27 Février 1995

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Extension beyond the GeV Domain
by Ground Based Observations**

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**Rapport présenté au colloque
'TeV Gamma-Ray Astrophysics'
Heidelberg, Octobre 1994**

GAMMA-RAY ASTRONOMY: EXTENSION BEYOND THE GEV DOMAIN BY GROUND-BASED OBSERVATIONS

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Abstract. Gamma-Ray Astronomy, originated with the OSO-3, SAS-2 and COS-B satellites, has been renewed during the last three years by Compton-GRO's discovery of tens of Galactic and extra-galactic sources up to ≈ 10 GeV. Also in the last three years, a ground-based observing technique has emerged for TeV gamma rays: the identification of gamma-induced air showers via their Cerenkov emission. Extrapolating this technique down to the present limit of satellite observations has become a realistic goal, allowing fundamental questions to be tackled which would remain open until the individual spectra were extended.

1. Present situation and Motivations

During the last five years the general situation in High-Energy Gamma-Ray Astronomy changed considerably. As regards space-based Gamma-Ray Astronomy, the C-GRO satellite (launched in 1991) significantly extended the catalogue of γ -ray sources previously available (Fitchel et al.). In particular, more than 30 sources were found to be Active Galactic Nuclei (AGN) whereas only one such source—the quasar 3C273—had been detected in the γ -ray range by a previous satellite which had opened the catalogue to extra-galactic sources: the COS-B satellite (1975-1982). The highest-energy range covered by C-GRO was explored by EGRET and extended up to about 10 GeV, limited above this by the small effective detection area ($\approx 0.15m^2$) and the rapid decrease in γ -ray fluxes with energy.

In the meantime, in 1992, an AGN was observed by the Whipple Observatory group (Punch et al.) in the TeV region: it is a BL-Lacertæ type object, Markarian 421, which was already in the catalogue of sources observed by EGRET. It is significant that the most intense extra-galactic source in this catalogue, the quasar 3C279, has not been observed; it is a very distant object (with a spectral red-shift of $z=0.54$), whereas Markarian 421 is the nearest source to earth in the catalogue ($z=0.03$). These observations can be interpreted as an effect of the absorption of TeV γ 's, which interact with the diffuse intergalactic infra-red radiation according to: $\gamma + \text{I. R. photon} \rightarrow e^+ + e^-$. By extrapolating the energy spectra of distant sources ($z > 1$) as measured by EGRET while taking into account this absorption, such objects are predicted to be accessible with ACT telescopes if the threshold energy is lowered to below 100 GeV (Stecker et al.). Observations of distant quasars at such energies would confirm the above explanation and provide the first measurement of the inter-galactic infra-red background light. This can lead

to a new estimation of the era of galaxy and star formation. This is critical to discriminate between Hot or Cold Dark Matter scenarios (MacMinn et al.).

Unfortunately, currently-operating ACT telescopes have thresholds greater than or of the order of 200 GeV. Since no space mission is expected to cover the energy gap between EGRET and ACT data in the near future, lowering ACT thresholds was recently recognised as a major goal in γ -ray Astronomy (Weekes). The 10 GeV to 200 GeV energy region turns out to be critical for many sources: the Crab pulsar signal (periodic signal) is observed in the GeV range but is not seen by ACT telescopes whereas the unpulsed signal (attributed to the Crab Nebula) is detected in both domains. The periodic signal should exhibit a strong cut-off in its spectrum which unfortunately is located in the unexplored region. The spectrum shape in this domain should shed some light on the production mechanism of pulsed γ -rays; this point is also true for other pulsars, and for supernova remnants.

2. The Atmospheric Cerenkov Technique

When viewed through its Cerenkov light, an air shower initiated by a cosmic gamma of a few tens of GeV is a long and straight object, starting in stratosphere—some 25 km above sea level (a.s.l.)—and extending down to about 5 kilometres, with a lateral extension which does not exceed about 20 meters. For an observatory at a typical altitude of 2000 m, the illuminated field on the ground is about 120 m in radius. The angular acceptance of the ACT detectors should be large enough—at least 0.6° —so as to embrace the entire apparent size of the long rods.

