THE MAGIC TELESCOPE PROJECT*

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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 Čerenkov 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.

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1. Introduction

Astronomical exploration is driven by curiosity and proceeds in two directions. Firstly, towards the most distant and weakest sources which require an ever-increasing sensitivity. Secondly, towards sources of electromagnetic radiation at all frequencies. Technical developments have so far allowed to observe the Universe from radio waves to γ-rays up to about 10 GeV and from about 300 GeV up to 100 TeV. A gap has remained unexplored between 10 GeV and 300 GeV which the MAGIC collaboration intends to investigate for the first time with the construction of a 17 m diameter telescope dubbed MAGIC (Major Atmospheric Gamma Imaging Čerenkov Telescope). Details of its design and technology, the scientific motivation for it, the feasibility of the project, and other issues have been discussed in detail in the MAGIC

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Telescope Design Study [1]. In this paper the major physics goals, the innovative technological developments allowing the MAGIC Telescope to reach such a low energy threshold and high sensitivity are addressed.

2. General overview

With the all-sky survey of the Compton Gamma Ray Observatory satellite (CGRO) a large number of gamma extragalactic sources (*e.g.* Active Galactic Nuclei (AGN), Gamma Ray Bursts) has been discovered at high galactic latitudes, with photon energies up to 10 GeV. The ground-based imaging air Čerenkov technique (IACT) with an effective photon collection area of typically 30,000 m^2 has only very recently achieved maturity after many years of pioneering studies led mainly by the Whipple collaboration. In spite of an energy-flux sensitivity superior to CGRO (for energy spectra extrapolated to higher energies), a much smaller number of sources has been discovered with the IACT technique above 300 GeV implying that most of the CGRO sources have spectra turning over between 10 GeV and 300 GeV. Very likely, pair-producing interactions of the gamma rays with low energy photons from the diffuse isotropic background radiation (far-infrared to ultra-violet) are responsible for this attenuation [2]. This flux of isotropic background is poorly known from direct measurements. By measuring the turn-over energies in the spectra of sources with the MAGIC Telescope we will be able to infer the low-energy background flux in a manner completely independent of conventional methods.

The MAGIC Telescope introduces major innovations compared to current technology IACTs: *(i)* a rigid light-weight carbon-fibre space frame mount yielding a very large light collection area and low inertia, *(ii)* light-weight, heated diamond-turned all-aluminium mirror elements, *(iii)* an active mirror control to counteract residual frame sagging, *(iv)* high quantum efficiency hybrid photomultipliers (HPD) for the second phase of the experiment, *(v)* analog signal transmission from the camera to the ground station for low inertia, low dispersion, and noise immunity, and *(vi)* ultra-fast FADC readout of the camera. These will dramatically increase the potential of γ-astronomy by providing a low energy threshold. A threshold of 25–30 GeV can be reached in the first phase by using a camera based on photomultipliers with conventional bialkali photocathodes.

The very high light collection power of the MAGIC Telescope will significantly improve the sensitivity in the energy domain of current and planned IACTs (*i.e.* 100 GeV to about 50 TeV). The new technology employed in the MAGIC Telescope project complies with quality standards common in accelerator physics and most of which have been tested in preproduction or prototype versions since 1995.

An effort complementary to the MAGIC Telescope project is the Gamma-Ray Large Area Space Telescope (GLAST). In the energy region of 10 GeV to 300 GeV GLAST will perform an all-sky survey and measure the diffuse γ-ray flux, whereas MAGIC with its much larger collection area will focus on high-sensitivity observations of individual sources. This is important, since most of the sources are strongly variable and require short integration times to measure their light curves. Targeting the MAGIC Telescope and GLAST on the same sources will for the first time provide the possibility of an absolute cross calibration of both techniques. In addition the identification of the physical mechanisms responsible for the production of the non-thermal radiation of the AGNs requires extensive multi-wavelength observation campaigns in particular with X-ray satellites, *e.g.* AXAF, ROSAT, RXTE, and XMM.

3. Key scientific problems

Opening a broad, unexplored band in the electromagnetic spectrum with the high-sensitivity MAGIC Telescope promises to turn into a fascinating and rich era of discovery touching fundamental problems in astrophysics, cosmology, and particle physics. A number of key problems where we consider the low γ-ray energy threshold of the MAGIC Telescope to be crucial are briefly discussed below.

3.1. Active Galactic Nuclei

Most of the AGNs of the so-called blazar type which have been detected by CGRO below 10 GeV must exhibit cutoff features below 300 GeV. This is illustrated by the fact that of the more than 60 blazars observed by EGRET below 10 GeV only 3 have been detected by the ground-based detectors, although their extrapolated power law spectra typically would have been well within the sensitivity range of the IACTs. Both coverage of the observational gap and the improvement of the sensitivity at current energies is therefore needed for the investigation of blazar-type AGNs.

