I discuss the recent exciting results of discovery of TeV photons from several galactic and extragalactic sources, and highlight some objectives of VHE gamma ray astronomy that can be achieved in the near future by means of new generation ground-based detectors.

1 Introduction

The branch of high energy astrophysics that studies the sky in energetic $\gamma$-ray photons – gamma ray astronomy – is destined to play a crucial role in exploration of nonthermal phenomena in the Universe in their most violent forms. The great potential of the discipline is provided by two key circumstances: (1) copious production of $\gamma$-rays in a variety of galactic and extragalactic sources, and (2) availability of effective space- and ground-based techniques of detection of cosmic $\gamma$-radiation in very broad energy range from several hundreds keV to $\geq 10$ TeV. This allows rather impressive coverage of a variety of ‘hot’ topics of the modern astrophysics and cosmology, such as

- Origin of galactic and extragalactic cosmic rays
- Acceleration and radiation processes at extreme astrophysical conditions, in particular in the pulsar magnetospheres, relativistic jets of active galactic nuclei, etc.
- Physics and astrophysics of relativistic objects – neutron stars and black holes
- Nature of enigmatic astrophysical phenomena like the $\gamma$-ray bursts
- Cosmological issues connected with the level of diffuse photon fluxes and magnetic fields on large extragalactic scales and their evolution in time; independent measurements of the Hubble constant; search for dark matter in the form of WIMPs through their characteristic annihilation radiation; test of the non-acceleration (‘top-down’) scenarios of production of particles observed in cosmic rays above $10^{20}$ eV, etc.

The recent exciting results from the Energetic Gamma Ray Experiment Telescope (EGRET) aboard the Compton Gamma Ray Observatory (GRO) start to confirm these prime motivations of gamma ray astronomy. Indeed, many typical representatives of different galactic and extragalactic source populations, in particular pulsars (Crab, Vela), supernovae remnants ($\gamma$ Cygni, IC 443), plerions (Crab Nebula), giant molecular clouds/star formation regions (Orion, $\rho$ Ophiuchus), quasars (3C 273, 3C 279), etc., which were predicted as potential GeV gamma ray emitters, now are among of more than 300 $\gamma$-ray sources detected by EGRET. This success has elevated the field to the level of truly observational...
discipline. At the same time, the nature of most of the EGRET sources remains unknown. Moreover, the origin of γ-radiation from even firmly identified objects is poorly understood. This clearly justifies the future gamma ray missions with new generation detectors like the Gamma-ray Large Area Space Telescope (GLAST).

The GLAST, with its large (almost 2π steradian) field of view and superior flux sensitivity, $J_{\text{min}} \sim 10^{-10}$ ph/cm²s above 1 GeV, seems to be an ideally designed instrument for deep surveys of the sky in GeV γ-rays with an ambitious aim to do “γ-ray astronomy with thousands of sources”\(^1\). The significant advances in the detection area, angular resolution and field of view of GLAST as compared to EGRET provide very strong, by a factor of 100, reduction in the sensitivity threshold (see Fig. 1) that ultimately could result in dramatic increase of number of γ-ray sources. In particular, it is expected that more than 1000 (!) active galactic nuclei will be detected in GeV γ-rays\(^2\). A detailed study of the spatial, temporal, and spectral characteristics of already identified γ-ray sources is the second major objective of the GLAST. Also, since most of the EGRET sources do not exhibit spectral cutoffs in the 1-10 GeV region, the extension of the study into the unexplored region beyond 10 GeV is believed to be another important issue for the GLAST. Meanwhile, the area limitations of space-borne detectors compels the region of very high energy (VHE) photons above 100 GeV to remain (except for the specific topics related to the diffuse galactic and extragalactic backgrounds) the domain of ground-based gamma ray astronomy.

2 The Status of VHE Gamma Ray Astronomy

The basic idea of study of the cosmic γ-radiation by means of ground-based instruments is linked to the detection of secondary particles and/or the Cherenkov radiation of electromagnetic cascades produced in the Earth’s atmosphere by very energetic γ-ray photons\(^3\). The history of the ground-based gamma ray astronomy dates back to early sixties, but unfortunately the development of the field over many years was rather slow and controversial. One of the likely reasons for the slow progress could be the fact that the ‘TeV community’ has only recently realized that the proper detection/identification of primary γ-rays requires more sensitive and sophisticated methods and detectors than the ones used in the past in traditional cosmic ray experiments. Indeed, the exploitation of the so called imaging atmospheric Cherenkov telescope (IACT) technique was soon rewarded by the 9σ detection of TeV γ-rays from the Crab Nebula\(^4\). This seminal result of the Whipple collaboration published in 1989 perhaps could be registered as the first reliable observation of γ-rays from a celestial object obtained with a ground-based detector.

