Constraints In Reducing The Threshold Of Imaging Cherenkov Telescopes

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Abstract

Currently existing gamma ray imaging telescopes measure above the energy threshold of about 300 GeV. In the nearest future some of the existing telescopes will be modified and new telescopes will be operating providing probably an energy threshold of about 100 GeV. It is very interesting to measure also in the energy range between 10–100 GeV, which is not yet explored due to the lack of detectors for this energy range. Here we show that a single large (15–20 m ø class) ground-based imaging telescope can provide measurements of gamma sources above the threshold of 10–30 GeV. Probably the systems of ≥ 3 such telescopes will found the future gamma ray observatories, allowing one to find, measure and classify sources in the whole 10 GeV – 100 TeV energy range.

1. Introduction

The 25th ICRC in Durban and this workshop have very convincingly demonstrated the success of VHE gamma ray astronomy and once more again underlined the fact that a new branch of astronomy has firmly established itself. The Whipple, the CAT, the HEGRA, the Telescope Array and the TACTIC collaborations (also the Durham group) have reported their measurements on highly variable Active Galactic Nuclei (AGN) Markarian-501 within several months of the source activity and demonstrated good agreement among their data measured on the same days by their rather different telescopes scattered on different continents on the Earth (Protheroe, 1997; Bradbury, these proceedings).

It is already the 5th workshop of the series devoted to the major atmospheric Cherenkov detector. At the 2nd workshop in Calgary T.C. Weekes has discussed the possible developments which might lead to the goal (Weekes, 1993). Since then there have been a lot of new developments in the field, but still, while we know what do we want (a Major Atmospheric Cherenkov Detector), it is not yet very clear how would it finally look like.

The Compton GRO satellite measures up to 10–20 GeV, the planned future missions can measure even somewhat higher energies, but the low flux sensitivity of satellite experiments, which is due to the limited detector area of $\sim 1\ m^2$, can not be dramatically increased. It seems that the wide field of view of satellite detectors and the very high flux sensitivity of very low energy threshold (VeLET) Cherenkov telescopes, which will be operating in the sub-100 GeV domain, are complementary to each other. The combination of both techniques can allow one to perform deep exploration of the Universe in the sub-100 GeV energy range.

In this report I will try to set forth *my subjective vision* concerning the future gamma-ray observatories. There are different views about it. While two of the proposed future arrays of gamma telescopes (the VERITAS and the HESS projects) are oriented to study sources

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in the energy domain mainly above 100 GeV, the MAGIC telescope project is intending to explore the possible sources above the ultimate threshold (of course, from todays point of view) of 10–30 GeV. One of the simplest arguments in favour of sub-100 GeV telescopes is, for example, the recent puzzling non-observation of EGRET of the AGN Markarian-501. While the source has been measured by Cherenkov telescopes of several collaborations, the EGRET detector on-board the Compton GRO satellite failed to measure any signal from it during the ToO company in April 1997, when the source was measured to be in high state (Protheroe, 1997). It seems that a sub-100 GeV Cherenkov telescope, which can provide at least $\sim 10^4$ times larger collection area and correspondingly higher signal rate than the EGRET, can allow one, providing even a moderate imaging ability, to investigate the source spectra also in the satellite energy domain.

The first publication concerning the sub-100 GeV γ astronomy by using Cherenkov telescopes has appeared already 20 years ago (Weekes and Turver, 1977). During the 1st workshop in Palaeseau in 1992 in his summary talk R. Lamb suggested to start thinking on the construction of 20–30 m ø telescopes, which might allow one to enter the sub-100 GeV domain.

Since its construction for $\sim$ 30 years ago the 10 m ø Whipple telescope is the largest one. This telescope, equipped with a 37 pixel imaging camera, had a threshold of $\sim$ 700 GeV in 1988 and provided the first highly significant gamma signal (9σ) from the Crab Nebula (Weekes, Cawley, et al., 1989). Since then the telescope has been given a 109-pixel high resolution camera. By improving the general performance of the telescope, as for example, by using light concentrators and giving a protective layer to Al mirrors, during the recent years the threshold of the telescope has been lowered till the current value 250–300 GeV. It is anticipated that improvements in the trigger logic and a new very high resolution camera, scheduled for the nearest future, will allow the Whipple team to achieve a threshold of 120–150 GeV.

The 10 m ø Japanese telescope, which is in the construction phase now, is planned to start taking data already in the next year, first by setting the mirrors in its central 7 m ø and then increasing the mirror coverage till the full diameter (Matsubara, these proceedings). The Durham group is using 120 m^2 total mirror area, shared between three telescopes on one mount (Turver, these proceedings). These are the largest existing or planned for the nearest future telescopes. About one year ago the Whipple collaboration has released the VERITAS proposal (Weekes, Buckley, et al., 1996). They are planning to built a system of nine 10 m ø telescopes. Already now this project is partially approved for the financial support. After VERITAS the similar HESS project has been followed in this year (Aharonian, Daum, et al., 1997). In HESS it is planned to built 4 telescopes of the same aperture as VERITAS (Whipple) at the initial phase and afterwards to complete it till 16. With both systems a somewhat lower, compared to a single telescope, threshold can be anticipated (probably in the range of ≤ 25 %). A more radical solution has been proposed by the MAGIC telescope project in 1995 (Lorenz, 1995; Bradbury, Bush, et al., 1995a). The 17 m ø imaging telescope can provide a lower energy threshold of 10–30 GeV depending on the applied light sensors. It may serve as a prototype for a future multi telescope gamma ray observatory.

Here I want to discuss the feasibility of sub-100 GeV ground-based gamma ray astronomy by means of 15–20 m ø class imaging telescopes. The current status of the technique of using solar power plants for very low energy gamma astronomy is extensively described in these proceedings (see Ong; Pare; Plaga).

We have performed Monte Carlo studies for the 17 m ø MAGIC telescope (Gonzalez, Mirzoyan, et al., these proceedings), which can be considered as a representative of the class of large diameter (15-20 m ø) telescopes. In this report I will use some results of our simulations for illustration purposes.

It seems that the developments in the field of imaging gamma telescopes are similar to developments in the field of optical and radio telescopes. We also want large telescopes in order to see deeper in the Universe. We also want many telescopes in order to measure more accurately.