3.2. Pulsed γ-ray emission from pulsars

Of the more than 800 known radio pulsars EGRET has revealed 7 to emit pulsed γ-rays up to ≈ 10 GeV. No steady pulsed emission from pulsars has yet been detected by ground-based IACTs above 300 GeV. To clarify the production mechanism, measurements in the 10 GeV to 100 GeV energy domain are crucial. In some models no pulsed emission is expected beyond some tens of GeV. The polar cap model for pulsed emission [3] explains this fact by the predicted sharp cutoff in the γ-ray spectra above a few GeV due to absorption in the strong magnetic field. Later detailed phase resolved modelling, however, showed that we expect the bridging emission between the two pulses to have harder spectra [4]. This prediction was recently confirmed by phase resolved spectroscopy of the Crab, Vela and Geminga pulsars [5]. For the harder bridging emission in the polar cap model the superior MAGIC Telescope sensitivity in case of the EGRET pulsars will lead to phase resolved rates above 10 GeV of up to more than 100σ per hour per 0.1 phase interval (after image analysis), or more than $\sim 10\sigma$ if no background cuts are made.

3.3. Gamma-ray Supernova Remnants

Supernova remnants (SNRs), possible sites of cosmic ray acceleration favoured in most models of the cosmic ray origin, seem to be more complex than previously believed [6]. Although four SNRs have been observed above 300 GeV (Crab nebula, Vela, PSR1706-44, and SN1006), the question of the origin of cosmic rays is far from answered. More sensitive measurements at lower energies will be of great importance in identifying the spectral component measured above 300 GeV in the four sources already discovered. With the low energy threshold of the MAGIC Telescope it may be possible to observe a two component γ-ray spectrum, which should then allow us to decouple the predicted leptonic and hadronic components in SNR shells.

3.4. Cosmological structure formation and diffuse background radiation

Recent data from the Hubble Space Telescope (HST) and the W.M. Keck telescope have shown star forming galaxies to be present at large redshift ($z > 3$), corresponding to a very early epoch of structure formation in the Universe. These data are corroborated by the density of absorption lines (Lyman-alpha forest) in distant quasars which require the Universe to be highly ionized due to a high density of star light already at $z \approx 5$. In redshift distributions extracted by photometric methods from the Hubble Deep Field (HDF) exposure, even large-scale structures like superclusters of galaxies seem to be present already at $z \approx 3$ [7] requiring both early and rapid structure formation. These data are in accord with cosmological models dominated by Cold Dark Matter (CDM) or models characterized by a non-zero cosmological constant Λ plus CDM (ΛCDM). However, it is important to find evidence for the bulk of galaxy-scale structure formation to have occurred at high redshifts to support the scenario. The Hubble Deep Field analysis has shown that galaxies visible at optical wavelengths have their maximum star formation rate at a redshift of 1.5, but most galaxies could hide their star forming regions behind large dust clouds re-radiating the stellar light in the infrared band. The total flux of infrared-to-ultraviolet radiation produced by early galaxies during their formation emerges as a diffuse isotropic radiation background. Knowledge of this background flux allows to infer the redshift of the bulk of galaxy formation. Number counts in the near-infrared and optical wavelength ranges, as well as a direct COBE measurement of the far-infrared background from the residual flux after model-dependent foreground subtraction have been achieved [8], but over many passbands the flux of the diffuse background due to galaxy formation is virtually unknown.

Ground-based γ-ray astronomy can contribute to this area of cosmology through an indirect measurement of the infrared-to-ultraviolet background density by measuring absorption effects on high energy γ-rays. In this case the infrared-to-ultraviolet background photons act as a scattering target. An instrument with a low γ-ray energy threshold like the MAGIC Telescope may also aim at determining its evolution with redshift which is closely related to the question of galaxy evolution. The measurement relies on the observation of a cut-off in the γ-ray spectra of extragalactic sources due to the process $\gamma\gamma \rightarrow e^+e^-$. To determine precisely the cut-off energy it is necessary to measure the γ-ray spectra extending over about an order of magnitude around the cut-off energy. With expected cut-off energies for the bulk of the extragalactic sources at $z \sim 2$ around 50 GeV [9], it is therefore necessary to also perform high-sensitivity measurements in the energy regime well below 100 GeV. As an illustration, figure 1 shows the effect of intergalactic absorption on high-energy γ-ray spectra for a few blazars located at various cosmological distances. The density of the infrared background assumed in this calculation is determined by Salamon & Stecker [10] based on an estimate of stellar emissivity as a function of redshift.

The low γ-ray energy threshold requirement is imposed by the energy dependence of the γ-ray horizon, which is defined as the distance corresponding to an optical depth $\tau = 1$ due to γ absorption on the diffuse background field (equating the mean free path to the cosmological distance of the source). The γ-ray horizon is shown in figure 2 for a model distribution of the diffuse isotropic background density in the photon energy range from 3×10^{-3} eV to 1 eV, based on a model of structure formation and evolution in the Universe [11].

