Vol. 35 (2004) ACTA PHYSICA POLONICA B No 6–7

GROUND-BASED GAMMA-RAY (γ) ASTRONOMY*

Eckart Lorenz

Max-Planck-Institute for Physics
Foehringer Ring 6, D-80805 Munich, Germany

(Received May 19, 2004)

Very high energy (VHE) gamma-ray astronomy is a very young field of astronomy. The main detection techniques, the status and the near term prospects will be reviewed.

PACS numbers: 95.55.Q+, 95.85.Pw

1. Introduction

The window of very high energy gamma-ray (γ)-astronomy has been opened only fifteen years ago with the observation of the first TeV γ source, the Crab nebula, by the Whipple collaboration [1]. Currently, about 15 sources have been identified, mostly with very high significance and by at least two groups. Figure 1 displays the sky map of sources emitting VHE γs above 300 GeV energy.

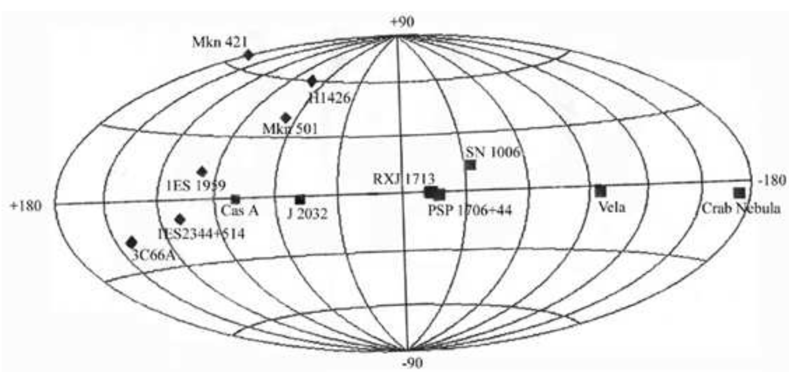

Fig. 1. The VHE γ sky above 300 MeV.

* Presented at the Cracow Epiphany Conference on Astroparticle Physics, Cracow, Poland, January 8–11, 2004.

2. VHE gamma-rays, messengers of ultra-relativistic particle processes in our Universe

Initially, the experimental activities in VHE γ astronomy were driven by the search for the sources of charged cosmic rays (CR), which are quite frequent in our galaxy (energy density nearly 1 eV/ccm, thus similar to the energy density of the cosmic microwave background) and which constantly bombard our atmosphere, while now the physics goals of this field are much wider. The sources, respectively the mechanisms for generating cosmic particles of such high energies are still, after nearly a hundred years after the discovery of the intense cosmic radiation, unknown or not well understood. The observed energy spectra of the CRs extend up to 10^{20} eV. Charged CR make up for more than 99.99% of the known energetic cosmic particles with the remaining ones being most likely γs, though their exact fraction is unknown. The fluxes of high energy neutrinos and possible dark matter particles (WIMPS, long-lived Neutralinos) are completely unknown, the reason being the lack of suitable detectors. Charged CRs are unsuitable for the search of their origin because of the weak galactic magnetic field is nevertheless sufficiently strong to scramble their initial direction, at least up to a few times 10^{19} eV in energy. Only long-lived neutral particles can be extrapolated back to the possible location of cosmic accelerators (more precisely to some target most likely near cosmic accelerators). From the three known long-lived particles, the neutron, the neutrino and the gamma quant, the two first ones can nevertheless currently be excluded as useful messengers. Neutrons are only useful to exploit the nearby cosmos of ultra-relativistic particle processes. Neutrons just don't live long enough, at least below 10^{18} eV energy, to survive typical distances of potential sources in our galaxy. Neutrinos, weakly interacting particles, require, for high statistics observation, extremely large detector volumes of at least a few cubic km of ice or water. The preparation for the first neutrino detectors has just begun, but no energetic source has been detected in the neutrino sky[1]. Only γs are suitable messengers. Their main features are:

- They are neutral particles and therefore not deflected by the cosmic magnetic fields. Therefore they can be extrapolated back to their origin.
- They have no mass and move with the speed of light. Therefore the observed time distribution (after correcting for any statistical fluctuations) reflects the original history of the production time distribution.

[1] Only two neutrino-emitting sources of low energy (in the context of this paper) have been observed up to now: the sun and SN 1989A.

- As high energy particles they set a lower limit on the energy of the particle processes leading to their production. VHE γs are therefore messengers of $\geq$VHE particle processes in our Universe.

Obviously, there are also some fundamental difficulties in VHE γ astronomy:

- The flux of VHE γs is very low. Therefore very large detection areas are needed. In general the fluxes follow over wide energy ranges power laws with coefficients -2 to -4.
- The background of charged CRs is many orders of magnitude larger and is for most experimental arrangements not easy to separate from the searched for γ signal.
- The Universe is not fully transparent for the higher energy γs due to interaction with the various low energy photon fields. This fundamental problem and related physics consequences will be discussed in a subsequent chapter.

