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Detection of cosmic γ-rays using a heliostat field: the case of GRAAL

F. Arqueros[1], J. Ballestrin[2], D. M. Borque[1], M. Diaz[3], R. Enriquez[1], H.-J. Gebauer[3], and R. Plaga[3]

[1]Facultad de Ciencias Fisicas. Universidad Complutense. E-28040 Madrid. Spain
[2]CIEMAT-Departamento de Energias renovables. Plataforma Solar de Almeria. E-04080 Almeria. Spain
[3]Max-Planck Institute für Physik. D-80805 München. Germany

Abstract.
Gamma-Ray telescopes based on a solar plant are able to accurately measure the spatial distribution and time structure of the Cherenkov shower front. Although this information should be sufficient for the reconstruction of several primary parameters, it will be shown that the restricted field of view of the optical detection system and the limited sampling of a realistic heliostat array impose severe limitations.

1 Introduction

Several years ago Danaher et al. (1982) proposed to use the large mirrored area of a solar power plant (heliostat field) as a γ-ray telescope with lower energy threshold than conventional ground-based devices. The GRAAL experiment (Arqueros et al., 2001) is presently using the existing heliostat field CESA-I at the PSA for the search of high-energy cosmic sources. In GRAAL four groups of heliostats reflect the light onto four Winston cones, each containing a single large area PMT in a central tower. This approach is somehow different from that proposed by Tümer et al. (1991) in which a secondary optics in the tower allows to focus the light of every heliostat in a single PMT. Presently several experiments are using this technique (CELESTE coll., 1999), (STACEE coll., 1999) and (SOLAR TWO coll., 1999). GRAAL is a much simpler and lower cost approach at the price of a higher energy threshold but still reaching the 200 GeV energy range and thus lower than other Cherenkov telescopes presently operating in the world.

In the solar plant technique the field of view of the detectors is limited to a value of about 0.6 degrees in order to minimize the noise sky light NSL contribution. With such a field of view a heliostat located near the shower axis is able to observe completely a γ-ray induced shower. However, heliostats far from the axis would reflect a small fraction of the light reaching the ground because the lateral spread of the shower at its maximum development is significantly smaller than the size of the heliostat field. This problem can be partly solved by operating in the so-called convergent view CV configuration in which the heliostats aim at a certain convergent point CP where the shower maximum development is expected (figure 1). This Shower Maximum Region SMR is named by other authors as the shower *core*. Instead, in this paper, *core* will be used for the intersection of the shower axis with the ground.

In principle the solar plant technique allows an accurate determination of both the spatial distribution of the Cherenkov light reaching the ground and the time structure of the Cherenkov front. As is well known, proton induced showers show higher fluctuations than γ-ray showers in both features and thus in principle γ/proton separation would be feasible with this technique. In addition, the measurement of the arrival time at the heliostats allows the reconstruction of the Cherenkov front and thus obtaining information on the primary direction. In this paper a study of the capabilities of a heliostat array for the determination of some primary parameters is carried out.

For this study a shower library generated by the simulation code CORSIKA (v5.20) (Heck et al., 1997) has been employed. The fluctuations of both light density (section 3) and arrival time of Cherenkov photons (section 4) have been evaluated for perpendicular showers initiated by 200 GeV γ-rays and 500 GeV protons under three detection configurations: 1) all the Cherenkov photons hitting the ground are collected on a full coverage array of ideal 40 m^2 mirrors within a circle of 80 m radius with a non-restricted field of view NRFV; 2) the same as 1) but assuming a restricted field of 0.6 degrees and in convergent view configuration RFCV to a CP 11 km above the center of the array, and 3) the GRAAL heliostats in CV with realistic loses (PMT quantum efficiency, reflectivity of optical collectors,..) but neglecting NSL fluctuations and assuming perfect peak-heliostat identification. It has been studied the dependence of fluctuations on the core positions for three cases: a) core position at the field center FC (r = 0); b) core position randomly generated within a radius of 30 m around the FC ($r < 30$ m), for which 200 GeV γ-rays fire the GRAAL trigger with high probability and c) the same as