Although current measurements are limited to energies in the few hundred GeV to TeV energy range, they have already contributed significantly to limiting the infrared photon density. Figure 3 shows the result of an analysis based on the observation of an unabsorbed energy spectrum extending to at least 10 TeV for the blazar-type AGN Mkn 501 at a distance of $z = 0.034$. The non-observation of a quasi-exponential cutoff feature was transformed into a stringent upper limit on the diffuse infrared photon density around 3×10^{-2} eV [13]. As also shown in figure 3, the existing direct upper

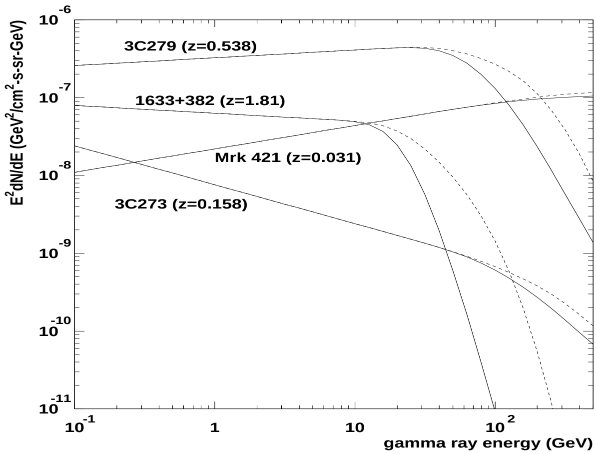

Fig. 1. Power-law spectra of selected blazars attenuated by absorption in the extragalactic diffuse infrared background field as calculated from stellar emissivity as a function of redshift [10].

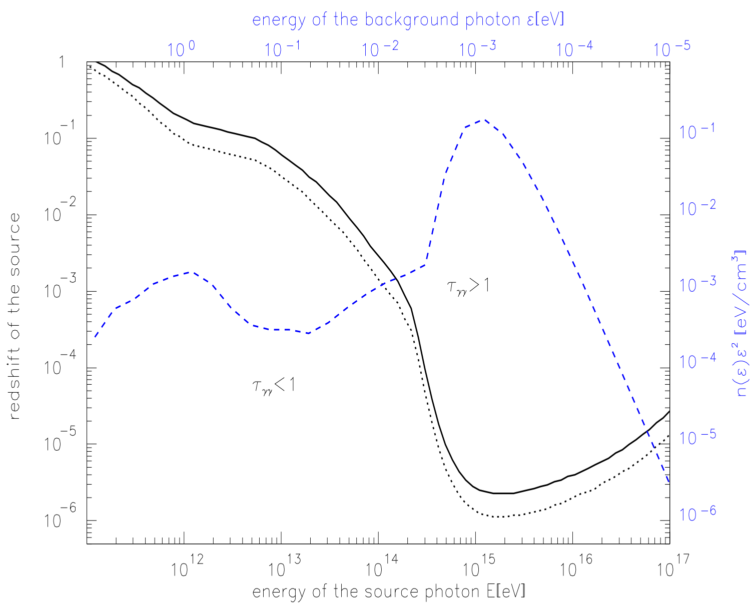

Fig. 2. The γ-ray horizon for the averaged diffuse background radiation model from MacMinn and Primack [11]. Solid line: Hubble expansion parameter $H_0 = 100$ km s^{-1} Mpc^{-1}; dotted line: $H_0 = 50$ km s^{-1} Mpc^{-1}. The diffuse photon background density (dashed line), has been added to the figure with an inverse energy scale.

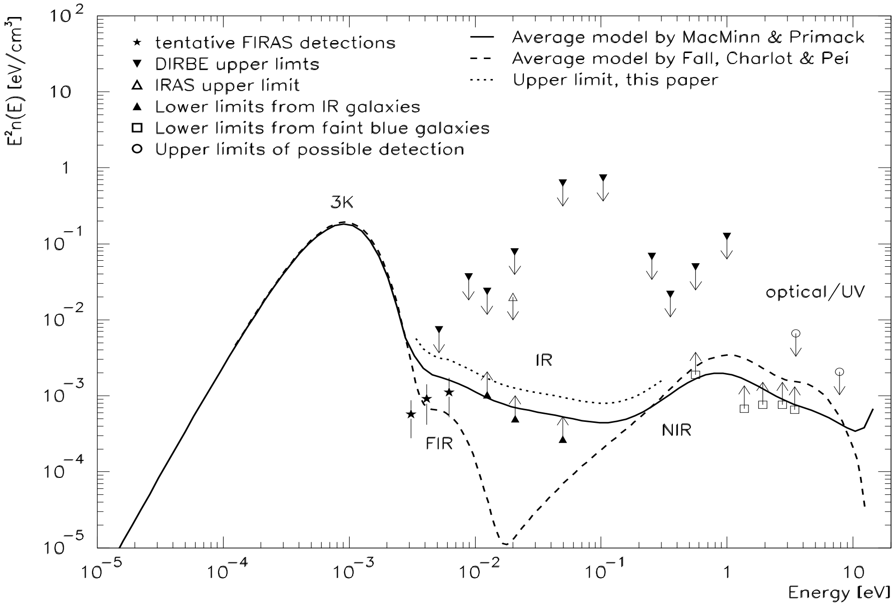

Fig. 3. Energy density of the extragalactic diffuse background radiation. Solid line: average model from MacMinn & Primack including the CMBR [11], dashed line: average model from Fall, Charlot & Pei added to the CMBR [12], dotted line: upper limit derived in [13].

limits were improved by more than an order of magnitude. Provided a large number of extragalactic sources can be observed and that the energy spectra will be understood (*e.g.* by correlating measurement at lower energies with the γ-ray data), actual measurements of the infrared photon density and possibly of its evolution with redshift can be envisaged.