3. Production processes of VHE γ-rays

Gamma quanta cannot gain energy by acceleration processes commonly known for charged particles. Therefore, VHE γs need higher energy parent particles. Basically, one can distinguish between 'bottom-up' and 'top down' processes.

'Bottom-up' processes are based on the acceleration of charged particles, either hadrons (protons…heavy nuclei) or electrons, for example in shock waves or strong electrical fields (generated for example by variable magnetic fields). The γ production takes place in possible follow-up interactions of the accelerated particles with some target 'matter' (of baryonic or photonic nature), which is assumed to be normally present at or close to the cosmic accelerators. The underlying processes for γ production are described by well-known particle reactions. Characteristic examples are:

(a) A $\geq$ VHE hadron interacts with some target material such as for example with nuclei in the interstellar gas or in the precursor wind of a Supernova. Such a hadronic interaction generates normally plenty of secondary particles, amongst them π^0s, which decay with a short lifetime (10^{-16} sec) into 2 γs. Besides π^0s, about twice as many charged pions are produced, which normally decay into neutrinos and muons (which in turn again decay into neutrinos and electrons)[2].

[2] The simultaneous observation of both γs and νs would be an unambiguous proof of the hadronic production process.

(b) VHE electrons can 'upscatter' low energy photons (normally there exist plenty of them around hot stellar objects) to nearly the maximum electron energy (Inverse Compton (IC) scattering). Quite often the seed photons are generated by synchrotron radiation when an energetic electron passes through a magnetic field, which is normally present in the environment of a shock wave and a necessary prerequisite to confine the charged energetic particles in the accelerating volumes of shock waves, respectively in cosmic 'betatron' accelerators in pulsars. This process, named the Synchrotron Self Compton (SSC) scattering process, was at first described by Harding and DeJager [2]. This process manifests itself by a double humped spectrum in the spectral energy density (SED) distribution. The SSC process links in first order the energies and intensities of the so-called synchrotron and inverse Compton peaks (for example in an νF_ν presentation) with the magnetic field strengths. A measurement of two of the quantities allows one to predict the third one or set at least limits.

(c) VHE γs can also be produced by a lower energy process, as described in (a) or (b), but taking place in a system moving with a high Γ factor towards the earth ('blue shifting' of γs, for example in Gamma Ray Bursts (GRB) or in jets of AGNs).

In the 'top-down' scenario one assumes that some superheavy (O 10^{16} GeV) particles, so-called Topological Defects, left over from phase transitions in the Early Universe, or Relic particles, can break down spontaneously. In the subsequent hadronisation plenty of high energy π^0s with a subsequent decay into γ's should be produced. It is expected that, if such particles exist, the decays would be uniformly distributed over the sky. Thus, one cannot correlate any signal with a steady point source, but expects γs to be seen from all directions. The search for so-called isotropic γs is a big experimental challenge, and present limits are rather poor. No compelling evidence for 'top-down' processes has been found up to now.

4. The Universe has a limited transparency for VHE γs

Our Universe is filled with a variety of low energy photon fields such as radio waves, the 2.7 K microwave background (BG), IR photons (not well known), visible and UV star light. VHE γs can interact with these low energy photons and thus limit the detection range of the former ones. This process, described by QED, has the largest cross section close to the threshold for e^+e^- production, *e.g.* [3]

$$\mathrm{E_{th}}(\gamma_{\mathrm{VHE}} + \gamma_{\mathrm{low\,energy}} \rightarrow e^+e^-) \approx 1\mathrm{MeV} \tag{1}$$

At around 10^{15} eV (photons of this energy interact predominantly with the ones from the 2.7 K MWBG) one can only observe sources up to about the extension of our galaxy, while at lower energies the Universe 'gradually opens up'. Around a few GeV the Universe becomes transparent up to high redshifts. As a consequence, the efforts to construct new detectors concentrate very much on pushing their threshold down to these limits but conserving the large detection area of ground-based instruments. In the region of interest of the new generation of ground-based instruments, the observability would be mainly affected by the interaction with the not so well known IR background. The interaction would manifest itself by a cut-off in the spectra (besides a possible cut-off due to source inherent limitations in the acceleration mechanism). It is now quite common to talk about a γ-horizon for sources at different redshift. The IR background is linked in part to the formation of stars in the early Universe. Therefore the measurement of the spectral cut-off of many sources might allow one to set a tight limit on this formation rate.