Our simulations show that the imaging telescopes can successfully measure above the threshold 10 GeV. Once large telescopes are built, one probably will use them for tens of years. Of course, new developments in the field of photon detection will always push one to built better cameras, this seems to be a running target.

It seems that the planning and the construction of telescopes of only modest reflector size of $\leq 10\ m$, which can provide a threshold of $\sim 100\ GeV$, will only be an intermediate stage in the development of the technique.

The large diameter ones, which can provide a threshold of 10–30 GeV seem to be within reach already now.

2. Constraints On Large Diameter Cherenkov Telescopes

In principle an imaging telescope is a rather simple construction, it is an ultra fast photo electronic camera in fact. It consists mainly of a concave reflecting surface and of a coordinate sensitive camera in its focal plane. The concave reflector collects Cherenkov photons from extensive air showers and images them in its focal plane, where they are detected by a position sensitive multi element fast electronic camera. One may consider two main constraints on large imaging telescopes, namely the physical and the mechanical ones.

2.1. The Physical Constraints

In the following I will discuss some factors which impose certain requirements on Cherenkov telescopes for their adequate functioning.

2.1.1. The minimum amount of measured charge per image

In order to measure *an image of a shower with the given energy* E_0 obviously one has to measure enough signal from it. Only then can one consider the measured pattern as an image. Our experience with the HEGRA telescopes showed that one needs at least 60–100 photoelectrons (ph.e.s) per image in order to parametrise it reliably (for the TeV energy range, for the given pixel size of 0.25° and for a single telescope).

2.1.2. The minimum surface area of the reflector

In order to measure images of showers with the energy E_0, given the ph.e. to photon conversion factor for the telescope, its reflector must have a mirror surface area which should be large enough in order to provide the necessary minimum signal.

Let us try to estimate the ph.e. to Cherenkov photon conversion factor $M_{ph.e./ph}$ for a large telescope, which uses a multi channel photomultiplyer (PMT) camera. By folding the simulated shape of Cherenkov spectrum of 50 GeV gamma showers (after atmospheric transmission) with the QE curve of a conventional bialkali PMT, assuming a 27 % QE for the latter in its maximum (at $\sim 370\ nm$), one obtains a spectrum averaged QE of ~ 18 %. Let us assume now the mirror reflectivity of 85 %, the light guide (L.G.) efficiency of 90 % and the PMT ph.e. collection efficiency of 90 %. One can calculate that the resulting conversion factor is about 12 %.

A gamma shower of energy E_0 provides on average $N(ph/m^2)$ up to the impact parameter $\sim 125\ m$ (position of the hump). Providing the value of the $M_{ph.e./ph}$ factor, one can estimate the minimum surface area of the reflector A_{mirror}, which is necessary for measuring images of showers with energy E_0, from: $N(ph/m^2) \cdot A_{mirror} \cdot M_{ph.e./ph} \geq 100 ph.e.s.$

2.1.3. The optical resolution of the reflector

The reflector of an imaging telescope must provide an optical resolution (an imaging quality) of better than 0.1° – 0.2° (this is the characteristic difference in size between the images of gammas and hadrons) within a field of view of 2°–3° in diameter (Mirzoyan, Fomin, Stepanian, 1996a). This sets constraints to the size of the mirror tiles of a tessellated reflector and to the latters F/D ratio (F is the focal length and D is the diameter). One believes that the mirror tiles of 0.5–1 m size are adequate for imaging telescopes. A reflector with $F/D \geq 1$ can provide the necessary optical resolution (this is true for both Davies-Cotton and parabolic designs, the first one providing somewhat better resolution for relatively large incident angles and in contrary, the second one for relatively small angles).

Another kind of optical aberration, the so-called *depth-of-field* type, depends on the D/L ratio, where L is the average distance to the shower maximum (Mirzoyan, Fomin, Stepanian, 1996a). For the sub-100 GeV energy range, for example, a 30 m, a 20 m and a 10 m ø telescopes will provide 9', 6' and 3' aberrations correspondingly, which are 15', 10' and 5' for the TeV energy range. One may conclude that a 15–20 m ø class telescope can provide a reasonable optical resolution both in the TeV and in the GeV energy regimes.

2.1.4. The gamma selection and rejection of different backgrounds

It is a well established fact that an imaging telescope provides an efficient gamma selection and a strong rejection of hadron background both in hardware and in software for energies above 300 GeV (Fegan, 1997).

The performance of a single imaging telescope for the $\geq 10\ GeV$ energy range is discussed in the paper (Gonzalez, Mirzoyan, et al., these proceedings) on the example of the MAGIC telescope. Earlier an investigation has been performed for the γ ray detection in sub-100 GeV energy range with a 10 m ø telescope (Tanimori, Sakurazawa, et al., 1995).

The simulations revealed that the performance of imaging telescopes degrades to some extent for energies below a few hundred GeV. The very low energy primaries produce less secondary particles in showers. The latter develop high up in the atmosphere where the air density is low and therefore the energy threshold for Cherenkov light production is higher. With increasing height in the atmosphere the air density decreases and therefore one radiation length corresponds to longer distances.

While air shower development is "sensitive" to the column density of the medium in terms of radiation lengths, an image of a shower is just a geometrical projection and therefore it is sensitive to the height and to the distance of the shower from the telescope. Due to both abovementioned reasons the fluctuations in sub-100 GeV images are large. Separation of gammas from the hadron background, based on the second moment analysis of both the shape (*length, width, concentration*) and the orientation parameters of images becomes less effective compared to energies above a few hundred GeV. In contrary, the hadron trigger efficiency decreases strongly with lowering the energy of the primary. For example, while the trigger efficiency for a 30 GeV gamma is $\sim$ 70%, for a 30 GeV proton it is only 0.025 % (Barrio, Fonseca, et al.).