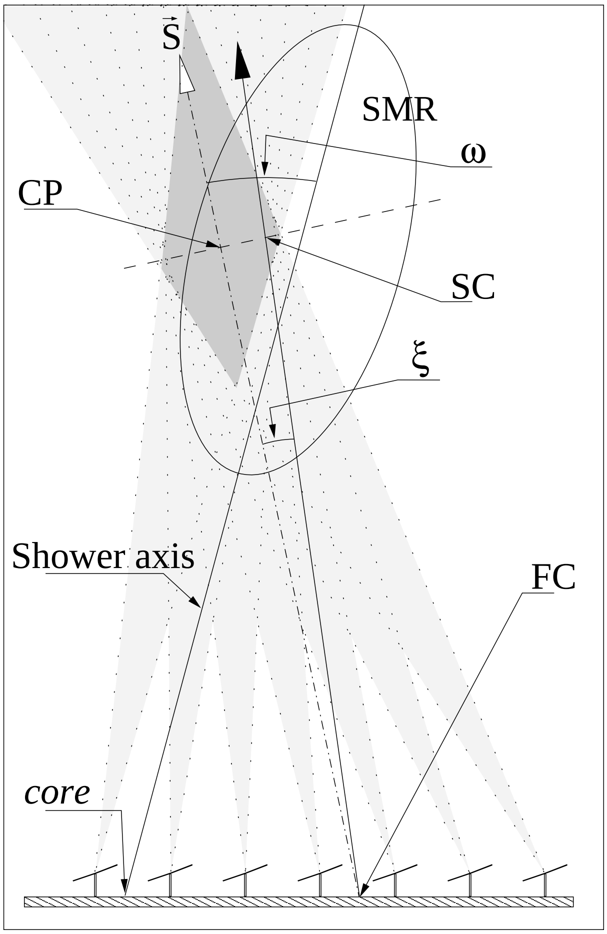

Fig. 1. Schematic view of a shower detected with a heliostat field pointing to $\boldsymbol{S}$ in convergent view. The heliostats aim at the convergent point CP. Only a fraction of the SMR is observed. The reconstructed direction is determined by the sphere center SC and the field center FC.

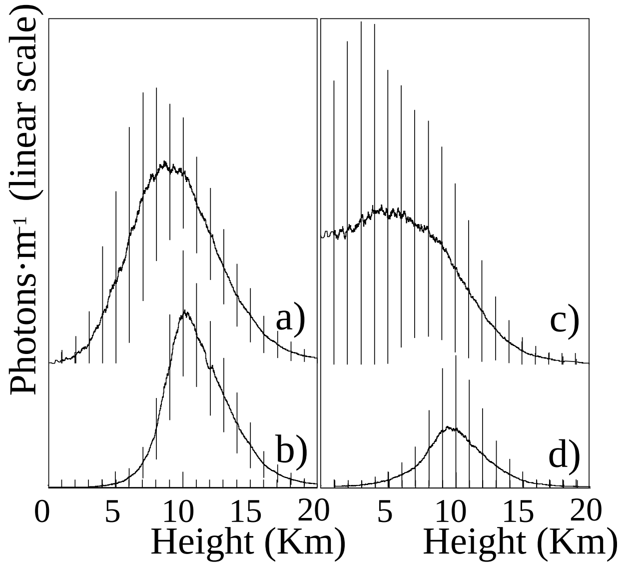

Fig. 2. Average number of Cherenkov photons generated per unit length of atmosphere depth for γ-showers (a) and protons (c). For curves b) and d) only those photons within the restricted field of the heliostats in convergent view (core position at the center of the array) have been counted. The error bars are the 1 σ deviations of the photon yield distribution at the corresponding height.

b) within a radius of 70 m. The results on angular resolution (section 2) were obtained with a detailed simulation of GRAAL including the NSL contribution.