5. Detection methods for ground-based γ-astronomy

The earth atmosphere has only a few transparent windows in energy for electromagnetic waves such as bands for radio waves, IR radiation and the visible spectrum. At higher energies, the atmosphere is not more transparent to allow direct detection of the astronomical messenger particles from ground. In the multi GeV/TeV energy range the expected γ fluxes are too low to be detected by balloon borne or satellite borne instruments because of too small detection areas. Nevertheless, one can observe from ground secondary effects when VHE γs hit the atmosphere. VHE γs, as well as energetic charged CRs, interact with nuclei of the upper atmosphere and produce so-called extended air showers, either a nearly pure electromagnetic (EM) shower if the incident particle is a γ or an electron, or a hadronic shower if the initial particle is a charged cosmic particle (Proton, $\alpha\ldots$Fe$\ldots$). In a shower, all the energy of the initial particle is transferred to a large number of secondary particles, where the charged ones loose (with a few exceptions) eventually their energy by ionisation, Cherenkov radiation (if the particles are faster than the speed of light in the absorber medium), or generation of

[3] The electrons in reaction (1) can upscatter again photons from the MWBG and generate again high energy γs. If the initial γ is well above 10^{15} eV, an electromagnetic cosmological shower can develop (until the secondary γ-energy falls below, say, 10^{13} eV).

scintillation light. With suitable detectors any of these quantities could be measured and the initial energy determined. Basically, the atmosphere, combined with a suitable detector, forms a fully active calorimeter. Air mass 1 corresponds to 27 radiation length and 11 hadronic absorption length; therefore, in first order, VHE EM and hadronic showers have similar longitudinal extension. While ionisation measurements are practically excluded, one can detect from VHE EM showers either the particles of the shower tail if one places the detector on high altitude or the Cherenkov light. Scintillation light (air fluorescence) from VHE EM showers is too faint to be detected (the conversion ration of the initial energy to fluorescence light is around 10^{-4}), also emission is isotropic, therefore the photon flux at ground for a typical VHE shower is $\ll 1/\mathrm{m}^2$. Cherenkov light emission in the atmosphere is very much collimated (0.4–1.4°, altitude dependent) along the direction of the initial particles. For a conversion ratio of the initial energy into Cherenkov photons of about 10^{-3} the light density on ground from a TeV EM shower is few hundred photons/m^2 for a TeV γ of vertical incidence. Fig 2 shows the correlation of the light flux (averaged over an area of $\approx 50\,000$ m^2) with the particle energy and different incident particles. For EM showers above 10 GeV the correlation between energy and light yield is nearly linear, *i.e.*, light flux measurements provide in first order a good energy measurement. If instruments are able to measure the arrival direction of the photons, one can also determine the principal shower axis and in turn the incident particle direction with quite some precision. The combination of the Cherenkov emission angle and the transverse blow-up of the shower result in the photons' being distributed nearly uniformly over a disc with ≈ 120 m radius (with some altitude and angle of incidence dependence). As a result, any suitable light detectors have a sensitive detection area of about 50 000 m^2, irrespective of their intrinsic light collection area. In EM showers the radial blow-up of the secondary particles is dominated by multiple scattering, and in second order by the earth magnetic field. Hadronic showers are much wider because of the transverse momentum 'kick' of secondary particles.

Historically one has tried to search for γ sources with large scintillator arrays. Except for very high altitude installations their thresholds were well above 10^{12} eV, *e.g.*, not well suited for VHE γ astronomy. Their advantages were a 24 h up-time and a large angular acceptance allowing for an all-sky monitoring. Severe limitations were a rather poor angular acceptance and energy resolution as well as basically no discrimination power between the huge BG from hadronic showers and γ-showers. Only a few arrays are still in operation [4–6].

All discoveries of γ-sources were made by so-called air Cherenkov telescopes (ACT), which record the Cherenkov light from particle showers in the atmosphere. ACTs resemble very much large optical telescopes for as-

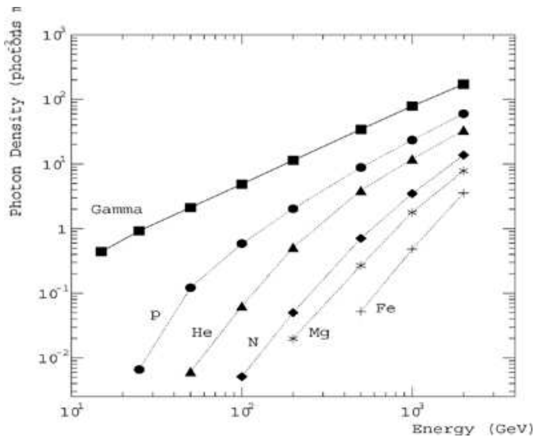

Fig. 2. Correlation between the number of Cherenkov photons/m^2 (300–550 nm) and the incident energy. Parameter: incident particle type [3].

tronomical observations. A large collection mirror focuses the Cherenkov light onto a fine grain matrix of fast photosensors in the focal plane. Optical precision is relaxed by a large factor (O 100–1000). As with optical telescopes one tracks also the source, whereas one observes with the former ones a point source at 'infinity', one records with an ACT a weakly 'glowing' extended shower at a few km above the instrument.