The additional high sensitivity requirement for a detector is imposed by the rapid time variations observed in the γ-ray fluxes emitted by the known blazars. As an example figure 4 shows the light curve of Mkn 501 as observed in 1997 with the HEGRA telescopes and as observed in the X-ray, the optical and the radio energy bands. In spite of the fact that most of the energy flux resides in γ-rays, the number of high-energy photons is still rather low when compared to that in lower energy bands. Only ground-based IACTs with effective collection areas of more than 10,000 m^2 are able to record the γ-ray light curves with the required temporal resolution.

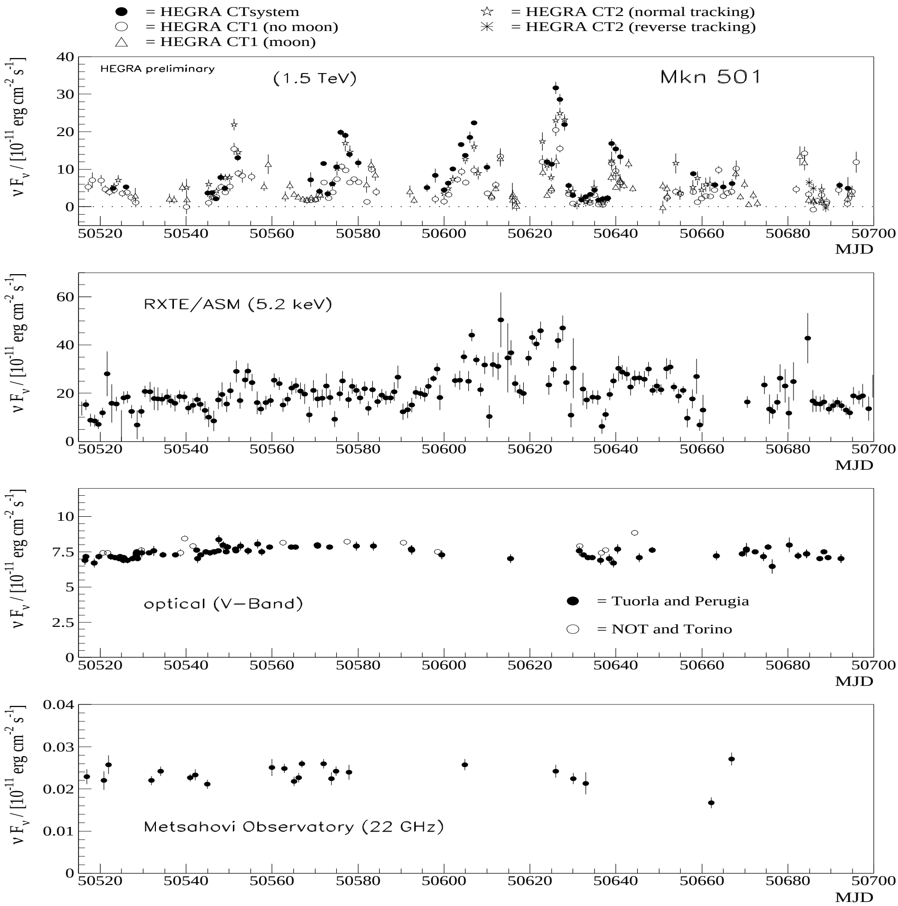

Fig. 4. The light curves of the active galactic nucleus Mkn 501 from March to September 1997 in the energy bands: $>$1TeV, 2–10 keV, optical and radio (22 GHz).

3.5. High-energy counterparts of Gamma Ray Bursts

Thanks to the accurate position determinations of GRBs by the Italian-Dutch BeppoSAX satellite [14], our knowledge of the properties of GRBs has grown considerably during the last year. X-ray, optical, and radio counterparts have been identified for several GRBs. The most prominent results were extracted from the optical counterparts of GRB970508 (with the notation GRByymmdd to specify the date of first observation) and GRB971214 through the observation of optical absorption lines and by the determination of the redshift of the host galaxy, respectively. The absorption lines observed in the optical spectrum of GRB970508 put the event at a cosmological distance of $z > 0.835$ [15, 16]. Even more spectacular is the recent discovery of the host galaxy of GRB971214 which has a redshift of $z = 3.42$ [17]. Figure 5 shows the optical counterpart obtained with the W.M. Keck telescope two days after the burst (left picture) and the faint host galaxy observed about two months after the burst (right picture).