The Monte Carlo studies showed that MAGIC, when operated with a classical PMT camera, can provide a threshold of $\sim$ 30 GeV and a Q factor (which is defined as the ratio:

$$Q = \frac{M_\gamma(after)/M_\gamma(before)}{\sqrt{N_p(after)/N_p(before)}} \tag{1}$$

where, for example, $M_\gamma(before)$ and $N_p(after)$ mean the number of γ and *proton* showers before and after analysis correspondingly) of $\sim$ 8 (Gonzalez, Mirzoyan et al., these proceedings). When operated with the enhanced QE light sensors with $GaAsP$ photocathodes (see the paragraph "The light detectors" below) it can provide a threshold of $\sim$ 8-10 GeV and a Q factor of 7–8. Note, that muon arc events (see below the paragraph "The Triggers From Muon Arcs") are included in the simulations and in the calculation of both of the above mentioned Q factors.

These Q factors are somewhat lower than their value above a few hundred GeV, but the remarkable fact is that still the imaging technique works so well even for these ultimately low energies. Note, for example, that a gamma shower of 30 GeV provides on average only $\sim$ 3 ph/m^2 within the Cherenkov cone.

Below $\sim$ 100 GeV the electron component in cosmic rays starts to play an important role for imaging telescopes. It follows a steep power low of (-3.3) exponent down to 10 GeV where it tails off. This "irreducible" background can substantially be rejected due to its isotropic nature and the angular resolution of the telescope.

2.2. The Mechanical Constraints

Telescopes undergo deformations due to gravitational force. These deformations can deteriorate the shape of the reflector and its point spread function as well as they can influence the relative positioning of the light detector. The mechanical mounts of telescopes are subject to both static and dynamic deformations, the latter varying depending on its positioning. Various deformations of the telescope mount should be kept small in order not to spoil the above mentioned minimum required optical resolution of $0.1° - 0.2°$. There seem to be two general options for designing big telescopes. The first one is to built a strong and heavy mount, where the deformations can be kept below the pre-specified value. The second option is to built a relatively light weight telescope where one can allow for small deformations, but which can be thoroughly monitored and corrected for by application of the active mirror control (Wacker, Barrio, et.al., these proceedings). While from the point of view of point spread function both options can provide similar results, one believes that the second option is cheaper and provides less inertia which is important for the fast positioning of the telescope.

The finite element analysis and construction technique allows one, by a proper choice of the material, of the number of layers, of the diameter and of the length of the used tubes to constrain deformations to be below the pre-specified value (Lorenz, these proceedings). Materials such as steel, Al or carbon fibre can be used for construction of telescope mounts. The latter two materials, while potentially providing the same stiffness as the steel, weigh substantially less, the lightest (and the most expensive) one being the carbon fibre option.

3. The Energy Threshold Of A Cherenkov Telescope

In the following I will discuss the factors which define the threshold for a Cherenkov telescope.

3.1. The threshold versus the mirror surface area

Generally the Cherenkov telescopes can be classified into two main classes, non-imaging (the first generation) and imaging (the second generation) ones. The non-imaging ones apply usually a single light detector in the focal plane and measure gamma sources just by looking for a possible excess in the number of measured showers from the so-called *on-source* direction (the direction of a possible point-like gamma emitter) compared to the *off-source* one (a direction, which is advanced or delayed by a few degrees in right ascension from that of the on-source, but which has still the same declination). Some of such multi telescope distributed arrays explore also the differences in the lateral light distribution from gamma and hadron induced showers for the rejection of the latter background.

An imaging telescope is using a coordinate-sensitive light detector in its focal plane and providing snapshots of showers in Cherenkov light. It is using the differences in the *shape* and in the *orientation* of patterns from gamma and hadron showers for improving the gamma signal.

By proper choice of the camera and the pixel sizes and of the trigger logic, the hadron background can efficiently be rejected both in hardware and software (Fegan, 1997). The imaging has been proven to be the most sensitive technique.

The trigger threshold of a non-imaging telescope is usually set at the level, which is exceeding the fluctuations of noise due to the afterpulsing in PMTs (Mirzoyan, Lorenz, et al., 1997a) and/or light of the night sky ($LONS$) by a factor of 3–4. The threshold of a non-imaging telescope $E(non-imaging)_{threshold}$, which can be defined as the shower energy which provides the minimum given signal/noise ratio during the given measuring (gate) time, scales with the mirror surface area A_{mirror} as:

$$E(non-imaging)_{threshold} \sim \frac{1}{\sqrt{A_{mirror}}} \tag{2}$$

This is due to the fact that the signal charge (which is proportional to the number of measured Cherenkov photons from a shower) is almost linearly proportional to the mirror area, while the noise fluctuations (r.m.s. value of the charge measured from $LONS$) are proportional only to the square root of it.

Together with the trigger threshold the imaging telescope has also another, a more decisive threshold, namely the imaging one (one needs at least ~ 100 ph.e. per image), which is usually few times higher than the trigger one (see the paragraph 2.1.1 above).

As the measured from a shower charge is almost linearly proportional to its energy, the energy threshold of an imaging telescope relates inversely to the mirror area:

$$E(imaging)_{threshold} \sim \frac{1}{A_{mirror}} \tag{3}$$

(Mirzoyan, 1996b; Mirzoyan, 1997b).

3.2. The other factors which define the threshold

Let us discuss now the other factors which define the threshold energy for an imaging telescope.

Cherenkov photons from a shower hit first the reflectors surface, then they are reflected into the focal plane, where some part hits the light sensors and some is lost between the not active area around sensors. Often non-imaging light concentrators are used in order to minimise the dead space between neighbour pixels and for the full utilisation of the reflected beam. They also limit the angular acceptance of the camera pixels, lowering thus the stray light contribution in measurements (see Fig.2 below).

The formula (3) can be presented in the form:

$$E(imaging)_{threshold} \sim \frac{1}{A_{mirror} \times LCE} \tag{4}$$

where the light collection efficiency (LCE) can be presented as

$$LCE = R_{mirror-reflectivity} \times L.G._{efficiency}(ifused) \times QE \times ph.e._{collection-efficiency} \tag{5}$$

(L.G. in formula (5) is abbreviation for light guides). Let us now discuss different terms in the above equation. The Cherenkov light from showers is concentrated mainly in the wavelength range 300–700 nm. Above 700 nm the intensity of $LONS$ is increasing rapidly and below 300 nm the Cherenkov photons undergo strong absorption in the atmosphere. The PMTs with bialkali photocathodes, used as a rule in Cherenkov telescopes, provide usually a QE of only 1-2 % at 600 nm, which strongly decreases for longer wavelengths.

