# The MAGIC Telescope Project

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**Abstract**

Up to now the 20–300 GeV energy range has been inaccessible to gamma-ray astronomy. Here we report on a design for a 17-m ⊘ air Cerenkov telescope, dubbed MAGIC telescope, which will have a threshold of 20 GeV, a large collection area of $> 10^5$ m$^2$ and a high gamma/hadron separation power. It is estimated that the hardware investments would be about 3.5 M$ and 2.5–3.5 years would be needed for the construction.

## 1. Introduction

Gamma ray (in short, $\gamma$) astronomy is at present the only well established method to explore the relativistic universe. Up to now, technical limitations have made the energy range between 20 GeV, the upper limit of contemporary $\gamma$ satellites, and 300 GeV, the lower limit of large air Cerenkov telescopes (ACT), inaccessible to research. Satellites are flux-limited because of their small collection area of typically only 0.1 m$^2$. Costs become prohibitively high for detection areas above a few m$^2$. On the other hand 20 GeV electromagnetic air showers still contain enough high momentum electrons above the Cerenkov threshold for ACTs to be able to detect them, provided the signal is large enough and can be distinguished from the background light of the night sky (NSB). In this paper, we wish to report on a novel design for an ACT which will possess a higher level of sensitivity.

## 2. The Physics Goals

The main research targets will be:

a) The study of active galactic nuclei (AGN) up to $z \approx 2.8$. Measurements of the energy flux between 20 GeV and 1 TeV will allow one to set stringent limits on the existence and size of the (hitherto unquantified) infrared (IR) background.

b) The systematic study of possible galactic $\gamma$ emitters such as supernova remnants (SNR), plerions, X-ray binaries, unidentified EGRET sources, etc., which will hopefully lead to the identification of the main sources of the galactic cosmic radiation up to about $10^{15}$ eV.

c) Testing of gamma ray bursts (GRB) in the new energy window. EGRET recently reported a GRB associated with $\gamma$s up to $\approx 20$ GeV (K. Hurley et al.). A telescope like MAGIC, whose collection area is between $10^5$ and $10^6$ times larger than satellite borne $\gamma$-detectors, should be able to provide an answer to the “galactic halo” vs. cosmological distance scenario by measuring the $\gamma$ energy spectrum in the range where it could be affected by IR and 2.7° K absorption.

d) The search for exotics such as for the lightest supersymmetric particle (SUSY), etc.

Finally it should be mentioned that it is of the utmost importance to overlap satellite and ground-based observations for making cross calibrations (for example for multiwavelength observations).

## 3. Steps to Lower the Threshold

Using the best telescope presently available, the Whipple installation, as a yardstick the following changes are being considered:

a) To increase the mirror area from 74 to 234 $m^2$, i.e. a collector of $\approx$ 17 m diameter.

b) To use photosensors with a GaAsP photocathode with about 45% quantum efficiency (QE), extended to 650 nm (S. Bradbury et al.). Low energy showers or showers at large zenith angles are stopped high up in the atmosphere and a sizeable fraction of the UV- and blue Cerenkov light is lost due to Rayleigh scattering. MC calculations show that a typical gain of 3 should be possible over conventional bialkali photocathodes. At large zenith angles the gain can increase to a factor of 8–10.

c) To use photosensors with basically 100% photoelectron collection and an excess noise factor close to 1; conditions which can be fulfilled by hybrid photomultipliers.

d) To use optimized light catchers, Winston cones, in front of the PM camera for $\approx$ 100% light collection and shielding against large angle background light.

e) We intend to lower the minimal number of photoelectrons/image to about 80. Limitations are given by the night sky background light (NSB), by the requirements of good $\gamma$/hadron ($\gamma$/h) separation and good angular resolution. The impact of the NSB can only be reduced by narrowing the aperture time for the pulse height recording system. One necessary condition is that the timespread in the optical system needs to be minimized. We intend to use an isochronous mirror profile and an 8-bit F-ADC system of $\geq$ 300 MHz. Another aim will be to work with a very fine pixel size of 0.1°. In essence, the chosen telescope parameters should result in only 1.5–3 NSB photoelectrons per pixel and aperture time of 6.6 ns.

f) Two additional goals will be to operate the telescope in the presence of moonlight with only a modest degradation and in general to achieve a full-sky coverage while maintaining a low threshold. In both cases a red-extended sensor is important for maintaining a low threshold.