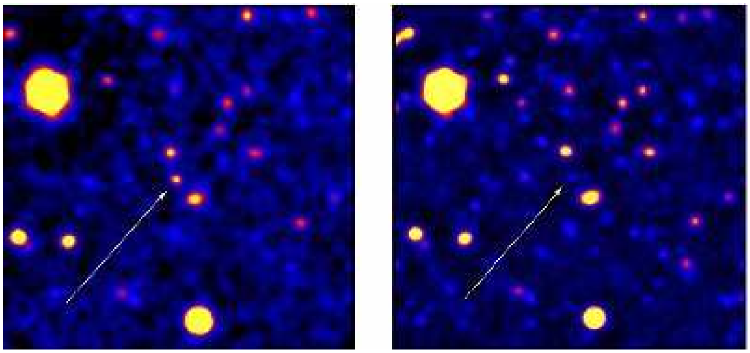

Fig. 5. Optical counterpart of GRB971214 as observed by the W.M. Keck 10 m-telescope on Mauna Kea, Hawaii two days after the GRB (left picture). About two months later the faint host galaxy of GRB971214 could be identified (right picture) and its redshift subsequently determined to z = 3.42. Image credit: S.G. Djorgovski and S.R. Kulkarni.

The identification of the GRB with the optical counterparts in both cases is now beyond any doubt as the three identified optical afterglows (GRB970228 [18–21], GRB970508 [22–24], GRB971214 [25]) rapidly faded over typically two week periods.

The γ-ray energy released in GRB971214, assuming isotropic emission, is about 3×10^{53} ergs, corresponding to about 16% of the rest mass of the sun converted into γ-rays alone. These recent data have thus not only answered the question of galactic halo versus cosmological origin of GRBs, but are also forcing astrophysicists to look for even more energetic events than the hitherto favoured neutron star coalescence models. The evidence that GRBs are among the most energetic phenomena in the Universe strengthens the case for one of the main design choices of the MAGIC Telescope, the rapid positioning capability of the telescope. This will allow to search for high energy GRB counterparts within typically 30 s after burst notification. Clearly this will be one of the most exciting fields of investigation of the MAGIC Telescope.

The very latest development is related to GRB980425 which appears to be a GRB in conjunction with a supernova explosion. This event was observed by the BeppoSAX Gamma-Ray Burst monitor [26] and was later identified to be in a nearby galaxy (distance $\approx$ 44 Mpc) and apparently correlated with a supernova explosion in a star forming region [27]. Together with the enormous distance of GRB971214 this development might be an indication of the existence of "hypernovas" which were put forward by Paczyński as a model for GRBs [28].

The EGRET detector on board CGRO recorded a number of GRBs typically lasting approximately 10–200 s. This gives a fair chance of detecting a burst with the MAGIC Telescope if the position of the burst can be reached within 10–30 s and if the possible high energy component would be emitted concurrently to the low energy (keV) γ-rays. We conclude that the movement should be as fast as possible, however the capability to turn the telescope through 360° in one minute appears adequate. A burst warning from measurements in the 100 MeV region does not seem to be necessary as all EGRET bursts also showed very strong signals at lower energies. For an energy spectrum of E^{-2} the sensitivity of the MAGIC Telescope will be 75 (190) times better at 10 GeV (100 GeV) than that of EGRET at 100 MeV. An especially interesting GRB was observed on December 8, 1997 (GRB971208), where the duration of the single-peaked burst was 800 s, about an order of magnitude longer than previously observed bursts of this type. This diverse character of the GRB time structures shows that the MAGIC Telescope has a real chance to observe GRBs, provided that the spectra extend towards higher energies.

One EGRET burst had a delayed high energy component about one hour later. No corresponding additional activity at lower energies was detected. The observation of this delayed component does not demand special telescope features, except the ability to be sensitive at large zenith angles, thus increasing the time window. With its red-sensitive photo-sensors, the second-stage MAGIC Telescope (using the HPD camera) will be ideal for observations at large zenith angles.

Note that due to the effects of γ-ray attenuation in the cosmic diffuse radiation background and the putative cosmological distribution of GRBs, the MAGIC Telescope's low γ-ray threshold energy represents an absolutely necessary prerequisite to make a major contribution to GRB research. Other air Čerenkov telescopes with thresholds above ~ 100 GeV can observe only the very closest GRBs which are extremely rare [29] This argument is corroborated by the fact that the identified bursts have rather large redshifts.

3.6. Search for a cold dark matter candidate

Experimental evidence for large amounts of dark matter in the Universe is found in a variety of astronomical data. Examples are the velocity dispersions of clusters of galaxies [30], the flat rotation curves of spiral galaxies [31, 32], bulk flows on large scales [33], the excess of mass density in the

Universe over that visible in galaxies [34], *i.e.* $\Omega_{\rm dyn} \gg \Omega_{\rm gal}$, and lens masses in gravitational lensing phenomena [35].

