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Non-imaging Gamma Ray Telescopes

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Abstract. Despite continual improvement of the Atmospheric Cherenkov Technique, the number of astrophysical gamma ray sources that have been well studied from the ground remains small (less than a half-dozen), due mainly to the nature of the cosmic accelerators themselves. For most Active Galactic Nuclei of the blazar class, the energy range in which imagers are sensitive lies beyond the inverse Compton peak, where the flux falls rapidly with increasing energy. A few galactic sources are very bright in EGRET but the spectra roll over (*e.g.* Geminga), while many have no break in the EGRET data but are intrinsically weak. The Crab nebula is an exception, along with a some others. Increasing the data sample thus requires a lower energy threshold, increased flux sensitivity, or a combination of the two. Long term progress will come with the imager arrays (HESS & VERITAS, beginning in 2002), the very large imagers (MAGIC & MACE) and with GLAST (2006). This paper reviews work-in-progress aimed at reaching the 50 GeV range using solar plants.

Key words: Gamma ray astronomy, Atmospheric Cherenkov technique

1. Introduction

So far, the glory years for ground-based gamma ray telescopes, beginning in 1989 with the detection of the Crab by the Whipple group (Weekes 1989), appear to have reached a local maximum in 1997, with the simultaneous detection of a flare of the blazar Mrk 501 by a variety of instruments (e.g. Djannati 1999). Since then, progress has been steady, although less spectacular. Examples of results from the field are increasingly detailed spectral measurements (such as for Mrk 421,see Piron 2001); the measurement of the flux from Cas A (Aharonian 2001); improved instrumentation in the Southern hemisphere (Kawachi 2001). Multiwavelength campaigns are increasingly the norm for studying the intrinsically variable blazars with contemporaneous data.

Nevertheless, the overall number of TeV gamma ray sources with measured fluxes remains small and hampers our ability to reach general conclusions. In a word, we would like to detect more sources.

What is happening is this: the EGRET detector on board the Compton Gamma Ray Observatory saw nearly 300 gamma ray sources around 1 GeV (Mukherjee, these proceedings). Almost all have spectra well described by a simple power law, and extrapolating to 300 GeV yields expected fluxes detectable by current instruments. Thus, the cosmic accelerators must run out of gas and the spectra roll over. The SSC (=Synchrotron Self-Compton) paradigm explains this easily for blazars (Boettcher, these proceedings), while the pulsar models (Kulkarni; Hirotani; de Jager; these proceedings) and SNR theory (Rowell, these proceedings) also predict rollovers.

Finally, to be able to study additional sources, either one stays at energies beyond the spectral cut-offs and tries to greatly increase sensitivity, or one tries to enter the energy range between the imagers and EGRET , to make measurements below and around the rollover energy.

(Ong 1998) and (Hoffman et al 1999) made comprehensive reviews of GeV to TeV γ-ray astronomy. (Catanese & Weekes 1999) and (Buckley 2000) are shorter and focus on current developments. (Weekes 1999, Weekes 2000, Smith 2001) give updates. Different lines of attack are currently underway to increase the number of detections:

1) Continuing the work of EGRET , in space (Fleury, these proceedings);

2) increasing imager sensitivity (C.L. Bhat; Finley ; Fleury: these proceedings);

3) wide field-of-view arrays to search for unexpected sources at higher energies (P.N. Bhat, these proceedings);

4) lowering the energy threshold using solar farms;

This review addresses the latter subject.

2. Solar Arrays : choosing lower energy

The magic formula for the energy threshold has been around a long time (Weekes 1985): $E \propto \sqrt{\phi\Omega\tau/A\epsilon}$, where ϕ is the night sky brightness (photons/cm2/s/sr), Ω is the solid angle seen by the phototubes, A is the mirror area, τ is the time during which the signal is integrated, and ϵ is the photon detection efficiency. Photomultiplier tubes still give the best combination of ϵ (20 to 30% around λ=400 nm), τ (a few nanoseconds fwhm) and intrinsic noise and remain the choice of all running experiments. Different groups are pursuing higher quantum efficiency photodetectors but to date no large scale application has materialized. Gamma ray detectors based on central tower solar facilities use the large mirror areas to lower the energy threshold well below the imager domain.