As shown in figure 2 the light flux is extremely low. Even in case of very large collection mirrors the number of detectable photons is low and many orders below the steady-state background light of the night sky (at dark nights outside the galactic plane: 2.10^{12} photons/m^2 sec sterad between 300 and 550 nm). Fortunately, the Cherenkov light flashes are extremely short in time (O few nsec), allowing nevertheless to record shower images which contain a few hundreds of photons by means of very fast photomultipliers. Best ACTs have a field of view of 3–5° diameter subdivided into a few 100 pixels allowing for a coarse sampling of the shower images. It should be mentioned that optical limitations of a single mirror (no secondary optics) and the statistical processes in the shower development do not necessitate the high resolution granularity of cameras in optical telescopes.

An important experimental challenge in γ astronomy is the suppression of the large hadronic background. In satellite borne detectors a scintillation veto counter above the γ-detector can efficiently achieve this goal. No such solution is at hand for ground-based instruments. In ACTs one tries to improve as much as possible the angular resolution in order to detect point sources as 'hot spots' on the sky map. Also, in ACTs with a large FOV and a fine-grain camera one can record an 'image' of the showers and carry out some structure analysis. This type of analysis, named after one of the pioneers in the field, 'Hillas' parameter image analysis, allows for a large reduction (factor O 50–1000, energy and camera parameter dependent) of the hadronic background. Further improvements are possible by observing individual showers by an array of telescopes (2,3,4...) which allow for a further improvement of the angular resolution and an additional reduction in hadronic background. The sensitivity improves normally by a factor $(1.2–1.4)\times\sqrt{N}$ while costs increase with N, N being the number of telescopes. The ultimate limit in background reduction is defined by the flux of cosmic electrons, which is negligible at TeV energies but is becoming increasingly important in the low GeV range.

The use of Cherenkov light as a tool to study cosmic rays has already been proposed around 1955 by Jelley [7]. Nevertheless it took about 35 years to observe the first VHE γ-source. After this discovery the development of improved telescopes progressed very rapidly and a new generation of high sensitivity telescopes is just starting to begin with observations (see below).

6. A short summary of the current physics objectives in VHE γ-astronomy with ACTs

The full discussions of the current physics objectives of ground-based γ-astronomy go beyond the limits of this paper. Therefore, only the main objectives are listed, and some selected results are presented below. The list of subjects is very rich and the order is not according to their importance:

1. Search for Active Galactic Nuclei (AGN) up to high redshifts, *i.e.* extending also up to the time of high star formation. These observations should shed light onto intrinsic γ production processes in AGNs, black holes and indirectly on the cosmological infrared (IR) background from γ-absorption processes (γ horizon).
2. Search for VHE γ-emitting Super Nova Remnants (SNR) from recently (up to a few 104 years ago) exploded Super Novae. The remnants are considered to be efficient particle accelerators and thus likely to be the possible origin of the charged galactic CRs. On the other hand much fewer γ-emitting SNRs than expected have been found up to now above 300 GeV.
3. Study of Plerions (Pulsars) which are expected to show in certain energy bands pulsed γ emission, *i.e.*, to test the validity of the polar cap or the outer gap model. A low telescope threshold, as close as possible to 10 GeV, is essential.
4. In the high energy band (1 MeV-10 GeV) about 270 γ-sources have been found by the EGRET detector on board of the recently decom-

missioned Compton Gamma Ray observatory [8]. Most of the sources could not be unambiguously correlated with known stellar objects, partly due to insufficient angular resolution, partly due to high diffuse γ-background. The new generation, low threshold and high sensitivity ACTs should help to clarify the situation.

5. Study of the diffuse γ emission of the galactic plane. Part of the flux can be correlated to charged CRs interacting with the interstellar gas, *e.g.*, information can be retrieved about the gas (dust) density in the galactic plane. Any large excess of diffuse γ-radiation could be a sign of possible dark matter (see 8). Cosmic electrons might loose quite some of their energy by synchrotron radiation when passing the magnetic fields in the galactic plane (expected to be much higher in the central region of the galaxy compared to the galactic halo, but it is unlikely that there will be any γ-emission in the VHE range).

6. Search for VHE γ-emission from Gamma-Ray Bursts (GRB), which occur 1-2 times per day and are still in many aspects enigmatic. In a few cases the EGRET detector observed a spectrum extending up to GeV energies [9]. In one case a gamma with 17 GeV has been observed occurring over 90 min after the original burst [10]. Today's ACT have collection areas exceeding the EGRET detector by five orders of magnitude. Provided the threshold is low enough one has the chance to detect a large flux of γ-rays from energetic GRBs. The main experimental problem is that ACTs have a very limited FOV and need both fast and precise alerts of the GRB position and also very fast telescope response. Estimates show that one has a chance to study 1-5 GRBs per year with the most powerful new telescopes.