To keep the night-sky light pollution within a tolerable level, the use of fast photon-detectors—such as photo-multiplier tubes (PMT's)—is required so as to take advantage of the quasi-simultaneity (within 2-3 ns) of the photon arrival times. The energy threshold of a detector is determined by the number of the shower photons and by the noise level. The noise can be expressed as the square root of the night-sky light integrated over the time of the coincidence (a few ns). The signal varies roughly as the shower energy. The gamma-ray signal and the noise, respectively, may be characterised by the following numbers (for $350 \leq \lambda \leq 550$ nm):

$$N_{\gamma\text{-signal}} = 0.04 - 0.1 E_{\gamma}(\text{GeV}) \text{photons}/m^2$$

$$N_{\text{sky-light}} = 0.4 \text{photons}/(\text{deg.}^2 m^2 \text{ns})$$

This leads to the following rule-of-thumb relationship between the threshold energy, E_{th} , and the mirror size A_E : $E_{th} \propto A_E^{-1/2}$.

A similar description would hold for a charged primary instead of a gamma. However, the chain of interactions initiated by a hadron differs signif-

Fig. 1. Cerenkov photon yield divided by incident energy for gamma showers (upper curve) and hadronic showers (lower curve). All Cerenkov photons within $350 \leq \lambda \leq 550$ nm are summed.

icantly along the shower path through the atmosphere. For these hadron-generated showers, the Cerenkov light is mostly from gamma-showers initiated by secondary π^0 decays. A smaller contribution comes from the charged pions and their resultant muons. Some of those muons may reach the ground and radiate near the detector. The large transverse momenta given to the π 's are responsible for a rather chaotic shower shape, as are the penetrating muons. At low energies, at which the shower is fed by just a few pions of moderate momenta, the angular perturbations become even more predominant.

As a result of the ≈ 0.1 GeV energy cut-off on the radiating electrons, the photon yield should suffer a smooth cut-off when the primary energy is reduced to a few GeV. This effect, shown in Fig. 1, affects the gammas and the protons quite differently. While for gammas the total number of Cerenkov photons remains nearly proportional to the incident energy down to ≈ 20 GeV, for hadrons the cut-off occurs at about 50 GeV. When their energy goes down to the 20 GeV region, their Cerenkov photon yield has essentially vanished. This quite favourable situation, which has been known for some time, is a result of the fast degradation in energy in the hadronic cascade before an electron is generated. Of course, hadrons of higher energies—say above 100 GeV—are still there and producing about as many photons as a 20 GeV gamma. Nevertheless, the spectrum of the CR flux is steep, so this natural cut-off is a blessing.

The diffuse cosmic electrons might become the major contributor to the background. An electron (or positron) shower is just like that of a gamma of the same energy. Good pointing determination can be obtained, as discussed below, which will constitute the only efficient control to this effect.

3. Multi-mirror alternative

To proceed further, the mirror strategy needs to be discussed. Since the A_E versus E_{th} rule of thumb is roughly correct, the total collection area needed for a 20 GeV observation may be extrapolated from the results obtained at higher energies. The most favourable basis for this extrapolation is provided by imaging telescopes. Even so, quite an impressive area of: 2000 – 5000 m² is required. Imaging techniques, based on a single mirror or possibly a few mirrors, would be quite difficult to adapt to such a large dimension, for simply mechanical reasons. The sampling approach, that of the THÉMISTOCLE and ASGAT experiments, could be more appropriate. The 7m-diameter mirrors of ASGAT might serve to give a scale. A few hundred such 7m-diameter mirrors would be needed. The sophistication—and cost—of a fine-imaging camera on each mirror could be avoided if the hadron rejection were based on the fine multi-mirror sampling which is available. The chaotic development of the hadronic shower which causes fuzzier images also affects the distribution of the “light-pool” of Cerenkov photons on the ground. For a 20 GeV gamma event, the light-pool distribution is flat and ends at about 150 m from the shower impact point after a ridge in the distribution. This ring is produced by the first generations of electrons in the shower, at about 20 km a.s.l. The ring may be exploited as a gamma signature to reject protons or even electrons although, as it contains not more than 10% of the Cerenkov photons, this is rather demanding in terms of the mirror collection area. A more statistically-efficient signature is based on the homogeneity of the photon distribution over the entire light-pool. Gamma events have a smooth distribution while protons tend to generate patchy patterns. *Most often, the same hadron events survive selection by either the imaging or the light-pool (homogeneity) criteria: for these events a secondary π^0 dominates in the cascade.*