## 4. The Telescope

The telescope is modelled after a 17-m solar collector (Schlaich, Bergemann und Partner). The main mirror support dish consists of a three layer space frame made from carbon fiber-epoxy tubes, which are both lightweight and rigid. One essential requirement is that the inertia of the telescope must be low so that it can be repositioned for GRB searches within 30–60 s at any position in the sky. A finite element analysis of the frame has shown that deformations can

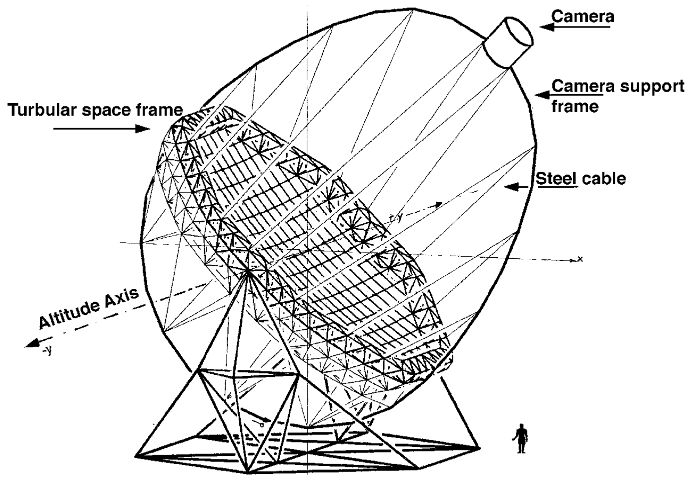


*Fig. 1: A model of the 17 m ⊘ MAGIC telescope.*

be held below 3.5 mm with respect to the nominal curvature at any position for a combined frame- and mirror weight of less than 9 tons. Figure 1 shows a computer generated image of the telescope. The telescope has a tessellated mirror with a basic element size of 50 $\times$ 50 cm. The elements are lightweight sandwich aluminium panels, equipped with internal heating to prevent dew and ice deposits. A high quality reflecting surface, with a surface roughness of $<$ 10 nm, is achieved by diamond turning. A preproduction series showed high optical quality with a typical focal spot diameter of 6 mm. We plan to use a novel technique for making mirror adjustments and small corrections during telescope turning in order to counteract small residual deformations of the 17 m frame. Four mirror elements at a time will be preadjusted on a lightweight panel together with a switchable laser pointer. The panel can be tilted by two stepping motors while being monitored by a videocamera that compares on demand the actual laser spot position on the casing of the camera with the nominal one. A prototype has been shown to work successfully. The telescope will have a 3.6° ⊘ camera with a pixel size of 0.1° in the central region of 2.4° ⊘ and a coarser one of 0.2° in the outer part. As photon detector we intend to use a novel hybrid PM from INTEVAC with a high QE (45%) red extended GaAsP photocathode combined with an avalanche diode as secondary amplification element. At present the photosensor is considered as the most critical component and it might be necessary to use a conventional PM camera from one of the HEGRA telescopes as a substitute in the beginning. We may decide to use silicon avalanche photodiodes (APD) with about 80% QE but major developments are needed in order to reduce the current noise from $\approx$ 20 photoelectrons to below 2 and to concentrate the light onto small diameter APDs by socalled light traps (Chiemtec patent). The camera will be connected to the electronics ground station by 100 m optical fibers working in the analog mode for the transfer of the fast PM signals. Signals will be digitized by 8-bit F-ADCs of $\geq$ 300 MHz. This allows for noise minimization, good timing measurements, buffering for the multilevel trigger system and possible the opportunity of attaching more telescopes for quasi-stereo observations. It should be mentioned that all the novel components have either already been tested or are in use in other research fields.

We estimate a hardware-price of about 3.5 M$ and a construction time of 2.5–3.5 years.

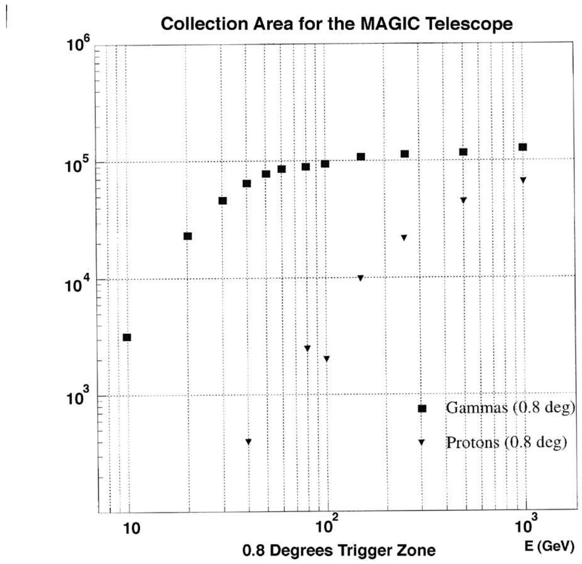


*Fig. 2: Collection area as function of $E$. In brackets: radius of trigger area.*