3.2.1. The mirror reflectivity

The mirrors, made out of pure Al (99.99 %) or its alloys ($Al : 95 - 99\% + Si + Mg + Mn$) provide a reflectivity of 85–92 % in the wavelength range of interest (see, for example, Fig.1 below).

After giving it a protective layer from quartz or from Al_2O_3 the reflectivity is still in the range of 80–90 % (Barrio, Lorenz, Mirzoyan, these proceedings). Recently we have measured the reflectivity of front aluminised and quartz coated glass mirrors used for the HEGRA telescopes in La Palma for more than five and half years (Mirzoyan, Kankanian, et al., 1994a). We measured the reflectivity in Cherenkov spectrum by using the Cherenkov spectrum simulator/reflectometer described in (Bradbury, Mirzoyan, Gebauer, 1995b). Close inspection of the mirrors showed lot of scratches on their surface caused by relatively frequent hand-washing (they were washed about once in two months) by using soft artificial leather. The measurements showed that during this relatively long period the mirrors lost their reflectivity only on ~ 5 %, providing still a reflectivity of ~ 80 %.

3.2.2. The light concentrators

The non-imaging L.G.s can be made hollow or out of a solid material. The hollow L.G.s can be made, for example, out of hard epoxy and then given a thin layer of aluminium. The hollow L.G.s can be made as focons or as Winston cones. For the latter the theoretical maximum light concentration $K_{concentration}$ is given by

$$K_{concentration} = \frac{1}{sin^2\theta} \tag{6}$$

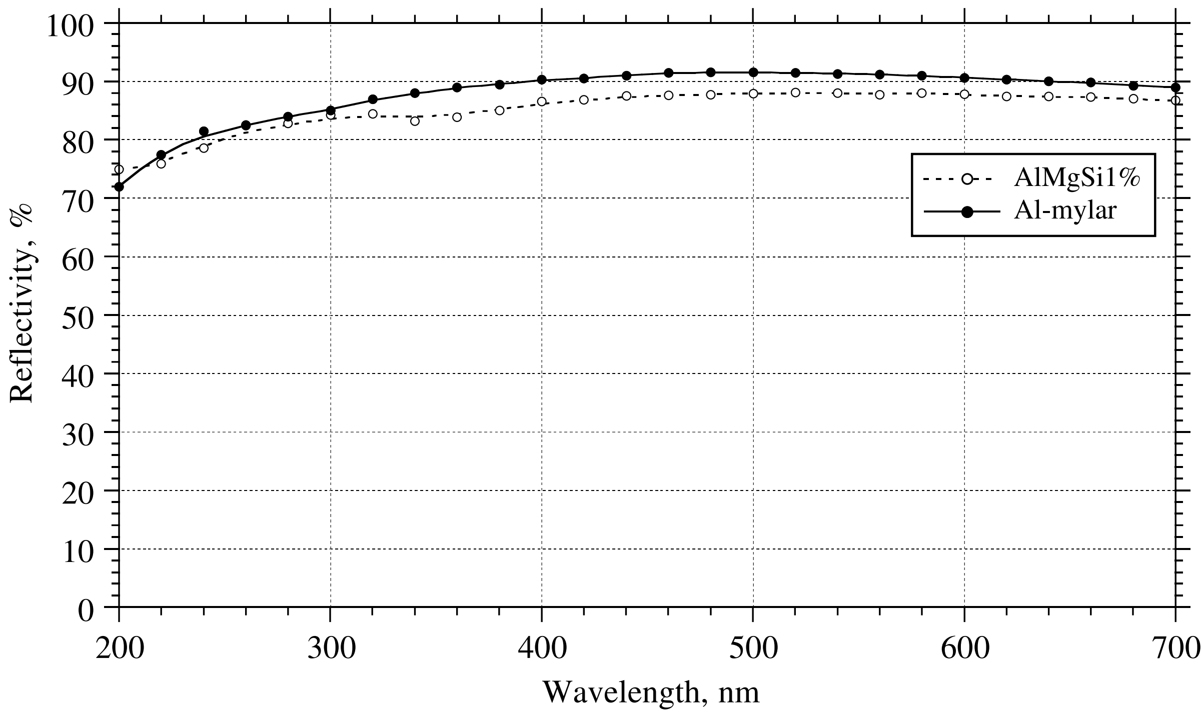

Fig. 1: The measured reflectivity of an Al-mylar foil (the Al side is exposed to the beam) and of a AlMgSi1% alloy.

where θ is the maximum angle of acceptance (Welford, Winston, 1978). Winston cones provide almost 100 % light concentration (excluding losses due to the finite reflectivity of the used material) and very sharp transition (within $1^\circ - 2^\circ$) from the acceptance to the non-acceptance region. The disadvantage of Winston cones is the fact that it is difficult to construct a multi-element matrix without dead space between the neighbour channels. Also, it is not trivial to machine its parabolic shape.

The focons have somewhat inferior, compared to Winston cones, characteristics, as for example, the transition region which is not as sharp. They have a conical shape, which is easy to produce mechanically. Also, it is possible to produce focons of hexagonal entrance window, which changes smoothly along the axis of the cone to the round shape at the output window (such cones are used for the HEGRA telescopes).

The L.G.s made out of solid materials as, for example, out of UV-transparent plexiglass or out of quartz, are working using the effect of total internal reflection and are superior in angular acceptance due to the refraction of light at the entrance window. They provide n times (where n is the refraction index of the used material) wider angular acceptance compared to hollow L.G.s.

The relativistic charged particles produce non-negligible amount of Cherenkov light in solid focons, which can initiate triggers. These events can be tagged by using a plastic scintillator shield around the camera (Wiedner, 1994).

Below on Fig.2 one can see the measured characteristics of a hollow focon, the internal surface of which is given a layer of Al mylar. The Al side is exposed to the beam.

Such L.G.s are used in high resolution cameras of the HEGRA telescopes. We still use also solid L.G.s made out of UV-transparent plexiglass (they were designed for the 0.43° pixel size cameras; currently they are used only for the HEGRA 2nd telescope) (Mirzoyan, 1993; Mirzoyan, 1994a). The measurements showed that, in spite of only ~ 90 % reflectivity of Al, the hollow focons provide a ≥ 90 % light concentration efficiency (this is possible because some part of light is hitting the photomultiplier tubes (PMTs) directly).