The high detection rate, the ability of effective separation of electromagnetic and hadronic showers, and the good accuracy of reconstruction of air shower parameters are three remarkable features of the IACT technique\(^5\). The recent reports about detection of VHE γ-rays from several objects by nine groups running imaging telescopes both in the northern (Whipple, HEGRA, CAT, Telescope Array, CrAO, SHALON, TACTIC) and southern (CANGAROO, Durham) hemispheres confirm the early expectations concerning the potential of the technique\(^6\),\(^7\), and provide a solid basis for the ground-based gamma ray astronomy\(^8\).
Figure 1: Sensitivities of satellite-borne and ground-based gamma ray detectors at the 5σ detection threshold compared with the flux of the Crab Nebula measured at MeV/GeV (COMPTEL/EGRET) and at TeV energies (only three recent TeV measurements by the Whipple (1995/1996) \[4\], HEGRA (1996/1997) \[5\], and CANGAROO (1994/96) \[6\], as well as the flux limit set by CASA/MIA \[7\] are shown). Two solid curves correspond to the calculated \[8\] synchrotron (S) and inverse Compton (IC) contributions to the Crab spectrum. The detector sensitivities correspond to the following conditions: INTEGRAL - exposure time \(10^6\) s \[9\], GLAST – 1 year all-sky survey \[2\], IACTs arrays – 100 h ‘on-source’ observations. The current sensitivities of the Whipple 10 m telescope and the HEGRA IACT system for 100 h observation time are also shown at the relevant energy thresholds. The sensitivities of the COMPTEL and EGRET approximately correspond to the fluxes of the Crab Nebula detected by these instruments.

### 2.1 TeV Energy Domain

Presently, four celestial objects are unambiguously identified as TeV γ-ray sources: Crab, PSR 1706-44, Mrk 421, and Mrk 501. These objects have been detected by two or more independent groups with \(\geq 10\) standard deviation statistical significance, and represent, most probably, two well recognized nonthermal source populations – pulsar driven nebulae (or plerions) and active galactic nuclei (AGN) \[13\]. Actually, three more candidates, detected with statistical significance of about 6σ or more, should be added to this viable list of TeV γ-ray sources: a pulsar driven nebula – Vela \[14\], a shell-type supernova remnant (SNR) – SN 1006 \[15\], and a nearby AGN – 1ES 2344+514 \[16\].

And finally, one has to mention some intriguing indications of episodic TeV signals from X-ray binaries. Two famous representatives of this population of compact galactic sources, Cyg X-3 and Her X-1 dominated VHE and UHE gamma ray astronomy in the 80’s, and played a crucial role in the renewed interest in ground-based γ-ray observations \[17\]. But unfortunately almost all the early claims about detection of γ-ray signals from these objects, both at TeV and PeV energies, were not confirmed by later, more sensitive observations \[18\]. Although one cannot exclude a long-term variability of these sources, many experts treat
the old results with a certain skepticism. Nevertheless, perhaps it is premature to draw final conclusions, especially if one takes into account the recent claims about detection of TeV signals from the cataclysmic variable AE Aquarii \cite{23, 24}, galactic black hole candidate GRS1915+105 (‘microquasar’) \cite{24}, X-ray binaries Vela X-1 \cite{25} and Cen X-3 \cite{26}. Interestingly, a \(\gamma\)-ray signal from Cen X-3 recently has been claimed to be detected also at GeV energies by EGRET \cite{28}. Although the statistical significance and/or systematic uncertainties of these results do not match the standards set by current IACTs, they indicate a necessity of monitoring these sources by new generation of imaging Cherenkov telescopes.

Along with above mentioned ‘firmly-detected’ and ‘possible-candidate’ TeV sources, there are several tens of objects that have been observed without finding significant evidence for a TeV signal. In some cases the flux upper limits, e.g. from the Crab and Geminga pulsars, and especially from shell type SNRs \(\gamma\) Cygni and IC 443, have begun to have important theoretical consequences \cite{29, 30, 31}. Also, several interesting searches for TeV \(\gamma\)-ray transients of different origins (e.g. due to evaporation of primordial black holes (PBH), or possible continuation of the spectra of low-energy gamma ray bursts (GRBs)) have been made by Cherenkov telescopes and air shower arrays. Meaningful upper limits have already been set to the PBH density, and upper limits to the delayed (or extended) TeV emission were derived from the immediate monitoring of GRBs using the BACODINE information network (see e.g. \cite{17} and references therein).

The implications of above mentioned results in the general context of scientific objectives of VHE gamma ray astronomy are discussed below (Sec. 4).