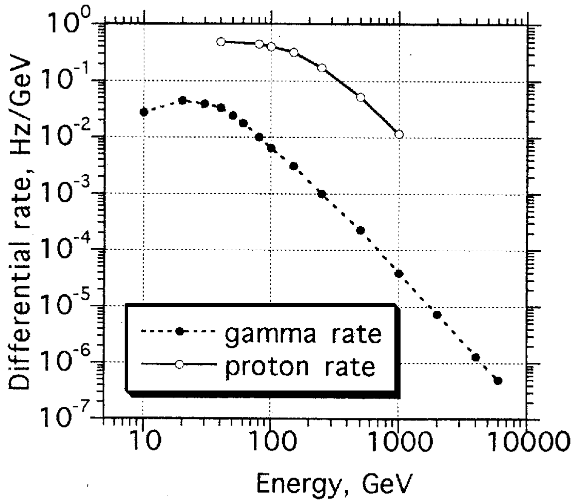


*Fig. 3: Differential counting rates as function of $E$*

## 5. Some Performance Data

MC simulations show that the telescope has a trigger threshold (= maximum differential counting rate) of slightly below 10 GeV, i.e. a threshold for high quality data around 20 GeV and a rather large collection area in the zenith position plateauing to $\approx 10^5$ m$^2$ (at ca. 100 GeV) when using a trigger area of 1.6° $\oslash$ in the camera. Opening the trigger area to the full camera diameter increases the collection area to $> 3 \times 10^5$ m$^2$ for TeV signals. Figure 2 shows the collection area as a function of energy $E$ while Figure 3 shows the differential rate (after image quality cuts) for a hypothetical gamma source with an integral flux of $10^{-11}$ cm$^{-2}$ s at 1 TeV and a slope of $-1.7$, together with the charged cosmic background. For large zenith angle observations the collection area will increase considerably but at the expense of a higher threshold. The quality factor obtained by using only image-shape parameters rises from about 3 in the sub-100 GeV region to at least 8 above 1 TeV. Simulations using new $\gamma$/h separation algorithms are ongoing. Details of the simulations are given in another contributed paper (J. C. Gonzales et al.)

## 6. Comparison with Other Projects

Currently, quite a few new projects are pursued (see contributions to this conference). Table 1 shows a comparison in minimal light flux needed for the detection of $\gamma$ showers for some contemporary telescopes, some new projects and MAGIC. One class of new projects concentrates on the use of existing solar arrays that can be converted from daily power generation into Cerenkov telescopes during night time. Due to the large mirror area the threshold should be similar to that of MAGIC while the $\gamma$-collection area will be lower compared to MAGIC. Also solar arrays have poorer “imaging” quality and lower energy resolution.

A quite different approach is followed by some other group. Based on the well proven 10 m class telescopes, a few of them are combined in the so-called stereo mode viewing showers under different angles. The stereo arrangement allows for an excellent hadron suppression but at the

*Table 1: Light flux sensitivity, thresholds and collection area of MAGIC and some contemporary telescopes*

| Telescope | Minimal photon flux (photons $m^{-2}$) | Threshold | Collector ($m^2$) | Comments |
|---|---|---|---|---|
| AIROBICC | 4000 | 12 TeV | $50 \times 0.125$ | Wide-angle detector |
| HEGRA CT1 | 220 | 1.5 TeV | 5 | $\geq$ 100 photoelectrons/image |
| HEGRA CT3-6 | 150 | 700 GeV | 8.4 | $\geq$ 100 " |
| " | 100 | $\approx$ 450 GeV | " | stereomode |
| CAT | 35 (?) | 300 GeV (?) | 18 | $\geq$ 30 photoelectrons/image |
| WHIPPLE | 35 | 300 GeV | 74 | $\geq$ 300 " |
| WHIPPLE 98 | 16 | 100 GeV | 74 | $\geq$ 100 " |
| VERITAS | 10/tel.? (coinc. mode) | 60 GeV (?) | $9 \times 74$ | |
| MAGIC | 1.1 | 20 GeV | 234 | $\geq$ 80 " |
| STACEE | 2-5 | 30-80 GeV (?) | | modest image |
| CELESTE | " | " | | " |
| GRAAL | " | " | | " |