3.2.3. The light detectors

For Cherenkov telescopes one needs light detectors which are at least a few nanoseconds fast, provide high QE, linearity in a dynamic range of $\geq 10^3$ and a low noise. The single ph.e. resolution of light detectors is a big advantage for Cherenkov telescopes while, for example, the tail cut in image cleaning procedure is sensitive to single ph.e. level; it is also an advantage in amplitude calibration of telescopes.

The classical and hybrid PMTs The classical PMTs provide most of the above mentioned features and therefore they are used exclusively in all of the existing Cherenkov telescopes.

The use of light sensors with higher QE than that of classical PMTs can be seen as an increase of the reflector size of a telescope (see formula 4). Obviously the latter is a much more difficult and expensive task compared to the exchange of light sensors. Also, increase of the reflector size beyond a certain limit is unwanted due to the increase of the *depth-of-field*

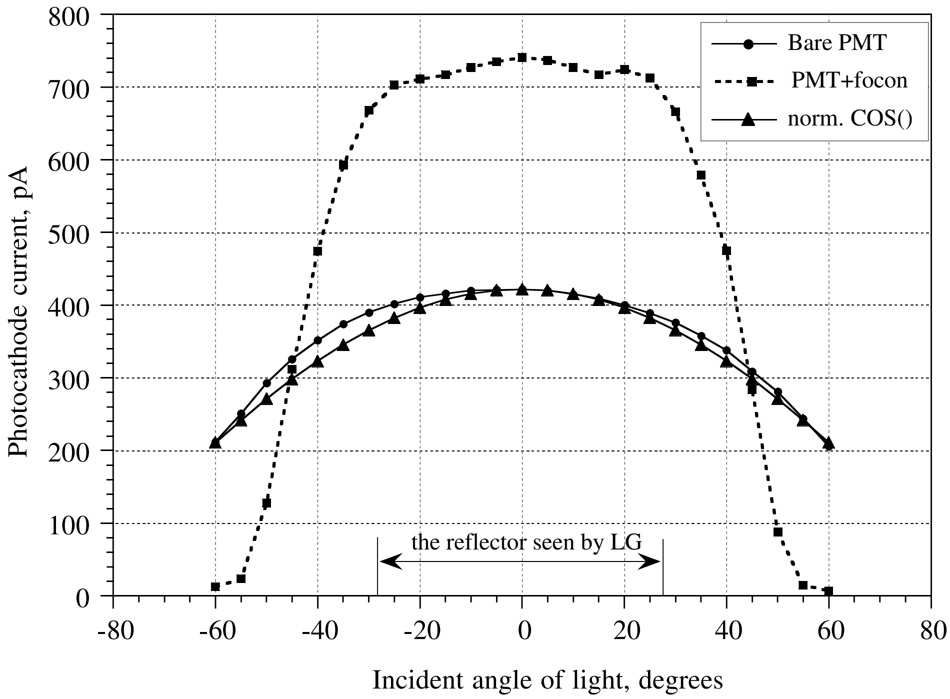

Fig. 2: The measured acceptance and light concentration of a hollow focon used for the HEGRA telescopes. Note, that the entrance window of the used PMT EMI-9083A has a convex shape.

type aberration. Therefore alternative photon detectors, which can provide higher QE (and correspondingly lower threshold) than the classical PMTs, are of high importance. Along with classical PMTs the hybrid PMTs (HPMTs, sometimes they are called also intensified diodes), due to the recent technological advances are finding wide applications. A HPMT consist of a photocathode layer deposited onto the entrance window, of an electron acceleration and focussing chamber and of a diode (or an avalanche diode, AD) serving as anode, where the accelerated electrons deposit their energy and create charge. The HPMTs with conventional photocathode materials provide of course the same QE as the classical PMTs, but they provide much lower noise in the electron multiplication. Application of HPMTs can substantially improve the precision of amplitude measurements.

The hybrid PMTs with $GaAsP$ photocathode The interest for hybrid PMTs has been boosted recently with the availability of hybrid tubes with $GaAsP$ photocathode and with AD readout from INTEVAC. The $GaAsP$ photocathode provides a QE of ~ 45 % in its maximum between 500–600 nm (see Fig. 3). By application of the wavelength shifting (WLS) technique we succeeded recently to enhance its QE to the level of 25–30 % also in the near UV part of the spectrum (Bradbury, Mirzoyan, et al., 1997). Further enhancement of its QE in the UV to the level of its maximum is anticipated with the thinning of the tubes entrance window (this work is in progress). Such a tube can then, by application of the WLS technique, provide an almost constant QE of 40–45 % in the whole spectrum between 300–600 nm. The total gain of these tubes is ~ 20000 (a single electron accelerated up to 8 KeV creates $\sim$ 1500 electron-hole pairs in the conversion zone of the $GaAs$ Schottky AD; this signal is further amplified by a factor of 12–15 in the avalanche region). It is anticipated that the $GaAs$ AD will be replaced by a Si one which, together with less electron backscattering (due to its lower Z compared to $GaAs$) and therefore better amplitude resolution, can provide higher gain. It should be mentioned that Si ADs with a gain of 50–80 are common nowadays. The higher gain will allow one to use cheap, moderately fast (~ 300 MHz) voltage amplifiers which can provide multi-ph.e. amplitude resolution in the data acquisition system. Such voltage amplifiers can allow one to measure the Cherenkov light pulse shape by using a fast flash-ADC readout ($\geq$ 300 MHz) which can provide additional discrimination of different backgrounds. HPMTs of a small size, fitting into the packaging of a TO-8 metal-channel PMT and with a conventional S20 type photocathode have been produced by Hamamatsu recently (Suyama, Kawai, et al., 1996). The company is working now on implementation of the $GaAsP$ photocathodes.