Above 200 GeV imagers are clearly the best. Below 100 GeV the game changes. Protons, the dominant background source, blink out as Cherenkov lamps. The total number of electrons at gamma shower maximum becomes small ($E/2$, for gamma energy E expressed in GeV, see de Naurois 2000), so that statistical fluctuations and geomagnetic scattering compromise the uniformity that distinguishes EM showers from proton showers. Diffuse cosmic electrons have a steeper spectrum than do protons or gamma rays and contribute more to the background than at higher energy - to reject them angular resolution counts more than morphology. The "wavefront sampler" approach pioneered by ASGAT (Goret 1993) and THEMISTOCLE (Baillon 1993), both of which saw the Crab (but nothing else), therefore merits a second look (Paré 1993, Ong 1996, Smith 1997).

While an imager measures the angular distribution of light at one place in the Cherenkov pool (or a few, for stereo), a wavefront sampler exploits the spatial and temporal distributions. The principal advantage of the solar farms is the huge mirror area more or less for free: at Solar-II there are 2000 heliostats of 40 m^2 each. The trade-off is having to adapt to a geometry that was conceived for a very different application. The adaptation is possible, however, and Solar Arrays have now seen "first light", via measurements of the Crab nebula flux (Oser 2001, de Naurois 2001).

Concrete example: CELESTE

I will illustrate the method by describing my own experiment, CELESTE, which is at the Thémis site along with CAT (2°E, 42°N, 1650m) (THEMISTOCLE and ASGAT have ceased operations). We use 40 heliostats, each roughly 7 x 8 meters in size (54 m^2) on individual alt-azimuth mounts. Thirteen more are being brought on-line. Figure 1 sketches the principle.

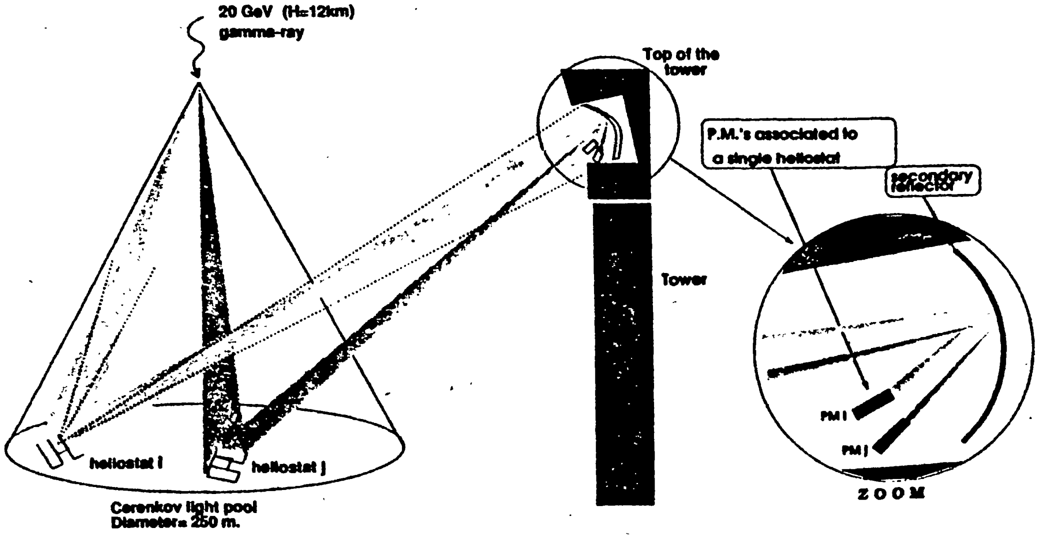

Figure 1: Principle of a solar farm wavefront sampling atmospheric Cherenkov gamma ray detector. Secondary optics at the top of the tower is essential to allow the several nanosecond coincidences that permit a low energy threshold.

The idea of using solar arrays to collect Cherenkov light came early (Danaher 1982) but the optical path lengths from the heliostats to their focal plane at the top of the central tower are large and, importantly, change with the earth's rotation while tracking a source. Thus, τ in the energy threshold formula, above, becomes so big as to counteract the large mirror area. Furthermore, the spot of light from a given heliostat is much larger than even a large photomultiplier tube, and overlaps with the spot from surrounding heliostats. Around 1990, T. Tümer thought of using secondary optics to separate individual heliostat images, thereby allowing τ to remain of the order of the duration of the Cherenkov flash, to improve the Cherenkov like collection while decreasing the night sky light collection (Tümer 1990). E. Paré rapidly executed a detailed study of the idea's application to Thémis and proceeded to build CELESTE , while Rene Ong and collaborators did the same at Solar-1, and later at Sandia (Ong 1996).

