C. Riverside, and initial work focussed on the Solar-1 facility near Barstow. Solar-1 work continues. But besides CELESTE, the project that has progressed furthest is STACEE, at Sandia Laboratories [22].

Form follows function, and the real differences between the two experiments are few. As examples, STACEE's secondary optics are off-axis parabolas; the trigger scheme is purely digital ; the mirror area with 32 heliostats is 1200 m^2. The current telescope is still in many respects a prototype and performance will improve. The gamma ray trigger threshold is near 80 GeV. The STACEE collaboration is currently analysing data acquired during this past winter and results should be forthcoming.

8. FIRST SOLAR FARM DETECTION OF GAMMA RAYS

8.1. Crab data sample

CELESTE tracked the Crab for the first time in February 1998 with 18 of the current 40 heliostats. The optics and photomultipliers were

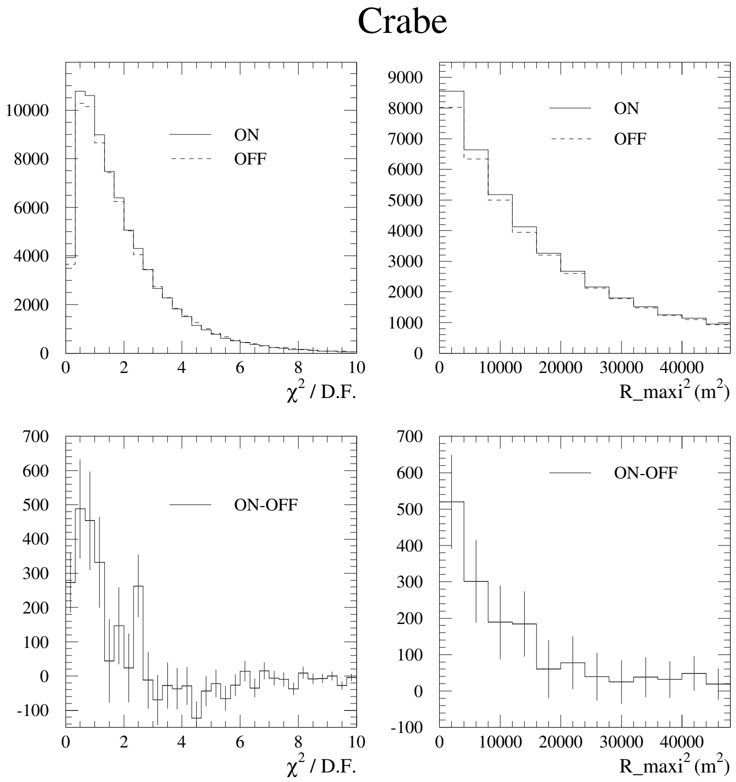

Figure 4. *$\chi^2/D.F.$ (left) and R^2 (right) distributions for Crab data. R is the distance from the center of the field-of-view to the reconstructed shower position. Top: superposition of ON and OFF source histograms. Bottom: Difference between the ON and OFF source data. With the cuts described in the text the signal is* 5.6σ *after 3.5 hours of observation.*

definitive. The trigger electronics was as well, configured in three groups of 6 heliostats each. The thresholds were 5.1 photoelectrons per heliostat, or 55 GeV. The trigger rate was 8 Hz.

Readout electronics and the overall acquisition architecture was temporary. In particular the Flash ADC's then in use contributed electronic noise to the readout. More importantly, only three FADC channels were available, forcing us to record three phototubes per ADC thereby increasing the fluctuations of the night sky noise underlying the Cherenkov signal by a factor of $\sqrt{3}$, for only 9 heliostats. By the time the telescope had been aligned and calibrated, the Crab was visible for only a short time after sunset, and the data set is small.

Cherenkov telescopes demonstrate a gamma ray signal by comparing data with other data taken while tracking the same path in the sky, just after (or before) the gamma ray source. In CELESTE each 30 minute "ON" run is followed by a 30 minute "OFF" run, and the difference between the ON and OFF rates, after applying cuts intended to reject hadronic showers while preserving electromagnetic showers, gives the gamma ray signal. The atmospheric conditions must thus be stable during an hour. After data quality cuts, 211 minutes of Crab data remained.