7. Search for γ-emission from possible Topological Defects, respectively Relic Particles left over from the Early Universe. In all above noted possible sources the VHE γs must originate from processes where initially charged particles are accelerated to $\geq$VHE energies. As previously stated, VHE γs can also originate from the decay of superheavy particles. Possible candidates are so-called Topological Defects or Relic Particles left over from the Early Universe. Topological Defects are assumed to be left over from phase transitions occurring at the time shortly after the Big Bang. Their expected mass is around 10^{25} eV. Topological Defects are assumed to decay spontaneously. In the follow-up hadronisation plenty of π^0s with subsequent decays in $\gamma\gamma$ are expected. Topological Defects are expected to be distributed isotropically; therefore any possible γ emission should also be isotropically distributed. Besides the isotropy, there should be an enhancement of γs in the upper energy end of the VHE range due to the

interaction with the photons of the microwave background and consequent multiplication processes following reaction (1) (see also related footnote). Theoretical models predict a large range for the possible γ-flux, but in any case well below the 10^{-3} level below the charged CR flux. The search for an isotropic γ flux in the VHE range is extremely difficult and an experimental challenge.

8. Search for the lightest supersymmetric particles. γs would be generated in annihilation processes. Such studies could contribute very much to the understanding of the open questions about Dark Matter.

9. Tests of quantum gravity effects.

In the following some recent results will be presented and briefly discussed. About half of the up to now observed VHE γ-sources are located in our galaxy and half are of extragalactic origin. All known galactic sources can be traced back to Supernovae, either Plerions or shell type remnants, while all observed high significance extragalactic sources are found to be active galactic nuclei (AGN).

6.1. Plerions

The first source discovered in the VHE region, the Crab, is a nearby galactic pulsar surrounded by an expanding gas cloud originating from a well-documented Supernova explosion in 1054. The Crab is one of the best-studied stellar objects. Electromagnetic emission has been observed spanning from radiowaves up to nearly 100 TeV. The Crab nebula is the strongest steady state VHE γ source observed up to now. Below 10 GeV a strong pulsed γ signal has been observed, while in the TeV region no periodicity in the flux could be detected. This could be explained naturally by different emission regions, *i.e.*, up to 1 GeV γs would be produced predominantly by electrons accelerated close to the pulsar, while TeV γs originate from particles accelerated in shocks in the surrounding nebula. The parent particles for the VHE γs are very likely also energetic electrons, which produce γs by IC up-scattering of low energy photons initially radiated by the same electrons by synchrotron radiation. Calculations based on the so-called SSC model [2], can explain the spectrum quite well.

VHE γs from the Crab have been observed by at least 9 ACTs. The Crab is nowadays used as the standard candle for ACT calibrations on the Northern Hemisphere. Similarly, PSR 1706-44 [11], a pulsar resembling in many aspects the CRAB, is used as standard candle on the Southern Hemisphere.

6.2. Shell type Super Nova Remnants (SNRs)

SNRs are considered to be the sources of the galactic CRs, *i.e.* these objects should show γ-production by energetic hadronic particles. Up to now three candidates (SN1006 [12], CAS A [13], RJX 1713 [14]) have been found (see figure 1), all of them with barely 5 σ significance, *i.e.*, with a rather low VHE γ flux compared to the Crab. These sources show in the so-called spectral energy density plots the characteristic double peak structure reflecting electron acceleration in shocks resulting in a low energy synchrotron emission peak and the inverse Compton scattering peak at higher energies. The observed low flux, which could be entirely explained by electron acceleration, together with the non-observation of TeV γ-emission from some other young SNRs (G 78, IC 443, Tycho...) casts some doubts on the assumption that SNRs will be efficient multi-TeV hadron accelerators. In SNRs the location of acceleration and γ-emission will be the shell. Therefore the source region of nearby SNRs will be extended and excellent angular resolution of the IACTs will be needed to resolve any structure. Quite a few SNR are observed by EGRET and are strong γ-emitters in the MeV/low GeV region. Unbroken power law extrapolations predict that many of these sources should be detectable above 300 GeV, the threshold of past ACTs. It will be one of the main challenges for the next generation IACTs to determine the spectral shape in the up to now unexplored energy range between 10 and 300 GeV and help to clarify the question about the origin of the charged CRs.