Removing the 30-ton heat receiver from the Thémis tower left a 5 x 5 meter opening 80 meters above the ground, where we installed the secondary mirrors, divided into three levels: those for the farthest heliostats, those which view the middle of the field, and those for the heliostats at the base of the tower. To decrease losses due to camera shadows, the latter two levels are subdivided into two and three subsections, respectively. The cameras at the secondary focal surface can accomodate up to 90 photomultiplier tubes, of the 160 heliostats available at the site. A solid Winston cone glued to the photocathode defines the diameter D of secondary mirror surface seen by a given phototube, such that the field-of-view (pixel size, Ω) is $D/L = 10$ mrad (full angle), where L is the distance to the heliostat. 10 mrad optimizes the Cherenkov signal to night sky background noise ratio.

A shower 11 km above the site is at an angle of 20 mrad from the source direction, for a heliostat 220 m from its impact point: the Cherenkov light will be outside of the field-of-view! We therefore point the heliostats not at the source itself but where shower maximum occurs. This in turn reduces the area sensitive to gamma rays from $> 100,000$ m^2 for an imager to $\sim 20,000$ m^2 for CELESTE (figure 2, right). The choice of which pointing optimizes threshold and sensitivity is under study.

The night sky background is 1 p.e./ns in the Crab direction (p.e. = photoelectron) which we integrate over several nanoseconds (our phototube pulse width is 5 ns FWHM at the trigger electronics, and the Cherenkov pulse duration is about 3 ns). For comparison, a 30 GeV gamma ray yields 3 p.e. per heliostat, on average (optics losses x photocathode efficiency $\simeq 10\%$). We trigger as follows: the 40 heliostats are divided into 5 groups of 8 each. Using switched cables to compensate for path length differences to within 1 ns (updated twice per minute as the earth turns), we sum the analog signals. The analog sums are discriminated, delayed to compensate for the path lengths between the groups, and the final trigger requires at least 3 of the 5 groups to have fired within a 10 ns gate. The analog sum assures sensitivity to small showers, while smoothing the fluctuations of the night sky ; the logic coincidence is essential to reject muons illuminating single heliostats, and phototube noise. Figure 2, left, shows the trigger bias curve. We typically use 4.5 p.e./heliostat but in excellent weather have run at 3 p.e./heliostat. (The upper curve is for a 4.5 p.e./heliostat threshold). A trigger which still has some efficiency well below threshold may make the difference when searching for a low energy pulsar (de Jager, these proceedings).

In parallel with the trigger circuits, the phototube signals are also sent to 1 GHz 8-bit Flash ADC's (Etep 301c, with 2 μs of memory). The trigger stops the FADC coding after which 100 ns of memory centered at the expected location of the Cherenkov pulse is read out and stored to disk. Offline analysis of the Cherenkov peaks provides the pulse height and timing information used to reconstruct the Cherenkov wavefront.

As stated, the night sky background is large compared to the Cherenkov signal. Small changes in this large background bias the data. For example, in the same field-of-view as Mrk 421 there is a magnitude 6 star that increases the anode current for those phototubes that see it by as much as 15% (in convergent pointing, not all heliostats see the same piece of sky). The increased night sky fluctuations make it easier for a small shower