Figure 2 shows the longitudinal development of γ-showers and proton showers in the energy range of this work as seen by a NRFV Cherenkov light detector and that based on a RFCV heliostat array. These plots clearly show that RFCV severely restricts the longitudinal development of the detected Cherenkov photons below the SMR, hiding important proton features. In the following we will show that both the restricted field of view and the limited sampling of a realistic heliostat array imposes limitations to the reconstruction of the primary parameters.

2 Direction reconstruction

Our simulations predict an spherical Cherenkov front with a curvature radius for RFCV of (11.0±1.1) km for γ-rays of 200 GeV. The algorithm employed in GRAAL for the front reconstruction has been developed and tested on the simulated events. It uses a χ^2 fit which simultaneously finds both the optimal peak-heliostat identification and the center of the sphere SC (constrained to a radius of 11 km) which is associated to the SMR from where most of the detected Cherenkov light was generated (see figure 1). Although the SC position is determined with good accuracy, for the full reconstruction of the shower direction it would be necessary to know the core position on the ground which is difficult to determine. Assuming the shower core is located at the center of the heliostat field, the angular error is mainly related to the uncertainty in the core position which is limited by the maximum core distance for which the trigger is fired.

Following this procedure we have reconstructed the primary direction of a sample of simulated γ-ray and proton showers including a detailed description of GRAAL. Gamma-showers were generated as a point-like source while proton showers income isotropically. The core position was randomly generated. The energy spectrum of the proton showers was that of the cosmic protons while for γ-rays the Crab spectrum was assumed.

The distribution of reconstructed directions was found to be slightly asymmetric in a two angular coordinates system, consistent with the spatial asymmetry of the GRAAL heliostat field. As an example (see Borque (2001) for more details) the two components width (63%) of the angular error (ξ in figure 1) distribution for γ-rays incoming with a zenith angle of 30 degrees and azimuth of 45 degrees (southwest) is found to be of 0.67 and 0.57 degrees. For the isotropic proton background, the two components width of the angu-

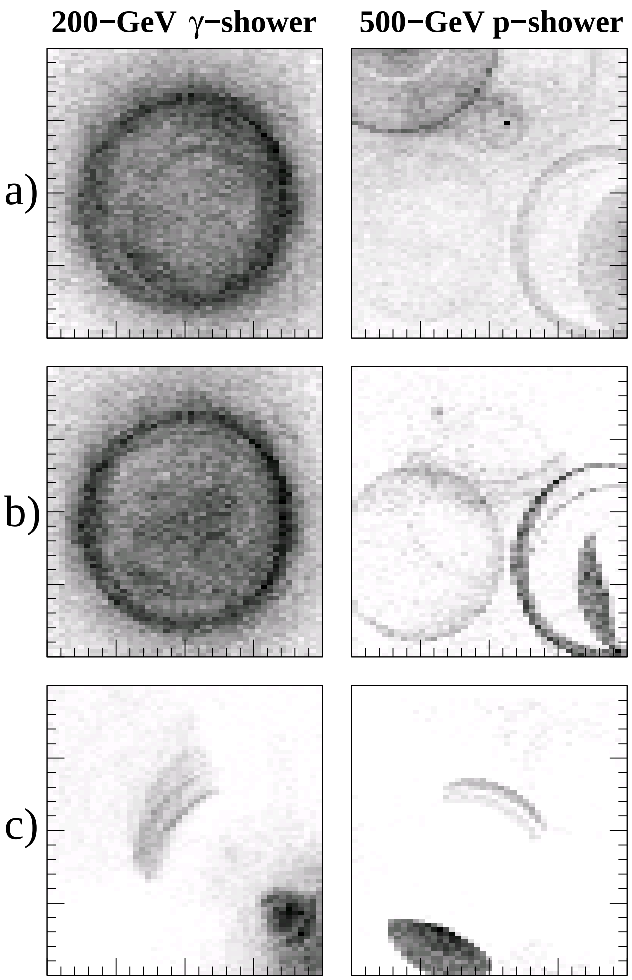

Fig. 3. Spatial distribution of Cherenkov photons in a square of 300 $\times$ 300 m^2 at ground (500 m a.s.l.) for both a 200 GeV γ-ray shower and a 500 GeV proton shower. a) All photons are plotted (NRFV); b) Only those photons detected by a restricted field/convergent view array (RFCV with r = 0); c) the same as b) but with the shower axis shifted by about 60 m.

lar distance distribution to the pointing direction after reconstruction (ξ in figure 1) is 0.78 and 0.78 degrees which can be compared with that obtained from the angular distribution of true incoming directions (ω in figure 1) firing the trigger (0.68 degrees).