In order to explain the flat rotation curves of spiral galaxies like the Milky Way, dark matter halos are expected to be described by centrally peaked density profiles

$$\rho(r) \propto \frac{1}{(r/a)^{\gamma}[1+(r/a)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

with a core radius a and model parameters α, β, γ. Within supersymmetric extensions of the Standard Model with R-parity conservation, the neutralino (the lightest stable supersymmetric particle) appears as a promising cold dark matter candidate. Being Majorana particles, neutralinos would annihilate into pairs of γ-rays through the reactions $\chi\chi \to \gamma\gamma$ [36] or $\chi\chi \to Z\gamma$ [37]. These γ-rays would prevalently come from the Galactic Centre, and would be observable by the MAGIC Telescope provided that the neutralino mass is above 10 GeV (50 GeV) for a southern (northern) site.

In a recent calculation Bergström, Ullio and Buckley [38] calculated detection rates for the upgraded Whipple telescope, a generic Southern Array of IACTs, and the planned GLAST detector using a number of halo density profiles, *e.g.* (α, β, γ) = (2,3,0.2), (2,3,0.4), (2,2,0). This calculation shows that the MAGIC Telescope would be sensitive to a large fraction of the SUSY parameter space. If the MAGIC Telescope is placed at a northern site, due to its improved flux sensitivity at large zenith angles, it will be sensitive to fluxes from neutralino annihilation which are about an order of magnitude lower than for a generic Southern Array of 10 m-class telescopes. Note that *e.g.* from the Canary Islands the Galactic Centre is observed under a minimum zenith angle of 57°.

4. Basic detector considerations

Extensive Monte Carlo simulations of air showers (energy above 10 GeV) for the MAGIC telescope in order to optimize the design and to get performance characteristics have been done. Whereas an energy of a few GeV is sufficient to produce air showers that contain many electrons above the Čerenkov threshold, a large fraction of the Čerenkov photons is lost due to Rayleigh and/or Mie scattering and ozone absorption in the atmosphere. This effect is most pronounced in hadron showers due to the higher Čerenkov threshold of hadrons and muons compared to electrons. The resulting average Čerenkov photon density within the light pool of an air shower is shown in figure 6 for an observation level of 2200 m above sea level (asl). Only for γ-ray induced air showers the Čerenkov photon density is almost linearly

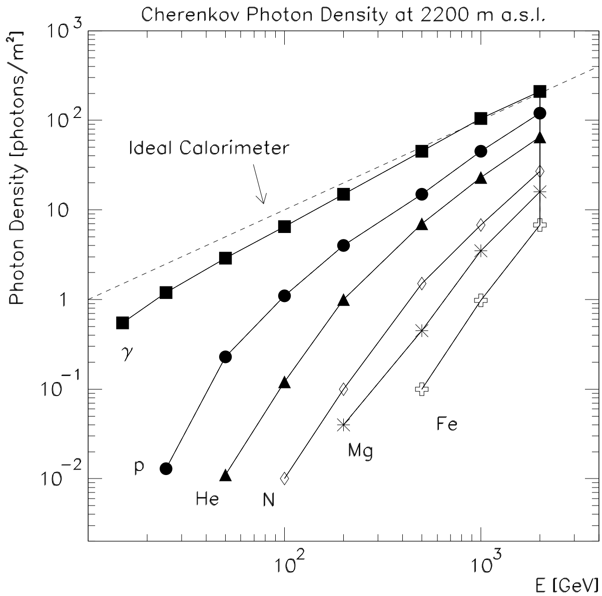

Fig. 6. Photon density (300-600 nm) at 2000 m asl as a function of incident energy and particle. The photon density is averaged over an area of 50 000 m^2.

dependent on the incident γ-ray energy down to the envisaged threshold energy of the MAGIC Telescope.

Current IACTs, for example the 10m ø Whipple telescope in Arizona [39], have a photon sensitivity of about 35 photons/m^2 corresponding to a γ-ray energy threshold of about 300 GeV. As hadron induced air showers produce less Čerenkov light than γ induced ones, a natural γ/hadron separation at the threshold is provided in all IACT applications. This inherent hadron suppression factor increases at lower energy. A telescope sensitive at $\approx$10 GeV will therefore have excellent intrinsic hadron rejection capabilities already at the threshold. The constraints on hadron rejection efficiency based on image analysis can thus be less demanding in this energy domain. On the other hand, the low absolute photon density within the light pool even for γ-ray induced air showers leads to the main requirements for the MAGIC Telescope: a large light collector, red sensitive light sensors, reduction of excess noise and improved photoelectron collection efficiency.