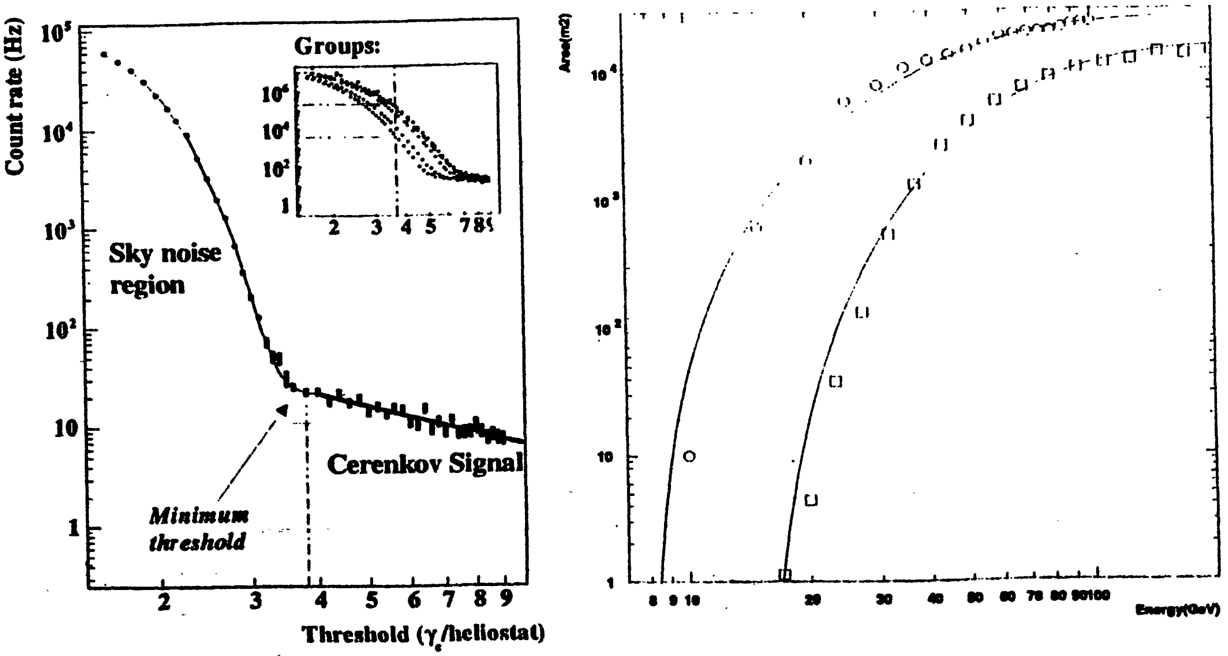

Figure 2: Left, CELESTE trigger rate versus threshold. The steep part at left is dominated by accidental coincidences of night sky light fluctuations. Above the breakpoint Cherenkov flashes dominate. STACEE shows similar curves. Right, the energy dependent effective area for CELESTE , for the trigger at Crab transit (top curve) and after analysis, averaged over Crab hour angles (bottom curve).

to trigger the detector and the rate is therefore slightly higher ON source than in the OFF source data used to normalize the background - a fake signal appears! Background light varies as the sky evolves through the night, causing similar (and sometimes subtle) biases for any source. To compensate for the trigger induced bias, we make an offline energy cut. Neutralizing the analysis bias is more subtle. We have adapted the padding technique developed by Whipple (Cawley 1993) to the Flash ADC data. We evaluate the background light in the ON and OFF data using the pedestal widths and the anode currents, and then we add simulated background light to the less noisy run of the pair to equilibrate. Various cross-checks give us confidence that spurious signals are eliminated. Details are provided in (de Naurois 2001).

After padding, the timing information is used to fit the arrival times to a spherical wavefront, the center of which locates shower maximum (lateral resolution of 15 m). The pulse height distribution amongst the heliostats allows us to estimate the impact point to within 30 meters. The shower direction is given by these two points, with a resolution of 3 mr. The gamma ray signal is the excess of ON-OFF near the source direction. While cutting on this variable improves the signal-to-background ratio it also decreases the statistics and doesn't change the significance of the signal. Our best variable (at present) is a measure of the uniformity of the pulseheight distribution over the heliostats. Our current sensitivity on the Crab is $1.75\sigma/\sqrt{h}$ for 11 km pointing, and

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$3.3\sigma/\sqrt{h}$ when we point half of the heliostats at 11 km and the rest at 25 km. This increase in sensitivity comes at the price of an increase in energy threshold of the order of 20 GeV. Figure 2, right, shows our energy dependent effective area for 11 km pointing. In a solar array, the light transmitted by the heliostats varies as the pointing direction changes, and the acceptance calculations must take this into account: to normalize the range of hour angles of our Crab data to transit is a 20% rate correction. Light collection of a solar plant is designed for the summer sun, which has the same declination as the Crab: energy threshold increases by 10 GeV from the Crab to zenith (where the famous blazars transit at Thémis).

In this conference, J. Osborne discussed the importance of atmospheric monitoring. In support of this view, we note that the raw trigger rate in CELESTE decreases from 20 to 25 Hz in the Winter to 10 Hz by early summer. Looking closely at CAT data reveals a similar effect although of smaller magnitude. STACEE runs at a much lower rate and has not as yet reported such an effect. We do not know at present how this effects the acceptance and energy threshold for Spring sources such as Mrk501 and PSR B1951+32.