expense of a lower collection area. Figure 4 shows the differential light flux $\varphi$ (photons/$m^2$) for 100 GeV $\gamma$s and 400 GeV protons as a function of the impact parameter $r$ and a detector height of 2200 m. Up to $r$ of about 120 - 130 m the light is generated by on-axis core particles and core subshowers, respectively. For $r > 150$ m the light originates only from halo particles. The Č-light from low energy (10 to few 100 GeV) proton showers has a much lower flux $\varphi$ but is distributed over a larger area compared to that from $\gamma$ intitiated showers. This is the consequence of the transverse momentum spread in hadronic interactions and because only a small fraction (typically 30-40%) of the total energy is converted into $\pi^0$s. Therefore, protons of large impact parameter and a few degree off-axis can generate subshowers that fall into the trigger acceptance of the telescope. For a qualitative comparsion of the stereo approach and MAGIC we assume that for the cost of MAGIC one can construct 3 (4) classical 10 m class telescopes with about twice larger pixels (henceforward called Mini-Classical MAGIC $\equiv$ MCM). In figure 4 the threshold flux of both MAGIC and an MCM telescope is indicated. At around 100 GeV an MCM telescope can "see" up to $\sim$ 120 - 130 m while MAGIC with its 10-15 times higher flux sensitivity detects light up to impact parameters of about 180 m. From this simple model it follows that in the coincidence mode the collection area of an MCM configuration is just the overlap of disks with 130 m radius. Assuming a 4-fold coincidence of 4 MCM telescopes placed at the corners of a, say, 95 m square, gives a collection area of only $\sim 10\,000$ $m^2$ compared to $\sim 100\,000$ $m^2$ of MAGIC. Therefore MAGIC is also competitive to stereo arrangements in the 100 GeV domain as long as its $\gamma$/h separation power is not worse than the ratio of the collection areas. Due to the fine pixel size and multiple time structure information in individual images the $\gamma$/h separation of MAGIC will be significantly better than that of contemporary telescopes. In addition, two background effects make a MAGIC type telescope quite competitive.

Detailed calculations show that at 100 GeV $\gamma$ energy the equivalent mean light flux is generated by protons of $\sim$ 300 - 500 GeV, i.e. due to the steep cosmic ray flux a natural suppression in the order of 15 occurs. On the other hand the background of cosmic electrons is