3 Spatial distribution of Cherenkov light

Figure 3 shows the spatial distribution of the Cherenkov photons at ground generated by both a 200 GeV γ-ray shower and a 500 GeV proton shower. The upper panel shows the well known behavior corresponding to a NRFV in where the light density of a γ-shower is nearly flat up to a core distance of about 120 m (the hump) where, after a local maximum, it sharply decreases. This feature could be used for the determination of the core position. A proton shower which generates a similar amount of Cherenkov light produces an irregular pattern with significant density fluctuations. The pattern recorded by a heliostat array in RFCV is similar as far as the core position is in the center of the field (middle panel). Although in principle this feature could be used for proton discrimination, note that these fluctuations take place at a scale larger than the usual size of a heliostat array and thus the detector is not able to get all the features appreciated in figure 3.

Core Position	Configuration	γ 200 GeV	p 500 GeV
$r = 0$	No restrictions	0.09	0.3
	RFCV	0.12	0.6
	GRAAL (no NSL)	0.42	0.6
$r < 30$ m	RFCV	0.14	0.6
	GRAAL (no NSL)	0.41	0.6
$r < 70$ m	RFCV	0.31	0.7
	GRAAL (no NSL)	0.42	0.7

Table 1. *Fluctuations of the Cherenkov photon number collected by a 40 m^2 heliostat in the various configurations for γ-rays and protons with the core position in the center of the array (r = 0) and randomly generated in a radius of 30 m and 70 m*

Lower panel shows, for the same showers, a more realistic situation in which the core is shifted about 60 m from the field center FC. Since the SMR is laterally shifted, many mirrors are not able to *see* the shower because of its restricted field of view. As a result, the γ-ray shower loses the hump mark and the spatial distribution becomes more irregular making the determination of the core position very difficult.

Quantitative results on the average fluctuations of the Cherenkov photon number hitting a 40 m^2 mirror for the various configurations have been determined as follows. For each individual shower i it has been obtained the average number of photons hitting a mirror $\bar{n}_i$. The fluctuation δn is the 1 σ deviation (68%) of the $\frac{n_{ij}-\bar{n}_i}{\bar{n}_i}$ distribution where the sub-index j run over all the mirrors.

The results for the various configurations are presented in table 1. Proton fluctuations are significantly larger than those of γ-rays in both configurations NRFV and RFCV though it can be seen that the ratio $\delta n_p/\delta n_\gamma$ diminishes with r. The table also shows that the γ-fluctuations are significantly increased when loses of a realistic array (GRAAL) are taking into account. From the corresponding distributions for this case, it is obtained a quality factor $Q = \epsilon_\gamma/\sqrt{\epsilon_p}$ (ϵ is the surviving fraction after the cut) of about 1.1. A detailed detector simulation including the NSL contribution and realistic peak identification shows that the above procedure is not able to produce any useful γ/p separation.

4 Time fluctuations of the Cherenkov front

As already mentioned, the Cherenkov front of a proton shower is much less well defined than that of a γ-ray shower and therefore a measure of the arrival time fluctuations could provide information on the primary particle (γ-ray or proton).