A widely shown plot compares the sensitivity of different detectors to each other and the Crab nebula flux, as a function of energy. It is called figure 13 in (Buckley 2000), figure 6 in (Weekes 2000), and so on. STACEE and CELESTE often share the same curve (depending on the version of the plot), which is reasonable in a first approximation.

The CELESTE curve dates back to the Monte Carlo studies done for our proposal. We have understood since then that the optical parametrization was too simple and masked a very important defect of the solar farm approach: the small field-of-view has the effect of making proton showers resemble gamma showers. The very detailed optical simulation we now use brings this out clearly. We pay the price for this at least twice: first, the gammas and the hadrons as seen in the detector have very similar arrival time distributions - a cut on the residuals to the spherical wavefront (or on χ^2) enhances the signal less than we stated in our proposal. Second, the pulseheight distribution on the ground is sensitive to the shower impact parameter and direction and is difficult to exploit for direction reconstruction. As a consequence, the $9\sigma/\sqrt{h}$ (h in hours) that we predicted for the Crab is at present unattained (a study now in progress may raise us to $6\sigma/\sqrt{h}$, comparable to CAT and Whipple). For the record I would like to note that to make the 5 sigma sensitivity curve correspond to our measured performance, it should be moved upwards by a factor of $9/3.3 = 2.7$.

Comparison by Contrast: STACEE

Form follows function, and naturally the different solar tower experiments resemble each other greatly. Yet they are not identical and exploring the differences helps grasp some of the more subtle points of the technique. Table 2 lists key points.

STACEE runs at Sandia Laboratory in New Mexico (35^0 N, 106^0 W, 1700 m). They are the first solar array group that succeeded in publishing the Crab flux (Oser 2001), although at 190 ± 60 GeV and with only $1\sigma/\sqrt{h}$, during the 1998/1999 observing season, using a 32-heliostat array (CELESTE announced a Crab detection at 80 GeV from the 1997/1998 observing season with an 18-heliostat setup but no flux measurement was derived from the data (Smith 2000).) Since then STACEE has significantly improved their apparatus and at this writing are well into analysis of a signal from the early 2001 flare of Mrk 421 (Hinton 2001), and have recorded data on Mrk 501 (Ong 2001). They now have 48 heliostats and will go to 64 this summer (37 m^2/heliostat).

	Celeste	Stacee
Optical field-of-view (diameter, mrad)	10	12.2
Night sky light on zenith (Crab), p.e./ns	0.7 (1.0)	1.7
Good weather nights this year	few	many
Current heliostat number (size)	40 (54 m^2)	48 (37 m^2)
Total mirror area, 2000-2001	2100 m^2	1700 m^2
Total mirror area, 2001-2002	2800 m^2	2300 m^2
Secondary optics	On-axis, 6 subgroups	Off-axis, 5 subgroups
Trigger architecture	3 of 5 analog sums of 8	L1: 5 of 8 L2: 4 of 6
Typical trigger threshold (Jan 2001)	4.5 p.e/heliostat	5.8 p.e./heliostat
Trigger threshold, at transit	40 GeV	90 GeV
Average analysis threshold	60 ± 20 GeV	120 ± 25 GeV
Trigger rate	20 Hz	4 Hz
Background after analysis cuts	1.5 Hz	.3 Hz

Table 1: Comparison of the Celeste and the Stacee experiments, for this year (the 2000-2001 observing season) and next year (2001-2002).

An important difference between the two experiments is that the STACEE secondary optics are off-axis, giving less camera shadow but accepting greater aberration losses than for CELESTE (smaller ϵ). Space constraints at the top of the tower, and also financial limitations, limit the overall quality of the secondary optics. They chose a wider optical field-of-view (Ω) to ensure a larger effective area at high energy. The site has some light pollution: during the period when they increased from 32 to 48 heliostats they resurfaced the ground around the heliostats to reduce albedo. They installed their definitive secondary mirrors, and re-aligned the heliostat facets for better focussing. The overall effect is that STACEE has more night sky background per phototube, and less Cherenkov light for the same gamma ray energy, than does CELESTE . Sandia however has better weather than Thémis and STACEE records more ON source data than CELESTE .