8.2. Analysis method

The first step in analysis is to find peaks in the FADC data, and thereby to estimate the Cherenkov amplitude and wavefront arrival time for each heliostat, on a shower-by-shower basis. Next, we use the pulse times to reconstruct a spherical wavefront of radius $(11km)/\cos\theta$ where θ is the zenith angle. The amplitude-dependent timing resolution was estimated by injecting software pulses into real data, and then reconstructing them. We imposed the following cuts:

- The sum of the peaks for all heliostats exceeds 90 photoelectrons (total energy cut).
- At least 8 heliostats have a peak of at least 4 photoelectrons.
- $\chi^2/D.F. < 2$ after a second iteration of the wavefront timing fit.
- $R < 125$ meters, where R is the distance of the reconstructed sphere's center from the line-of-sight.

With only 9 phototubes digitized, and with the increased night sky light per channel, the spatial distribution of the pulseheights does not allow an estimation of the shower impact point. For this reason no explicit shower direction reconstruction was attempted.

The raw data rates varied by a few percent between the ON and the OFF data, with sign depending on the source, due to small differences in the night sky background. The first two cuts reduce this effect, as will be discussed further, below. The remaining cuts are intended to reject hadron showers while preserving the gamma signal. For the Crab data, the raw OFF rate exceeded the ON rate by 5%.

Figure 4 shows the χ^2 and R distributions after the first cuts. The excess of events at small values in the ON data are as expected for gamma rays. The significance of the excess is 5.6 sigma in 3.5 hours and the rate is 6 gammas per minute. (Naive expectations are for 11 gammas per minute, assuming 100% detection efficiency.) The minimum energy after analysis cuts is 80 GeV. We emphasize that these results were obtained with an incomplete detector and that the work necessary to properly quantify the results will not be done, since we are now analysing data from the 40 heliostat detector, obtained in much improved experimental conditions. This result is therefore merely a "proof-of-principle".

8.3. Cross-checks

Two other data samples from the 18 heliostat array were analysed. 167 minutes of "OFF-OFF" data were obtained by tracking a direction near, but not on, Mrk 421 *i.e.* away from any known gamma source, as well as a corresponding OFF region. A 1% excess in the raw ON rate was reduced to 0.1% by the first two cuts. After the complete analysis, a -0.5σ non-signal was obtained.

Similarly, we analysed 234 minutes of Mrk 421 data. This analysis is trickier: a 6th magnitude star coincident with Mrk 421 increases the raw ON source trigger rates to several percent more than the OFF. After analysis, an artifact of this initial difference remains and our interpretation is that there is no signal. The CAT imager reported that the average intensity of Mrk 421 was one-third of the Crab during this time (March 1998), below the sensitivity of the 18 heliostat telescope.

9. CONCLUSIONS AND PROSPECTS

We have argued that the solar farm variant of the wavefront sampling technique is a good way to measure gamma ray spectra from astrophysical sources in the unexplored energy range between satellites and current ground-based devices. The advantages of the imaging technique as compared to wavefront sampling at 1 TeV are not as strong when one descends below 100 GeV. The cost is relatively modest because we exploit the substantial infrastructure available at solar central receiver power facilities.

We have thus built the first gamma ray telescope sensitive between 30 and 300 GeV. The full 40 heliostat array is taking data and analysis is underway. This energy range is critical to test AGN models in the extreme case of blazars, and to constrain the extragalactic diffuse infrared background via gamma-photon absorption.

Data taken when only half of the heliostats and one tenth of the digitization channels were available has been analysed, and we have presented the first signal from the Crab nebula at 80 GeV. The result in of itself is modest - systematic uncertainties remain large and the energy threshold and flux sensitivity are short of those expected with the full detector - nevertheless it is a satisfying validation of the experimental approach.

The 40 heliostat array has a 30 GeV gamma ray energy threshold, and the Crab nebula should be detectable in a matter of minutes. Sources with $1/20^{th}$ of the Crab's intensity should be seen in 20 hours. Combining extrapolations of the power law source spectra measured by the EGRET instrument on board the Compton Gamma Ray Observatory satellite with the predictions of spectra for known x-ray selected BL Lac objects not seen by EGRET, CELESTE should detect 20 blazars before the next generation of telescopes comes on line beginning in 2003.

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. We dedicate this work to his memory.*

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