5. The telescope

The telescope is modelled after a 17m solar collector. 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 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 7 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° $\oslash$ camera with a pixel size of 0.1° in the central region of 2.4° $\oslash$ 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 we will use a conventional PM camera from one of

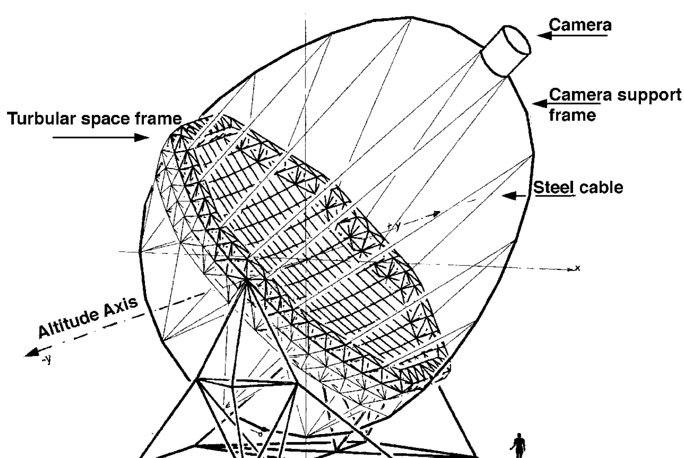

Fig. 7. A model of the 17m $\oslash$ MAGIC telescope.

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 ≈ 20 photoelectrons to below 2 and to concentrate the light onto small diameter APDs by so called light traps (Chiemtec patent). The camera will be connected to the electronics ground station by 100 m optical fibres working in the analog mode for the transfer of the fast PM signals. Signals will be digitized by 8-bit F-ADCs of ≥ 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. The details of these features can be found in the MAGIC Design Study [1].

6. Performance

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 $1.6^\circ \oslash$ 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 8 shows the collection area as a function of energy E while Figure 9 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 γ/h separation algorithms are ongoing.

The sensitivity of the MAGIC Telescope using the HPD camera (phase 2) is shown in figure 10 together with that of a few current IACTs and for the EGRET detector. For the classical PMT camera used in phase 1 the flux sensitivity above $\sim$50 GeV is similar to the flux sensitivity obtained for the HPD camera. Also it is shown the sensitivity as quoted for the planned 9-telescope VERITAS array and the planned satellite detector GLAST.

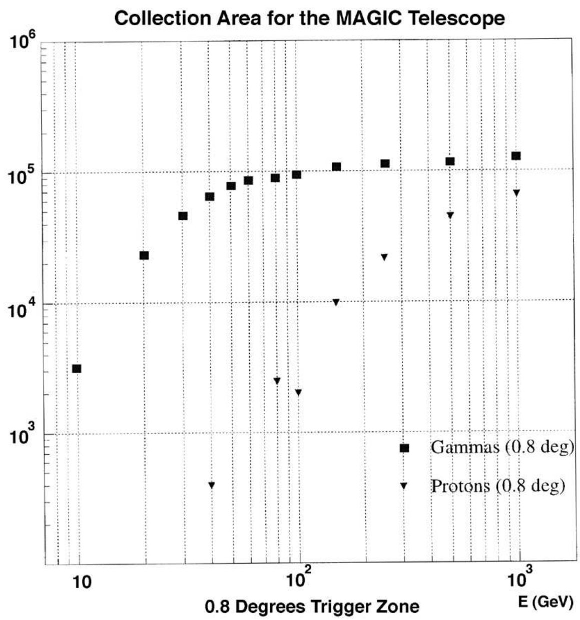

Fig. 8. Collection area as function of E. In brackets: radius of trigger area.

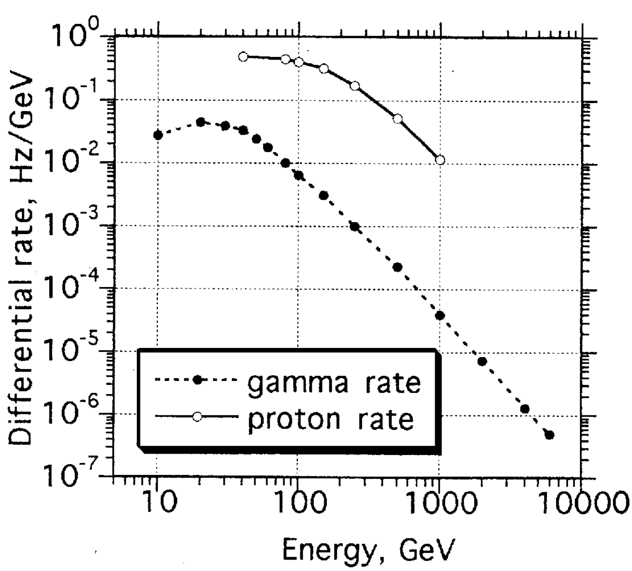

Fig. 9. Differential counting rates as function of E.