6.3. AGNs

A number of some radio-loud, BL-Lac types AGNs are also VHE γ-emitters. EGRET has found 66 AGN γ emitters in the MeV region (Third EGRET catalogue [8]). In the VHE range 6 sources have been identified, two of them, Mkn 421 [15] and Mkn 501 [16], with very high significance. Within the statistical errors all sources show rapid time variability. In some cases a strong correlation with X-ray variability was observed, favoring again electron acceleration and IC scattering as the primary production mechanism. No clear evidence for hadron acceleration has been found. The unambiguous proof might come from the future large ν detectors.

The first discovered AGN, Mkn 421, sometimes showed intense flaring of up to 8 times the Crab flux with doubling time of less than a 1/4 hour [17]. This fast flaring is an indication of the acceleration volume being very small. Even taking into account a typical Γ factor of 10, the volume can only have an extension of a few tens of light hours. Strong and persistent flaring was observed in 2001 from the AGN Mkn 421 (see the light curve figure 3(a)). The source Mkn 501 also showed a remarkable variation in γ intensity. In its year of discovery, 1995, the mean γ-flux was only a few % of that of Crab.

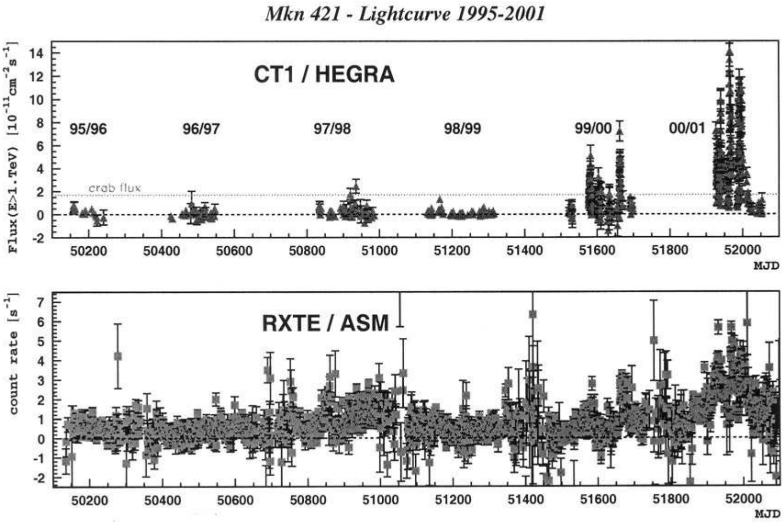

Fig. 3. (a) Compilation of the light curve of Mkn 421, as measured by the HEGRA CT1 telescope and RXTE.

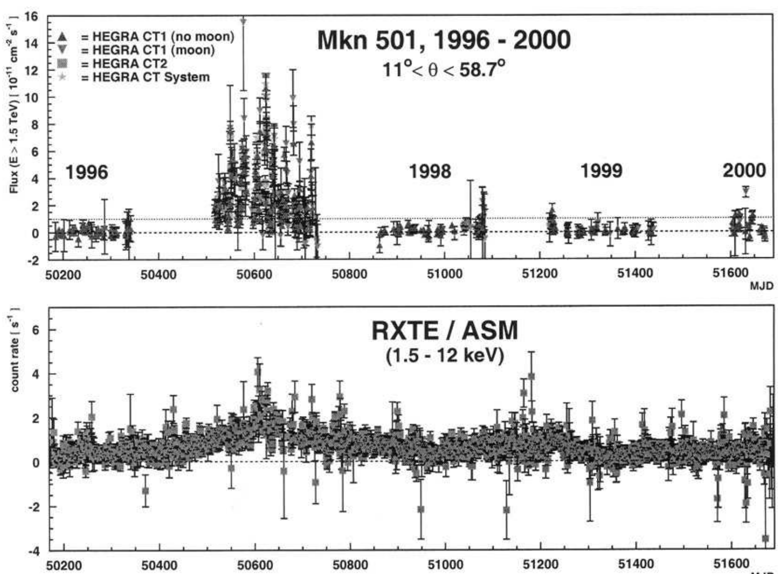

Fig. 3. (b) Compilation of the light curve of Mkn 501, as measured by the HEGRA CT1 telescope and RXTE. Compilation by Martin Kestel and Daniel Kranich.

Nearly all throughout 1997, Mkn 501 showed persistent but seemingly chaotic flaring of up to 10 times the Crab flux. At the same time, a significant increase in the X-ray spectrum was observed, but nearly no change in the radio emission or visible spectrum was seen. Since early 1998, the VHE γ flux is again very low (see figure 3(b)).