3.1. OBSERVATION STRATEGIE

To maximise the number of collected shower photons relative to the night-sky noise, the field of view of each individual mirror should be kept small. A 0.6° aperture suffices to contain the shower image, provided the image is roughly centred with respect to the optics. This centering can be achieved for all the mirrors by varying the tilt of their optical axes according to their position in the field. Each mirror is oriented toward a central fiducial volume at the common altitude of the shower maxima, at ≈ 13 km a.s.l. Of course, the centre of this fiducial volume should vary according to the direction of the cosmic source under investigation, in such a way that its projection along the line of sight falls on the centre of the site. The method combining tilted axes and narrow mirror-acceptances trades an improved signal to noise ratio—and thus a lower energy threshold—against a reduced fiducial area, which

still remains as large as $\approx 10^4 m^2$. Furthermore, this method discriminates against the hadrons, for which only 10% of the light is contained within the 0.6° acceptance angle compared to 60% for the gammas.

3.2. ANGULAR MEASUREMENT

Above a few TeV, the wave-front has a conical shape, the axis of which may be determined by timing measurement, as in the THÉMISTOCLE experiment. Such a method cannot be used below a TeV, because the wave-front then reduces to an expanding sphere having its (fixed) centre at the shower maximum. The position of this centre can be determined by the time-samples: the linear term gives its direction and the second-order term its distance (the radius of curvature of the wave front should match the expected altitude, some 13 km a.s.l.). However, the shower axis remains undetermined unless some other information can be used, such as its impact on the ground.

The centre of gravity of the light-pool is an estimator of the axis' impact, at least if the light-pool is fully-contained within the field of mirrors. An alternative method is to fit an ad-hoc distribution—of pre-set size and shape—to the observed population. The occurrence of the sharp edge, with its ring-shaped enhancement, facilitates the fit. But even so, at the lowest energies the method suffers from the effects of the Earth's magnetic field; this tends to make the light-pool edges more diffuse on the East and West sides as the light-pool illumination is influenced by the magnetic deflections of low-energy secondary electrons.

3.3. AN IDEAL SET-UP

To give a more quantitative evaluation of an ACT multi-mirror array, a rather idealised set-up is now considered (referred below as the "ideal set-up"). The ideal set-up is assumed to sit at a medium altitude of 1.7 km a.s.l. (chosen as that of the Thémis site). The array of telescopes of the ideal set-up will cover a disk 400 m in diameter so as to contain fully the light-pools of γ -showers of ≈ 300 m diameter having their impacts within a 100 m diameter central "fiducial" zone.

The size of each mirror and the mirror inter-space in the array define the effective collection area for a shower. Assuming a $38m^2$ area and a mean distance of 14 m (as for the heliostats of the Thémis solar plant), the mirror occupation factor is $A_{\text{mirror}}/A_{\text{total}} \approx 20\%$. To equip such a 400 m-diameter field, 640 mirrors are needed. The mirror reflectivity is assumed to be limited by the transmissivity of glass to $\lambda \geq 350$ nm. The loss in photon yield is $\approx 25\%$ for the use of more robust back-plated mirrors (or sandwich of glass panes as for the Thémis solar heliostats) instead front-plated ones. It is assumed that the mirrors are isochronous to within 2-3 ns and that their optical aberrations are kept within 0.15° (about a fourth of a shower image).

The camera is made of a single PMT subtending 0.6° acceptance. The information that may be collected at each mirror includes the PMT output charge integral—which is a measure of the number of collected photons—and the time of these signals. It is here assumed that both data are exploited for the evaluation of the shower energy, the hadron rejection and the direction measurement.

The trigger is assumed to be based on 4-mirror sub-sets, requiring analogue adjustable delays between the elements of a sub-set, but only within a 20 ns total range (this is manageable with existing computer-controlled delay-cable boxes). Per sub-set, the expected average number of detected photons of night-sky light piling up within the 2-3 ns PMT pulse duration is ≈ 7 . To be sensitive to a 20 GeV gamma, the trigger at the sub-set level must be validated whenever it sums up to 15 photoelectrons or more. In order to trigger on showers falling in the central fiducial region, only a third of the sub-sets (those around the centre of the field) are taken into account at this level. The final trigger is generated whenever 30 sub-sets respond simultaneously—i.e., within $\leq 10\text{ns}$ —their respective delays being duly corrected for (as is currently done in the THÉMISTOCLE experiment's electronics). The expected rate of accidental triggers should be negligible as long as the sky-light does not increase by more than 50 %. In addition to the diffuse night-sky light, the brighter stars would distort observations in their vicinity. A 4th magnitude star falling in the field of view of a mirror would double the average night-sky light. The odds for the presence of a star brighter than this in an angular acceptance of a square degree is less than a percent. The tilted-axis strategy partly relieves this difficulty since the telescopes are not looking at exactly the same patch of sky.