Another difference between the two experiments is the trigger electronics. STACEE has a discriminator for each channel, and developed special deadtimeless programmable logic delays to handle the high singles rates when running at low threshold (they've reached 5 p.e./heliostat). They require, at this writing, 5 of 8 heliostats to fire a group, and 4 of 6 groups for a trigger. The advantage of this scenario is a sharp trigger turn-on, presumably more stable with respect to night sky variations than CELESTE 's. Thus their trigger-level energy threshold is higher than CELESTE 's, but it remains to be shown whether CELESTE can preserve the full advantage after data analysis. The trigger rate is 3 to 4 Hz. Their current threshold energy is 120 ± 25 GeV and they will be pushing it down to the 70 GeV range. STACEE also uses a 1 GHz Flash ADC based acquisition system (Acqiris), which because it is a more recent design than CELESTE 's performs somewhat better. A recent detector update can be found in (Covault 2001).

Up and coming, and a bold try: PACHMARI, SOLAR-II, and GRAAL

The PACHMARI wavefront sampler array, quite similar to THEMISTOCLE (but with 25 instead of 18 stations) is online in India. This reincarnation of the wavefront sampling approach has an energy threshold in the several hundred GeV regime. It is presented in detail in these proceedings by P.L. Bhat.

Solar-II is located in southern California in the desert east of Los Angeles (35° N, 116° W, 600 m). The site is ten times bigger than either Thémis or Sandia and in particular is the only site that is actually bigger than a typical Cherenkov light pool: avoiding acceptance biases intrinsic to both CELESTE and STACEE, as well as a significantly larger overall gamma ray collection area, are possible only here. With this in mind they chose a 16 mrad field-of-view which leaves open the possibility of effective area and energy & direction reconstruction superior to CELESTE's. The price is a higher threshold energy, compounded by the fact that the Cherenkov light density is lower at their lower altitude. The team is small but having chosen to recycle STACEE and CELESTE's developments whenever possible they have made impressive progress rapidly (Mohanty 2001). They currently use 32 heliostats and are building to 64. They have recorded Crab data this season, but using temporary electronics, with a 1 Hz data rate. They will soon be upgrading to a CELESTE-designed trigger and to the same FADC's as used in STACEE.

GRAAL ran at the Almeria site in Spain (Trigo 2001). Back when the different solar array groups were being formed, the GRAAL collaboration chose a risky path: to quickly be the first to establish this new technique, dropping the secondary optics in favor of hardware simplicity and thus speed. They have only four large phototubes, each with a Winston cone that sees 13 to 18 of the 63 heliostats used. Readout is via a single high quality digital oscilloscope. They report a 4.5 σ Crab signal in 5h50m of data ($1.9\sigma/\sqrt{h}$) but because of the huge night sky background that comes from summing so many mirrors per channel, their energy threshold is a few hundred GeV.

3. Results from Solar Tower Experiments

The Crab, and other galactic sources

After STACEE-32's measurement of the Crab nebula flux at 190 ± 60 GeV (Oser 2001), CELESTE followed with a measurement at 60 ± 20 GeV (de Naurois 2001). Both experiments have searched for the Crab pulsar. Figure 3 summarizes the situation. The pulsed flux measured by EGRET is well described by the sum of two power laws (Fierro 1998). If one assumes that the cutoff in the spectrum at high energy can be described by a simple exponential, e^{-E/E_0}, then CELESTE's result excludes $E_0 > 32$ GeV.

CELESTE has 15 hours of data on PSR B1951+32, another EGRET pulsar, but no evidence for a pulsed signal. The data were taken in a variety of experimental conditions and at present an upper limit hasn't been calculated (Dumora 2001).

Both STACEE and CELESTE are studying supernova remnants, of which IC443, CTB80, Cas A, and γ-Cygni are the most promising. Data has been acquired on some of these and analyses are in progress.

Blazars

Both STACEE and CELESTE have detected Mrk 421 during flares (Hinton 2001; de Naurois 2000 ; Le Gallou 2001a,b). Figure 4 is from (Le Gallou 2001a). The good weather at Sandia has allowed STACEE to record a large data sample during the 2000-2001 season. In non-flare periods our signal goes away: before mastering padding this was non-trivial. At this writing CELESTE has upper limits for Mrk501 and 3C66A, and STACEE is analysing their data (Ong 2001).