Due to their sizeable distance (redshift of $z = 0.03$ of Mkn 421 and $z = 0.034$ of Mkn 501) the γ spectra of both AGNs (as well as that of the other extragalactic sources) could be affected above a few TeV by γ-interaction with the still unquantified cosmological IR background. The spectrum of Mkn 501 shows a strong deviation above 5 TeV from the generally expected power law shape,which thus could be interpreted as a cut-off around 6 TeV due to γ interaction with the IR background. As an alternative interpretation one could explain the steep drop in the spectrum as an intrinsic source effect. The spectrum of Mkn 421 shows within the statistics a much steeper slope and a cut-off at a somewhat lower energy around 3–4 TeV. Within the errors the two cut-off values are in agreement. From the current observations one can already conclude that the IR density around 10 μ wavelength must be very low, *i.e.* the star formation rate in the early phase of our Universe must have been rather low. It will be one of the most important goals of future lower energy observations to measure the γ spectra of high redshift AGNs to determine cut-offs as a function of z, *i.e.* to determine the so-called γ-horizon as a function of energy. The spectra of the other observed AGNs have too large errors for deriving any additional conclusions about possible cut-offs except the spectrum from the recently discovered AGN 1H 1426 [18, 19]. Due to its redshift of $z \approx 0.134$ the spectrum should already be significantly affected by the limited transmission of our Universe for γs above 1 TeV.

7. The new ACTs for the coming years

Until the year 2000, the best ACTs had a threshold of $\approx$ 300 GeV, *i.e.*, an observation gap existed between around 10 GeV (the upper end in sensitivity of the EGRET satellite detector) and 300 GeV. A number of new IACT projects for VHE γ astronomy are being pursued now worldwide in order to close this gap. The new telescopes should result in a quantum jump in sensitivity and will have significantly lower threshold energies, *i.e.*, well below 100 GeV. As pointed out in previous chapters, the prospects of observing distant sources increases dramatically when the threshold is reduced well below 300 GeV. At around 10-40 GeV the Universe becomes basically transparent, and one should be able to see γ emitting objects as far as a redshift of > 3, *i.e.*, a time where star/galaxy formation should have been much stronger than in present times.

Two quite different directions are followed for the new instruments: (a) the exploitation of readily available large mirror area solar power plants based on a multitude of tracking mirrors focussing the light on a receiver mounted on a tower, and (b) the development of dedicated large telescopes. For the former approach only the camera has to be built and the tracking program for the heliostats be modified. The camera normally replaces the central receiver during night-time. On the one hand these solar power plants have total mirror areas of up to a few thousand square meters, while on the other hand these plants were designed at non-optimal altitudes, for limited angular range, and have non-optimal optics. In most cases the individual heliostat mirrors of typically 40–50 m^2 area are focussed onto one PMT each, which measures both the arrival time of the Cherenkov light front as well as the local intensity, *i.e.*, one samples the Cherenkov light disc at many different positions. A disadvantage of the approach is, that these detectors lack the powerful image analysis of optimized ACTs and have therefore a very limited γ/h separation. Search for sources is done by the classical ON/OFF counting mode, *e.g.*, one records alternatively the counting rate with the detector pointing towards the source and then for the same time at a position a few degrees away from the source, and measures the rate differences, which are, in general, quite small. Atmospheric changes or bright stars in the FOV can often make the analysis very difficult and reduce the duty cycle. Up to now only the strongest sources could be observed with sufficient statistics.

Currently, two instruments take data, CELESTE [20] and STACEE [21], while a third project, SOLAR I [22], is still under construction.

TABLE I

Main parameters of the new generation high sensitivity, low threshold ACTs.

Project	Location	Number, ∅ of mirror	Threshold	Ref.
CANGAROO III	Australia	4 x 10 m ∅	≈ 100 GeV	[23]
H.E.S.S.	Namibia	4 (16) x12 m ∅	≈ 60 GeV	[24]
MAGIC	Canary Islands, Spain	1(2) x 17 m ∅	≈ 30→15 GeV	[25]
VERITAS	Arizona, USA	4 (7) x 10 m ∅	≈ 80 GeV	[26]

Other groups pursue the construction of dedicated ACTS with mirrors of at least 10 m diameter and fine pixelised cameras of 4–5° FOV. Table I lists the main parameters and references of these projects, two on the Northern and two on the Southern hemisphere. The Cangaroo III, the H.E.S.S and the

MAGIC telescope already take data, while the VERITAS project is under construction on the Kitt Peak. Three projects pursue a cluster of telescopes allowing either for stereo observations or the parallel observation of more than one source. As mentioned above, the stereo systems have a higher sensitivity and a somewhat lower threshold compared to a single telescope of the same type.

The new projects will allow one to close the gap between satellite borne instruments and previous ground-based telescopes. In 2006/7 it is planned to launch a powerful new satellite detector, GLAST [27], with a sensitivity exceeding the previously best detector, EGRET, by ≈100 in sensitivity, much better angular resolution and an upper detection threshold of 300 GeV. Figure 4 shows a predicted sensitivity curve of a few running instruments and the new generation ACTs. It is expected that with the new ground-based instrument a quantum jump in VHE γ-astronomy will be achieved.