The avalanche photodiodes Another candidate light sensor for Cherenkov telescopes is the avalanche photodiode (APD). This semiconductor detector has a very high QE, which is on the level of ~ 80 % in the whole spectral range of interest. The QE is less than 100 % due to the reflection at the APD surface (Si has a high refractive index) and some light losses in the passivation and protective layers. The APDs fit mostly to the needs for light sensors for Cherenkov telescopes, their disadvantage being the relatively large noise. It sounds reasonable to consider using APDs with 3–5 mm active ø in future telescopes, which can further be increased by using L.G.s. The measurements carried out for a 3 mm diameter S5344 from Hamamatsu showed ~ 20 ph.e. noise (the r.m.s. value) (Lorenz, Natkaniez, et al., 1994). The single $ph.e.$ response of APDs is anticipated with further increase of their internal gain to the level of a few thousands, which will be well above the amplifier noise (Mirzoyan, 1996b). Though it is expected that the APDs with single ph.e. response will have a relatively poor amplitude resolution (the expected F factor is ≥ 2), their availability in future may have the same consequences for the use of classical PMTs as it has happened with the electronic valves with the appearance of transistors. In Table 1 are shown the main characteristics of the above discussed light sensors. Below on Fig.3 are shown the measured QEs for a 19 mm ø EMI-9083A bialkali PMT, for an INTEVAC HPMT before and after coating with the WLS film and for an APD S5345; the latter measurement we took from (Pansart, 1997).

Table 1: Comparative characteristics of low light level detectors for Cherenkov telescopes

The main characteristics	Classical PMTs	GaAsP high QE HPMTs	APDs
Typical gain	10^6	2×10^4	50–100
Maximum QE, %	25–30	45	70–80
Response time, ns	1–5	0.2–2	1–10
F-factor	1.1–1.4	< 1.1	≥ 2
Single $ph.e.$ resolution	yes	yes	no
Noise	very small	very small	$\geq 20 ph.e.(r.m.s.)$
Afterpulsing	yes	small	no
Vacuum, Pa	10^{-5}	10^{-8}	no
Price	moderate	expensive	cheap

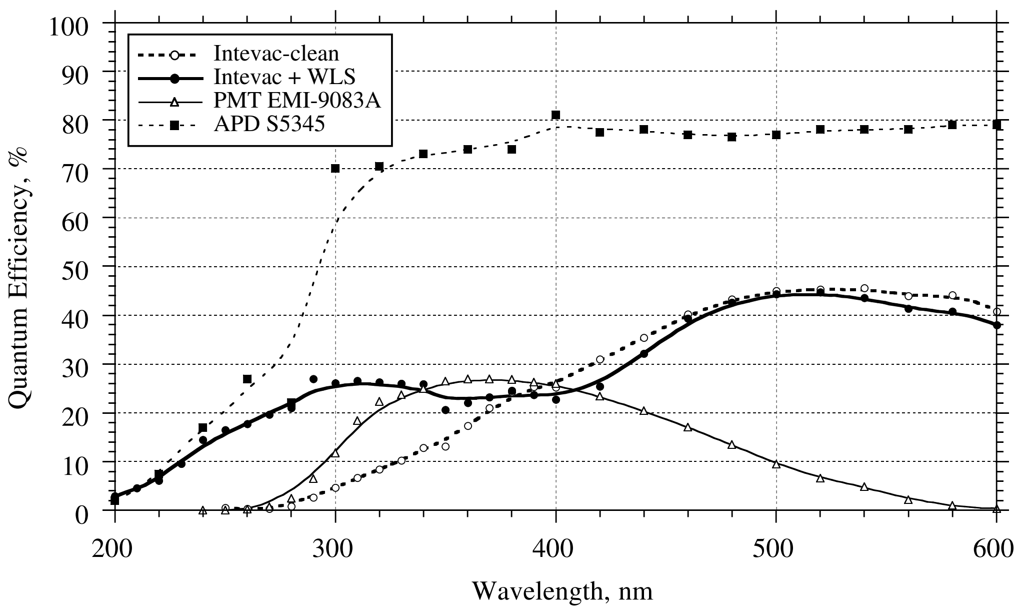

Fig. 3: The measured QE curves for a 19 mm EMI-9083A PMT, for an INTEVAC tube with and without WLS coating and for an APD S5345.

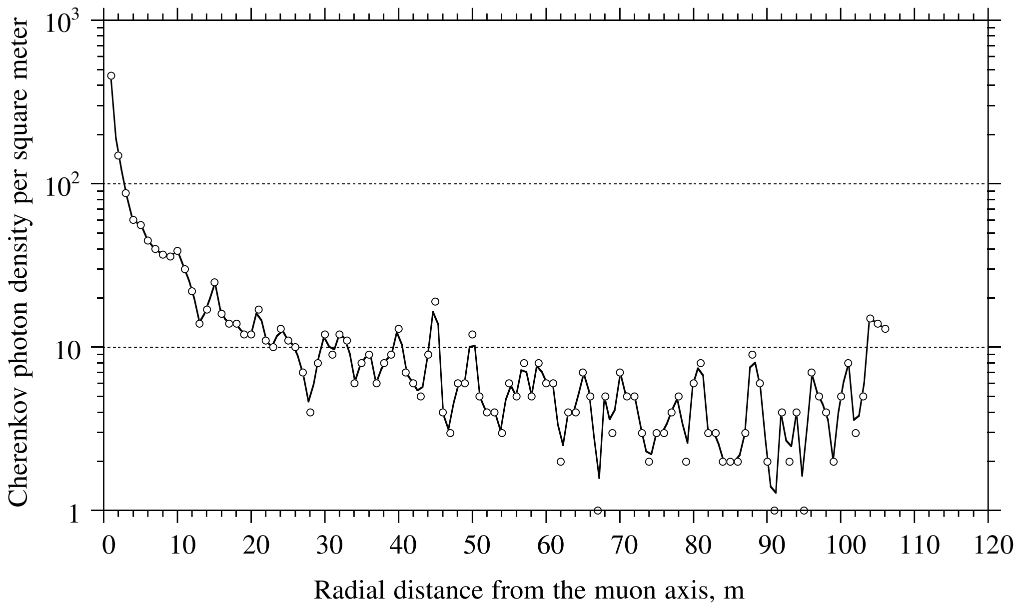

Fig. 4: The simulated lateral Cherenkov light distribution from a 20 GeV muon injected 15 km high in the "US standard" atmosphere.