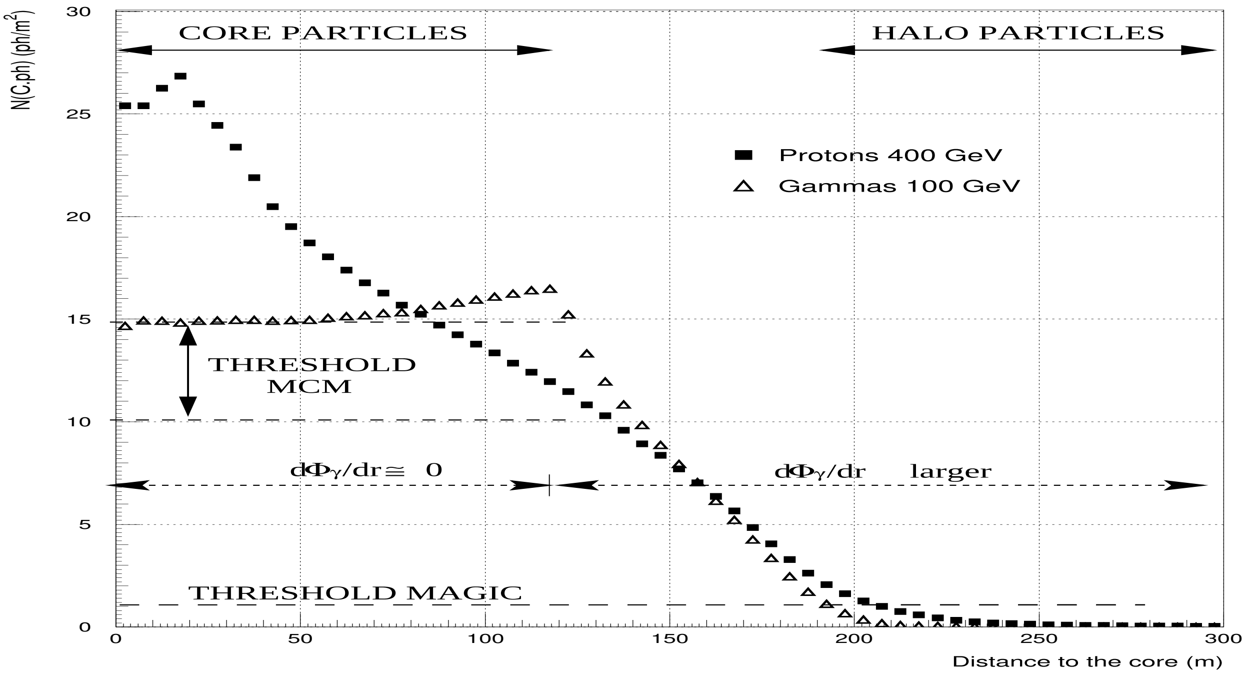


*Fig. 4: Light flux $\varphi$ (photons/m$^2$) as a function of the impact parameter $r$. Proton background generated parallel to the $\gamma$s.*

non-negligible and cannot be suppressed in any present telescope. Even with 100% hadron suppression, one has to cope with the irreducable electron background and only a larger collection area will increase the sensitivity.

It is advocated that the stereo configuration allows for a better energy determination compared to a stand-alone telescope because one can correct for the impact parameter dependence. From Figure 4 follows that in the 100 GeV domain and the important impact parameter range up to 130 m the gradient $d\varphi/dr$ is small, respectively zero. As $\varphi$ is a good measure of the energy one sees immediately that a correction due to a precise knowledge of $r$ will hardly improve the energy resolution (at much higher energies $d\varphi/dr$ is large even below 120 m and stereo measurements are important). Conversely, a MAGIC type telescope with $\sim$ 15 times more photoelectrons/shower will integrate light over longer track length, respectively more subshowers and fluctuations should be lower. Showers with an impact parameter $> 130$ m will have less light and a large $d\varphi/dr$. Due to the typical steep spectra, as expected for all sources, one will have only a small admixture of background in the sample of up to 120 m. MC simulations predict for MAGIC an energy resolution of $\sim$ 10% at 200 GeV. Ultimately the energy resolution is limted by a) shower depth fluctuations and b) by energy partition between the $e^+e^-$ in $\gamma$ conversion at energies close to the Cerenkov threshold. Stereo observations can improve the energy resolution provided the error in $x_{\max}$ determination is smaller than the natural $x_{\max}$ fluctuations.

In summary, MAGIC has the advantage of a lower threshold, ability to measure in the presence of moonlight with a threshold below that of the 10 m class classical telescopes at dark night and the superior observation quality for large zenith angle observations. In the energy range around 100 GeV MAGIC's much larger collection area compensates for poorer $\gamma$/h selectivity when compared to equal cost 3 (4) 10 m class telescopes in stereo configuration. In the domain where the electron background dominates the hadronic one after $\gamma$/h selection procedures, MAGIC will have a higher sensitivity compared to a 4-fold coincidence configuration of 4 MCMs.

## 7. Status

For four of the six novel detector elements, namely the carbon fiber space frame, the diamond turned light-weight all-aluminium mirrors, the active mirror control and the fast analog signal transmission by optical fibers, the first phase of R & D has been completed. We are now trying to convert prototypes into industrial production. The development of a 300 MHz FADC system has been initiated in industry and prototypes should be available around the end of 1997. The main bottleneck is the industrialisation of the GaAsP hybrid photomultipliers. Recently we have established contacts to two other manufacturers in order to accelerate the development of this photon detector which should have also a large potential outside $\gamma$-astronomy. In view of the slow progress of the GaAsP sensor it has recently been decided not to slow down the construction of the telescope but to equip it at first with a classical photomultiplier camera. This raises the threshold from $\approx$ 20 GeV to about 45 GeV (trigger threshold from 10 GeV to 30 GeV).

A design report including reports on developments and prototype test results will be available soon.

At least eigth institutions have declared their interest to form a collaboration to build and operate the telescope.

## 8. Conclusions

In summary it seems possible to construct a telescope with a low threshold of 20 GeV, high $\gamma$/h separation power, a large collection area, nearly full-sky coverage and the ability to measure in the presence of moonlight. The telescope has the potential to discover and study several hundred new $\gamma$ sources. Compared to satellite borne $\gamma$ detectors the collection area is larger by a factor of at least $10^5$ whereas the investment would be in the range of only 1–5%. The telescope could also be built in a much shorter time.

## 9. Acknowledgements

Herewith I would like to thank my colleagues from the MAGIC design group for providing information and for many fruitful discussions. Part of the development work for component studies has been supported by the German BMBF and the Spanish CICYT.

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