3.4. SIMULATION RESULTS

Simulations were run for incident gamma rays (or electrons) and hadrons, following the shower development through the atmosphere and tracing the Cerenkov photons down to the mirrors and up to the cameras. Sky noise was taken into account and timing resolution was assumed to be the same as in the THÉMISTOCLE experiment.

The resolution in the measurement of the shower axis, as shown in Fig. 2, is $\approx 0.1^\circ$ in the projected angle. The angular resolution is nearly two times better in the parallel direction of the earth's magnetic field than in the perpendicular direction. This is ten times better than EGRET's. The improved angular resolution would permit a better separation of point-like sources in the dense region of the Galactic plane, opening new possibilities for the study of extended sources. From 20 to 200 GeV, the effective collection area remains high, at about $8 \times 10^3\text{m}^2$.

The γ yield expected from the Crab—summing the pulsed and unpulsed contributions—is given in table I, according to the different selection lev-

Fig. 2. Distribution of the measured direction of the shower axis for the events selected on shape only: for the gammas (black area), for protons, and for electrons (shaded).

els (trigger and analysis). The expected shower rate due to cosmic primary protons and electrons are also shown. The off-line “shape criteria” selection is based on a chi-squared fit of the number of detected photons per mirror according to a smooth distribution law (constructed as a bi-dimensional Gaussian distribution centred on the impact point together with a Gaussian-shaped ring). A selection is also made on the basis of the timing measurements, by requiring that the wave-front be approximately spherical.

TABLE I

The rates of events for a 400 m diameter field with 650 $38m^2$ mirrors. The energy threshold is expected to be $E_{th} \leq 20GeV$.

	flux ≥ 10 GeV $\times 10^8/cm^2s$	Trigger evt/s	Shape sel. evt/s	Ang. sel. evt/s
Gammas from Crab	1	0.53	0.36	0.3
Electrons	$2.5/deg.^2$	1.6	1.0	0.08
Protons	$600/deg.^2$	15.	1.0	0.05
Gamma/(Electrons+Protons)	1/600	1/30	1/6	2/1

The performance of the apparatus as expressed in Table I can also be summarised as follows:

- within an observation time of 5 minutes, the Crab signal should reach a statistical significance of 7 standard deviations.
- within 10 hours of observation, a cosmic source with a flux above 10 GeV of $5 \times 10^{-10}cm^{-2}s^{-1}$ could be seen at the 5 standard-deviation level; this is about one twentieth of the Crab flux.

- taking into account the sensitivity of the EGRET detector and its measured energy spectra, any source observed by EGRET should be detected by the ACT set-up if the source's declination permits. This remains true for sources at large cosmological distances, since the infra-red light absorption, which can be drastic above 100 GeV, remains inoperant at ≈ 10 GeV. This telescope will also be sensitive to sources that EGRET only set limits on.

3.5. USING EXISTING SOLAR PLANTS

Before starting a major program along the multi-mirror scheme, tests should be carried out. A major drawback is that the construction of a prototype would be of no value unless it were tailored to run below 50 GeV, the domain where charged cosmic rays are fading out. This would already be quite a major construction program. Following a suggestion by Tümay Tümer (Tümer) to re-use the "Solar-1" solar plant in California, we have investigated the use of the Thémis solar plant in the French Pyrénées, which is the site of the THÉMISTOCLE and ASGAT experiments. These solar plants are extensive fields of large ($\approx 50m^2$ mirror) heliostats, focusing the solar light on a single furnace at the top of a tall tower. Instead of an independent photo-detector at each mirror, there is a unique photo-collecting furnace. As first noted by Tümer, the fact that the focal point is relocated to a common focus does not rule out the independent collection of each heliostat's photons. This is essential to allow the individual adjustment of delays and to avoid an exceedingly large night-sky light collection. Replacing the solar furnace by a secondary optical system—a large Fresnel lens (as proposed by Tümer) or a mirror—would provide a solution. For each heliostat, an individual PMT may be placed at its image position in this secondary optical system which will collect the photons reflected by each individual heliostat. The rather small acceptance of 0.6° needed for observation of the shower results in a moderate aperture for the secondary optical system, of the order of 1.5-2.5 m diameter. In practice, this secondary optical system must be divided into several sub-units in order to subdivide the large solid angle of the field as viewed from the top of the tower.