4. The Triggers From Muon Arcs

The triggers from muon arcs is one of the most frequently discussed topics concerning the performance of VeLET telescopes. There is a vague believe in gamma community that VeLET telescopes will be subjected to a very intense trigger rate from the so-called muon arcs (Vacanty, Fleury, et al., 1994), and this will strongly deteriorate their sensitivity. One of the reasons for such a scepticism is the high flux of single muons in the atmosphere. In Fig.4 we show a simulated lateral distribution of Cherenkov photons for the observation level of 2200 m a.s.l. from a 20 GeV muon injected 15 km high in the (US-standard) atmosphere. For simplicity we did not take into account the atmospheric transmission and multiple scattering effects.

Unlike currently existing telescopes, which trigger on muons hitting the ground in the immediate vicinity within few meters (which means that one collects light from the last few hundred meters of their track), the large ø ones will trigger also on muons which are many kilometres high up in the atmosphere. A large telescope "sees" a track of a muon within ~ 2 radiation lengths.

One can see in Fig.4 that if a telescope has a photon sensitivity of less than 3 ph/m^2, it will trigger on 20 GeV muons till the impact parameter ~ 110 m. A muon produces images of arcs of different lengths depending on the impact parameter. The central hit produces the well-known full rings, while with increasing the impact parameter arcs are becoming shorter and shorter. Those hitting at more than 80 m produce just *"blobs" of very high charge concentration*, which can have a size less than two pixels of $0.1°$ each and only due to aberrations of the reflector they will appear somewhat smeared and larger.

One obtains a high trigger rate from muons when trying to simulate them as a separate component in cosmic rays. It seems that the reality looks somewhat different. First of all,

all muons measured by ground-based detectors are produced in hadron showers. They are produced by bunches, i.e. there can be multiple muons in one shower. Therefore the trigger rate of single muon events can not exceed the trigger rate of hadron showers. This means that if there are muons in a given shower, which are within the telescopes field of view, then they appear within the shower image. The latter is especially true for VeLET telescopes because of their very high photon sensitivity i.e. they almost always will measure part of the parent shower. Note, that this is not necessarily the case for higher energy threshold (less sensitive) telescopes, where often a single muon rings are measured in the apparent absence of the parent shower image.

It would seem that the proper simulation of hadron showers, providing the simulation code is correct, will automatically include also the triggers due to single charged relativistic particles. I mean the hadron showers should be simulated within much larger, than the trigger radius of the camera, solid angle. This is important because sometimes a muon can have a rather large deviation from the shower axis i.e. the shower can be outside of the field of view, while the muon itself can be within the latter and can initiate a trigger. Also, it is essential to simulate hadron events, in spite of their extremely low trigger efficiency, also for very low energies. We checked, for example, that a substantial part of simulated triggers from 60 GeV proton showers are due to arcs from charged particles for MAGIC.

5. The Influence of LONS

The intensity I of LONS has been measured in La Palma to be (Mirzoyan, Lorenz, 1994b) $I = (1.7 \pm 0.4) \cdot 10^{12}\, ph/m^2\, s\, sr$. Integrating this flux for the parameters of MAGIC one obtains $\sim 3 ph.e.s$ and $\sim 1 ph.e.$ per pixel and per gate time of 10 ns correspondingly for the enhanced QE HPMT and classical PMT camera versions.

6. The Stars In The Field Of View

It is known from star counts that in a 1° x 1° viewing angle in the sky, outside of the galactic plane, there are on average:

magnitude	stars
6^m	0.12
8^m	1
10^m	8

Therefore in the field of view of a 3° ø camera one should expect on average:

magnitude	stars
6^m	0.85
8^m	7
10^m	56

Light contribution of a 10^m star into a 0.10° pixel will make $\sim$ 40 % additional effect compared to LONS. The VeLET telescopes will operate probably cameras with more than 500 pixels. It means that about 10 % of all channels will have a star in their field of view which will increase the noise fluctuations. Therefore one should probably use extensively the software padding

(Cawley, 1993). Also, one should probably try to develop new methods against the excessive starlight in pixels.

7. The Performance

The classical PMT camera can provide a γ threshold of $\sim$ 30 GeV for MAGIC, while the application of the HPMT camera with enhanced QE can provide a threshold of $\sim$ 8-10 GeV (Gonzalez, Mirzoyan, et al., these proceedings).

We studied the angular resolution of MAGIC for a point source of gammas. It will provide a resolution of 0.2° (this is 1 σ of the two-dimensional gaussian fit) for an energy spectrum $\geq$ 10 GeV. It is already mentioned in the text that the precision of the measurement of angular parameters of shower images is deteriorating with lowering the energy (Gonzalez, Mirzoyan, et al., these proceedings). One can obtain better angular resolution for higher energies.

Due to increase of the fluctuations with lowering the energy also the energy resolution is degrading for a VeLET telescope. While it can provide a rather good resolution above a few hundred GeV due to less fluctuations and high ph.e. statistics in images, in the very low energy domain it can provide an average resolution of only $\sim$ 35 %.

The simulations show that above the threshold MAGIC can provide a Q factor of 7–8 in software analysis for both camera options. Together with high trigger efficiency in hardware for gammas and very low efficiency for protons, the above mentioned Q factor will provide a very high sensitivity for the telescope.

It seems that it is the electron background which will deteriorate to some extent the sensitivity of VeLET telescopes. Fortunately due to isotropic character of the electron flux one can perform a moderate rejection. The electron events which will remain after imaging analysis and On/Off subtraction in the gamma domain, can be considered as a pedestal, the level of which can be carefully studied and taken into account.

Estimates show that one can achieve a flux sensitivity of $5 \cdot 10^{-11} ph \cdot cm^{-2} \cdot s^{-1}$ in 100 hours of *'On'* measurements above 10 GeV threshold with the HPMT enhanced QE camera. For example, in order to measure a gamma signal of $\sim 5\sigma$ from Crab Nebula, the EGRET instrument on-board GRO have to observe for about one day, while the MAGIC type telescope can measure a similar signal in about 1 minute!

8. The Major Gamma Ray Detector. *A Vision*

It seems that there exist no principal obstacles for the construction and successful operation of VeLET telescopes. It is feasible to build large diameter telescopes which can allow one to measure gamma sources above a threshold of 10–30 GeV. The proper design of the data acquisition system of these telescopes can allow one to extend the dynamic range of measurements till 50–100 TeV.