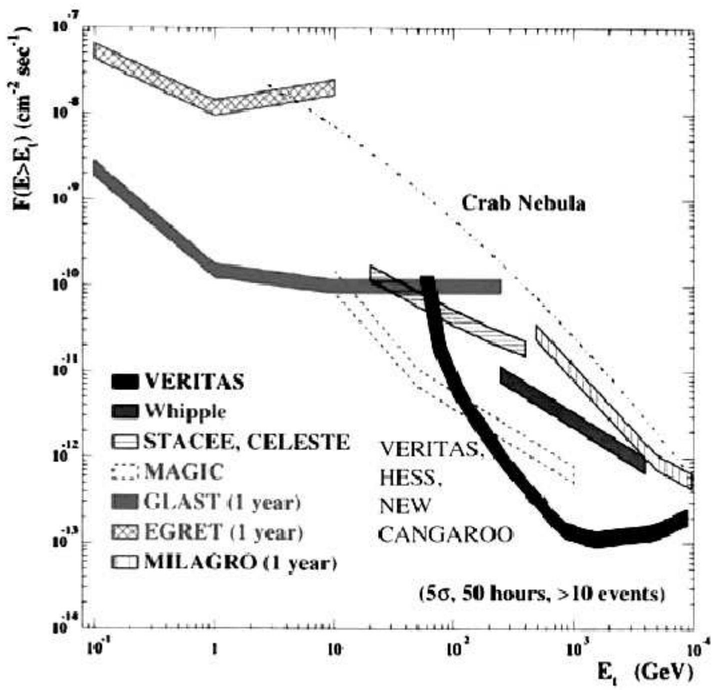

Fig. 4. Sensitivity as a function of energy for some current and future γ detectors. Also shown is the flux curve of the Crab nebula.

I would like to thank my colleagues from the MAGIC collaboration for many suggestions and comments. Also, I thank Sybille Rodriguez for assisting in preparing this manuscript.

REFERENCES

[1] T.C. Weekes *et al.*, *Astrophys. J.* **342**, 379 (1989).

[2] A. Harding, O. DeJager; *Astrophys. J.* **161**, 396 (1989).

[3] M. Chantal *et al.*, *Nucl. Instrum. Methods*, **A408**, 468 (1998).

[4] J.F. McCullough *et al.*, Proc. 26th ICRC (1999) HE 6.1.02.

[5] T. Yuda *et al.*, Proc. Int. Symp. On EHECR (1996) 175.

[6] The ARGO-YBJ Collaboration: 'The ARGO Astrophysics with ARGO', Proposal 1996.

[7] J. Jelley; *Cherenkov Radiation and its Application*, Pergamon Press, 1958.

[8] R.C. Hartmann *et al.*, *Astrophys. Suppl.* **123**, 73 (1999).

[9] B. Dingus, *AIP Conference Proc.* **558**, 383 (2000).

[10] E.J. Schneid *et al.*, *A&A* **255**, L13 (1993).

[11] T. Kifune *et al.*, *Astrophys. J.* **438**, L91 (1995).

[12] T. Tanimori *et al.*, *Astrophys. J.* **497**, L25 (1998).

[13] G. Puelhofer *et al.*, Proc. 26th ICRC (1999) OG. 2.2.17.

[14] H. Muraishi *et al.*, Proc. 26th ICRC (1999) OG. 2.2.20.

[15] M. Punch *et al.*, *Nature*, **358**, 477 (1992).

[16] J. Quinn *et al.*, *Astrophys. J.* **456**, L83 (1996).

[17] J.A. Gaidos *et al.*, *Nature* **383**, 319 (1996).

[18] G.D. Rowell *et al.*, Proc. 28th ICRC 4 (2003) 2345.

[19] H.M. Badran, T.C. Weekes; Proc. 27th ICRC (2001) 2653.

[20] E. Pare, Proc. 'Towards a Major Atmospheric Cherenkov Detector V' (1997) 228.

[21] R.A. Ong *et al.*, *Towards a Major Atmospheric Cherenkov Detector V*, 1997, p. 247.

[22] J.A. Zweerwink *et al.*, Proc. 26th ICRC (2000) OG 4.3.04.

[23] M. Mori *et al.*, 'The Cangaroo III Project', Proc. TeV γ Workshop, Snowbird, Utah, USA, 1999.

[24] A. Kohnle *et al.*, Proc. 26th ICRC (1999) OG 4.3.13.

[25] J.A. Barrio *et al.*, The MAGIC Telescope Design report, MPI Institute Report, MPI-PhE/98-5, March 1998.

[26] T. Weekes *et al.*, Veritas Proposal to SAGENAP.

[27] GLAST: `http://www.glast.stanford.edu`