From that point on, everything should be about the same as for the ideal set-up...except that the solar plants exist. The Solar-1 and Thémis solar plants are not identical. The heliostat array is sufficiently large at Solar-1 and somewhat sparse at Thémis. The higher altitude (of 1650 m), better mirrors (with an angular resolution of $\approx 0.15^\circ$), the free access (with no conflict with a primary user) favour Thémis. The new imaging telescope to be built on this site, the CAT project—with an expected threshold of 200 GeV—will further increase the opportunities for tests. Attempts should be made to validate the scheme for 20 GeV gamma astronomy by the use of either site. Preliminary tests are running on both sites.

As a first step towards reactivating the Thémis heliostats, simulations have been run along the same lines as for the study of the ideal set-up above. If we take into account the collection efficiency of the secondary optics, the mirror effective area per heliostat reduces from nominal $54m^2$ to something more like the $38m^2$ of the ‘ideal set-up’. Because the diameter of the field is smaller (250 m) angular resolution decreases to 0.15° . Hadronic rejection is also degraded. An energy threshold of about 25 GeV should be attainable. Even with partial use of the field—using 40 of the 160 heliostats—the signal from the Crab, which could be seen in even a short time of observation, should permit the validation of the method.

TABLE II

Expected energy threshold and yield from the Crab nebula for two phases of exploitation of the Thémis heliostats.

Nb of heliostats	Threshold	Selected γ	γ -Crab/(e+p)	γ -Crab: σ /hr
160 (total)	25 GeV	0.2 / s	1 / 2	12
40	50 GeV	0.08 / s	1 / 2	8

4. Comparison with future satellites and other ACT techniques

On the basis of the great success of EGRET, a new generation of satellite observatories for high energy gamma ray astronomy with improved angular resolution and sensitivity to lower fluxes is under study (Godfrey; Hunter). The characteristics of the future satellite detectors have been based on evaluations given for GLAST. Above 10 GeV, the angular resolution is good enough to completely reject the background from diffuse gammas. The sensitivity is only limited by statistics as the effective area of $1m^2$ is still small. For the weakest sources detectable by Thémis, GLAST will see only 2 events a month above 10 GeV and only 2 events a year above 100 GeV. So quantitative study in this energy region, such as the attenuation of the AGN gamma spectra by the extragalactic infrared light, will be nearly impossible. Nevertheless satellites will be complementary to ground based ACT as they can continuously survey the whole sky whereas ACT telescopes can only look at one source at a time and thus depends on a pre established catalog.

The sensitivity of the “ideal set-up” is limited by the electron background which can only be reduced by improving the angular resolution. Up to now the best performance has been obtained with the imaging technique. To lower the energy threshold to 10 GeV, we need an array of ≈ 100 25m-diameter reflectors, each one equipped with a very high resolution camera (0.1° pix-

el size) to be able to reconstruct the axis of the shower images. The total number of PMT's is $\approx 50\,000$. We have have run simulations with such a set-up taking into account the sky noise but neglecting optical aberrations. The surprising result is that, at 20 GeV, the angular resolution is approximately the same as the "ideal set-up" (0.1°). This is 5 time worse than a naive statistical extrapolation of the Whipple results. It seems that the earth magnetic bending and the multiple scattering on the very beginning of the shower are responsible for this poor angular resolution. *At low energy, the angular resolution of ACT telescopes seems to be intrinsically limited. Very sophisticated, and very costly, telescopes might not perform much better than solar arrays.*

5. Conclusion

After the Whipple group established that, among the numerous air showers, the few having a common point-source in the cosmos could be pinned down, construction of new experiments and upgrades of existing ones began, aiming at enlarging the domain of investigations. The developments may concern the extension of the energy domain and the improvement in the sensitivity to cosmic sources of lower flux. The efforts are based on variations on the imaging techniques, either by a duplication of the telescope for stereoscopic observation, or by improving the camera performance. Another approach based on the sampling of the Cerenkov light pool by simultaneous use of many heliostats has been validated by the THÉMISTOCLE and ASGAT experiments. This multi-mirror strategy might well be appropriate to the low energy domain for which a huge collection area is needed, as could be tested with the use of solar heliostats. Combined with the CAT imaging telescope, to be built in 1995 on the Thémis site, aiming at a 200 GeV threshold, the fine imaging and the dense sampling techniques could then be used simultaneously on the same events. It is hoped to open investigation in a new range of energies.

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