Core Position	Configuration	γ200	p500
$r = 0$	No restrictions	0.2	2.3
	RFCV	0.2	0.4
	GRAAL (no NSL)	0.7	0.8
$r < 30\,\mathrm{m}$	RFCV	0.4	0.6
	GRAAL (no NSL)	0.7	0.9
$r < 70\,\mathrm{m}$	RFCV	0.9	0.9
	GRAAL (no NSL)	0.7	0.9

Table 2. *Arrival time fluctuations (ns) of the Cherenkov front as observed with 40 m^2 heliostats in the various configurations for γ-rays and protons with the core position in the center of the array (r = 0) and randomly generated in a radius of 30 m and 70 m*

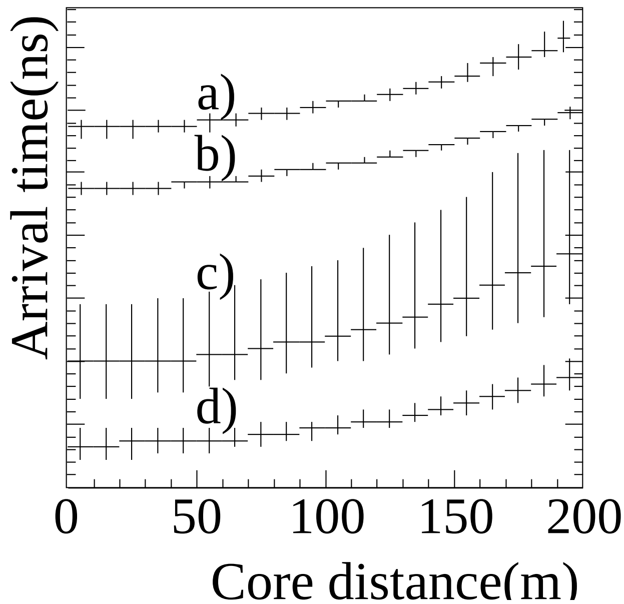

Fig. 4. Cherenkov front shape for 200 GeV γ-rays (a, b) and 500 GeV protons (c, d) as seen with a unrestricted field of view (a, c) and with a restricted field and convergent view (b, d).

Figure 4 shows the average Cherenkov front corresponding to both NRFV (curves a and c) and RFCV with the shower core in the center of the array (curves b and d). For every shower the front has been calculated from the mean arrival time at the corresponding core distance. The fronts of figure 4 are the median of the corresponding distributions of all the showers and the error bars represent the 68% fluctuations (34% arriving later and 34% sooner than the median front). Fronts a) and c) show that the fluctuations under NRFV are much higher in proton showers as compared with γ-rays. In addition, fluctuations are nearly independent of the core distance up to 80 m and thus they could be used as a distinguishing feature even if the core position is unknown.

In a real experiment, shower front fluctuations can be measured on individual showers by comparing the arrival time of the Cherenkov pulses at the different mirrors. For each individual shower it has been calculated the mean value of the photon arrival time distribution $\bar{t}$ and the absolute delay $\delta t_j = |t_j - \bar{t}|$ for every mirror j. In NRFV and RFCV configurations t_j and $\bar{t}$ have been calculated as a function of the core distance while for GRAAL $\bar{t}$ it is obtained from a sphere fit (see section 2).

Table 2 shows the 1 σ deviation of the δt_j distribution. In the first place this table shows that the restricted field of view lowers significantly the time fluctuations of protons. From figure 1 it can be seen that the RFCV reduces the SMR which can be observed by the heliostats and thus, decreasing the time fluctuations. While this effect is small in γ-showers, it is very significant for protons since the corresponding showers are longer (see figure 2) and broader. The large time fluctuations are visible when all the shower development is observed but they do not show up when the lowest part of the shower is not detected (see figure 1). On the other hand, for the GRAAL case (no NSL) time fluctuations increase for both primaries resulting in a Q factor of about 1.1 (similar to that of density fluctuations) in such a way that no γ/p separation is possible in the real detector.

5 Conclusions

An accurate measurement of the arrival time of the Cherenkov front to the heliostats allows the reconstruction of the incoming direction with an angular error mainly given by the uncertainty in the core position (impact point).

In principle γ/p separation would be possible by an accurate determination of several parameters which can be measured by a heliostat field, in particular the fluctuations in both the shower front and the Cherenkov light density. However the restricted field of view of the heliostats tends to significantly diminish the differences, mainly in the time fluctuations. Additionally the potential separation capability of these methods is restricted by the limited sampling and loses of a realistic detector, specially in those methods based on the light density fluctuations.

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