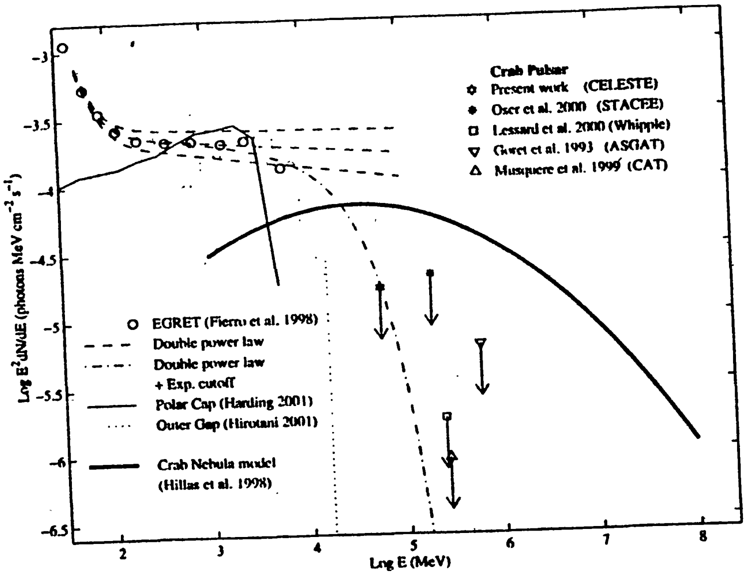

Figure 3: Crab pulsar spectrum, showing the EGRET double power law, with uncertainties (dashed), STACEE's upper limit, and the softest exponential cut-off allowed by the CELESTE data (dot-dashed curve).

4. What next ?

If 1997 was a squall in the progress of ground-based gamma ray astronomy, 2001 may well be the lull before the storm. The Solar Arrays are reaching their final configurations (53 heliostats for CELESTE, and 64 for STACEE and Solar-II). A new round of instruments is coming up to speed: HESS leading off the big imager arrays, and of course Whipple which continues to lead and to surprise the rest of us. Several source candidates seem to be just at the limits of our current performance: HEGRA saw Cas A through a marathon performance, but IC443, a pulsar, and a few XBL's may come within the reach of the sprinters before too long. The future will tell.

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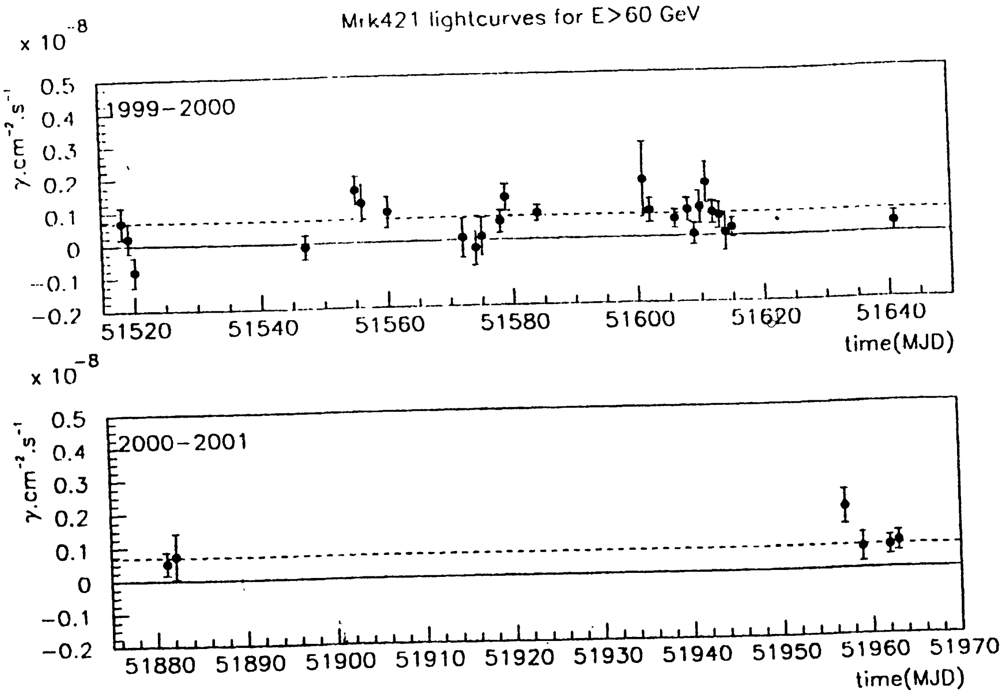

Figure 4: Light curve obtained for Mrk 421 with CELESTE .

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