By applying the $size$ cut ($size$ is the sum of the measured charge from an image and is a measure of the primary energy) in software analysis one can study the source spectra above any given energy within the dynamic range. Note, that for higher energies a VeLET telescope will measure from several hundred to tens of thousand $ph.e.$s per image, which can allow one to reveal fine structures in images and improve the signal as well as the energy and angular resolutions.

Our studies showed that with increasing the threshold energy in analysis MAGIC provides much higher gamma/hadron separation (will be published elsewhere).

I believe that the construction of VeLET telescopes is rather a financial than a technical problem. Taking into account the modest costs for the construction of such telescopes (the estimated cost for a single telescope is $\sim$ 3 Mln USD) and the big scientific expectations, one may conclude that they are inexpensive. A system of $\geq$ 3 VeLET telescopes, situated on some optimised distance from each other, can be a very powerful instrument for source measurements and can cover the whole energy range from 10 GeV till 50–100 TeV. Such systems meet the requirements for a Major Atmospheric Gamma Imaging Cherenkov detector and will probably found the future gamma ray observatories. Once the telescopes with reliable mounts are built, they will be used for tens of years in future. The progress in the field of light sensors will always push one to use better detectors in the focal plane, one can see it on the example of optical telescopes. 3 telescopes can be arranged, for example, as a triangle with a side length of $\sim$ 130–180 m (of course, it is necessary to perform Monte Carlo studies for optimisation of the distance).

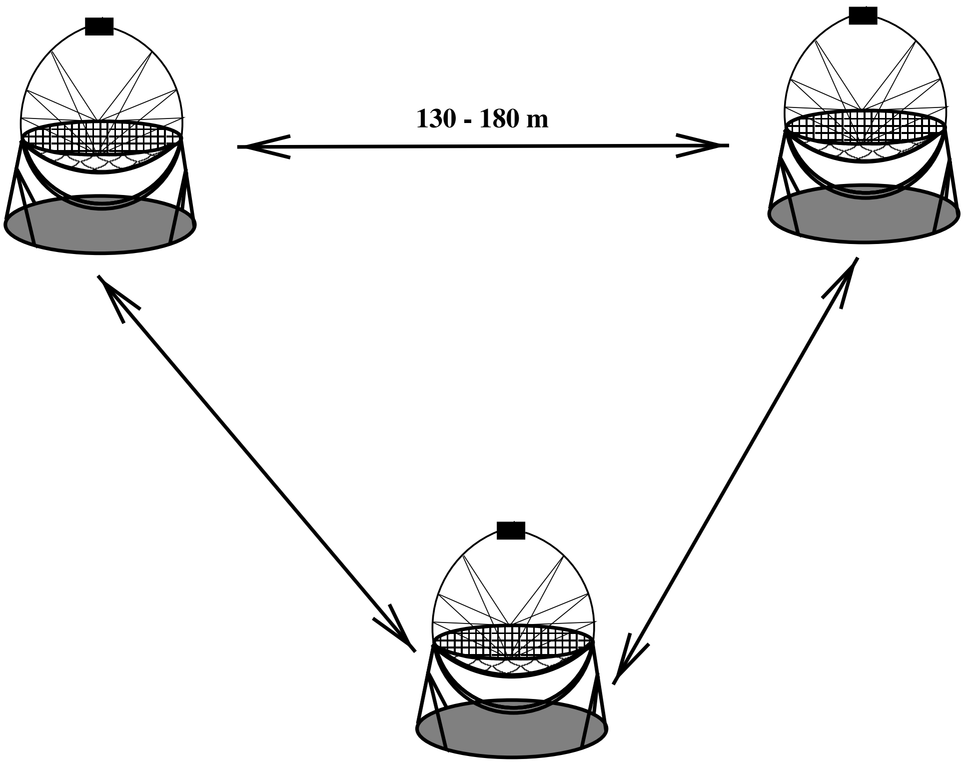

Fig. 5: A minimal configuration with 3 VeLET telescopes of 15-20 m ø class as a future gamma ray observatory.

Such a configuration can provide the necessary flexibility for the system. Due to the relatively large distance between the telescopes they are quasi-independent on one hand (one can observe different sources) and still one can use them in coincidence mode for observation of a single source with higher precision. In the latter case the effective collection area will be limited to the central region inside the triangle. On the one hand the closer are the telescopes to each other, the lower is the trigger threshold of the system. On the other hand already a single VeLET telescope can provide a very low energy threshold and a high trigger efficiency within the Cherenkov pool diameter of 250 m. Therefore the low threshold of the system seem not necessarily have the first priority in optimising the distance between the telescopes. The relatively large distance between the telescopes will also allow one to perform stereo observations of sources at large zenith angles providing still relatively large collection area.

Note, that once the APDs with single $ph.e.$ resolution will be available, they can be used for the construction of a camera for *an imaginary imaging telescope with a reflector ø of* $\sim$ 30 m, which should allow one to measure γ sources down to ~ 1 GeV. Below energies of a few tens of GeVs the hadrons are not producing Cherenkov light anymore. The main background will be due to electron showers. Fortunately the electron spectrum tails off below ~ 10 GeV.

Perhaps somewhere, somebody will come along with a project for a 30 m ø imaging telescope within the next 20 years.

9. Conclusions

The field of ground based γ ray astronomy is developing very fast. Here I have tried to show that the 15–20 m ø class imaging Cherenkov telescopes can successfully measure above an ultimate threshold of $\sim$ 10–30 GeV. The proper design of the imaging camera and of the data processing and acquisition systems can allow one to extend the dynamic range of measurements up to $\sim$ 50–100 TeV. Systems of ≥ 3 Cherenkov telescopes of 15-20 m ø class can be very powerful instruments and will probably found the future gamma ray observatories.

10. Acknowledgements

I wish to thank C. Raubenheimer, O.C. De Yager and the other members of organising committee for their kind invitation to present this talk and for this very fruitful workshop.

Also, I am indebted to many of my colleagues from the MAGIC design group, especially to Dr. E. Lorenz, J.C. Gonzalez, Dr. J.A. Barrio and D. Petry for numerous useful discussions.

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