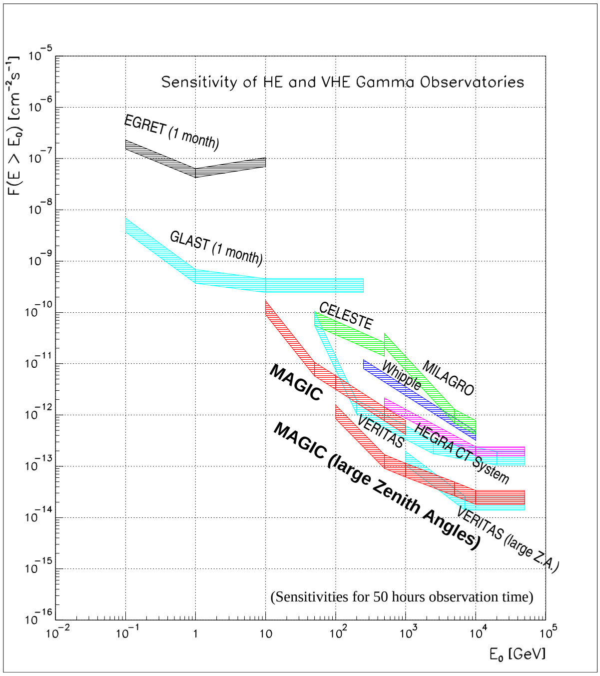

Fig. 10. Comparison of the point-source sensitivity of the MAGIC Telescope at 0° zenith angle and at zenith angles of about 75° (labelled MAGIC (large Zenith Angles)) to the point-source sensitivity of existing (HEGRA CT system, MILAGRO, Whipple) or planned ground-based installations (CELESTE, VERITAS) and to the sensitivity in 1 month observations for the existing (EGRET) and planned (GLAST) space-borne high energy $\gamma-$ray experiments. Above approx. 50 GeV the sensitivity of the MAGIC Telescope using the classical PMT camera will be similar to the sensitivity shown for the HPD camera.

7. Comparison to other IACTs

Table I shows a comparison of a few existing air Čerenkov detectors in terms of sensitivity and corresponding physics energy thresholds for γ-rays, and the minimum number of photoelectrons (ph.e.s) that have to be recorded for a successful image analysis. The trigger thresholds are usually 15–30% lower than the physics thresholds.

Note that the minimum number of ph.e.s per image required for a successful image analysis is a function of the pixel size, the noise level, and the speed of the camera which ultimately is limited by the degree of isochronicity of the mirrors. The pixel size and to a certain extent the camera speed have *e.g.* been optimized by the CAT collaboration in order to achieve a

TABLE I

Sensitivity of operating, upgraded, and planned Čerenkov telescopes in terms of the minimum number of photons/m^2 in the Čerenkov light pool. In addition the required number of photoelectrons for reconstruction of the image parameters is given. Physics energy thresholds are also given; trigger thresholds generally are lower by 15 to 30%. We added the numbers for the planned CELESTE solar array experiment for comparison; here N stands for the number of heliostats used in the experiment. For some of the quoted numbers we could not rely on published material but had to infer the numbers from other known telescope parameters and we thus list approximate numbers. For the MAGIC Telescope the three light sensor options, PMTs, HPDs, and APDs are listed.

Telescope	Mirror size (m^2)	Sensitivity (Ph./m^2)	Threshold E_{thres} after cuts	ph.e./image
Operating Telescopes				
HEGRA CT1	5	120	1.5 TeV	$\geq$ 60
HEGRA CT3-6	8.4	50 - 70	$\sim$ 500 GeV	$\geq$ 60
CAT	18	$\approx$ 35	$\approx$ 300 GeV	$\geq$ 60
WHIPPLE	74	35	300 GeV	$\geq$ 300
Planned Telescopes				
VERITAS	9 x 74	16 (?)	$\approx$ 100 GeV	$\geq$ 100
HESS	16 x 80 (?)	14 (?)	$\approx$ 100 GeV	$\geq$ 100
MAGIC (PMT)	236	4-5	25–30 GeV	$\geq$ 80
MAGIC (HPD)	236	1.1	12–14 GeV	$\geq$ 80
MAGIC (APD)	236	0.6	$\approx$ 7 GeV	$\geq$ 120
CELESTE	N$\cdot$ 40	1–3	30–50 GeV	–

low threshold with a comparatively small mirror area. In the case of the MAGIC Telescope, however, the very low photon densities cause the first and second factors to dominate; hence the requirement of at least 80 ph.e.s for successful MAGIC Telescope image analysis.

8. Site

The MAGIC Telescope will detect Čerenkov light produced in extensive air showers in the 290–700 nm range. Important criteria for possible sites for such an instrument are:

(1) dry maritime climate (stable atmosphere with low aerosol content);

(2) good visibility (low Rayleigh and Mie scattering);

(3) low natural light (*e.g.* aurorae) and man-made light pollution (allowing observations to at least 80 degrees from the zenith);

(4) cloud cover less than 15 % (maximizing the observation time);

(5) a large, preferentially flat area (allowing to build additional telescopes);

(6) low atmospheric water content (minimizing absorption in the blue).

All these criteria can be met by choosing a high-altitude site in a dry climate. Such a site would also satisfy the general conditions for a good astronomical site. A site in or close to Europe would be preferable from logistical and financial points of view. Also essential would be good access roads, electricity (about 30 kW) and water supplies (2 cubic meter per month for mirror cleaning alone) as well as buildings for laboratories. The rent paid for the site and the corresponding travel costs to it should not be a major fraction of the operating expenses. Taking all factors together the preferred site would be on the Canary Islands within the European Northern Observatory, *i.e.* La Palma or Tenerife.

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