2.2 PeV Energy Domain

Despite intensive efforts in the early 90’s that were motivated by early claims about detection of PeV \(\gamma\)-rays from Cyg X-3, all sky surveys by sensitive air shower detectors CASA-MIA, Cygnus, EAS-TOP, HEGRA, SPASE, Tibet etc., could not detect point sources of ultra high energy (UHE) \(\gamma\)-rays above 20 TeV \cite{32}. Although very important, and in some cases astrophysically meaningful, e.g. the upper limits on the diffuse galactic and extragalactic \(\gamma\)-ray fluxes set by the CASA/MIA \cite{32, 33}, these results hardly can change an impression that the early promise of UHE gamma ray astronomy has not been fulfilled. To a large extent, this might not be considered a big surprise. The production of photons of such high energies requires existence of accelerators of parent charged particles with energy exceeding \(10^{14}\) eV. Although the spectrum of the observed cosmic rays (CRs) extends to \(10^{20}\) eV, it is quite possible that the efficiency of acceleration of protons and nuclei in many galactic sources, for example SNRs, drops at \(10^{14}\) eV \cite{35}. Thus even in the case of sufficient target material, the \(\pi^0\)-decay \(\gamma\)-ray emission above 10 TeV would be strongly suppressed. The same problem of high-energy cutoff in acceleration spectra obviously exists also for production of \(\gamma\)-rays due to the inverse Compton (IC) scattering of ultrarelativistic electrons on the ambient low-frequency photons. In addition, the severe synchrotron losses and reduction of the IC cross-section due to the Klein-Nishina effect makes this mechanism at such high energies significantly less efficient than in the TeV energy region. From this point of view, nonthermal extragalactic sources like powerful radiogalaxies which are able to accelerate particles well beyond \(10^{15}\) eV \cite{36} might appear as more promising objects (than the galactic
Figure 2: The attenuation lengths of protons (dotted curve) and $\gamma$-rays in the intergalactic space calculated [37] for the current density of DEBRA. The $\gamma$-ray pathlength at $E \leq 10^{14}$ eV and $E \geq 10^{19}$ eV presented by curves a,b,c and 1,2,3, respectively, reflect the uncertainty of the level of the photon background at the IR/O ($\lambda \sim 0.1 - 100 \mu$m) and radio ($\nu \sim 1 - 10$ MHz) wavelengths. Meanwhile the $\gamma$-ray pathlength in the energy region from $10^{14}$ eV to $10^{19}$ eV is dominated by the interactions with 2.7 K MBR.

sources) for $\geq 10$ TeV observations. However, the absorption of such energetic $\gamma$-rays in the diffuse extragalactic background radiation (DEBRA) inevitably leads to strong attenuation of fluxes of $\geq 10$ TeV $\gamma$-rays being produced beyond 100 Mpc (see Fig. 2). Thus any new (more effective) campaign of study of the sky in $\geq 10$ TeV $\gamma$-ray photons perhaps could be done only after significant (by a factor of 10) improvement of detector sensitivities compared to the sensitivities of current air shower arrays, $J_\gamma \sim 10^{-14}$ ph/cm$^2$s at 100 TeV. Since the angular resolution of such arrays, as well as their ability to separate the $\gamma$-ray induced showers from hadronic showers produced by CRs are strongly limited, an essential improvement of flux sensitivities of conventional air shower arrays can be achieved only by enlarging drastically the collection areas. This however seems to be not very attractive approach. More justified perhaps could be a reduction of the energy threshold of particle arrays towards 1 TeV by using water Cherenkov detectors like MILAGRO. Although the sensitivity of this detector is not very impressive (detection of the Crab requires $\sim 1$ year observation time) by the standards set by current imaging telescopes, the large field-of-view and 100% duty cycle of MILAGRO would allow effective searches for TeV $\gamma$-rays from GRBs or for other serendipitous VHE phenomena.

On the other hand, the IACTs operating at large zenith angles may serve as an alternative method for detection of $\geq 10$ TeV $\gamma$-rays from persistent astrophysical objects. Indeed, this technique may provide, in addition to the good angular resolution and gamma/hadron separation ability, huge detection areas exceeding the collection areas of the largest ex-
isting particle arrays by a factor of 10. The recent detection of \( \gamma \)-rays at energies up to \( \geq 50 \text{ TeV} \) from the Crab Nebula (the first positive detection of the UHE gamma ray astronomy!) by the CANGAROO collaboration presents not only great astrophysical interest, but also demonstrates the high efficiency of the technique.

3 The Potential of Ground Based Gamma Ray Detectors

3.1 Single Imaging Telescopes

The standard IACT consists of a large (from a few to 10 m diameter) optical reflector equipped with an array of photomultipliers in the focal plane of the reflector, and fast (nanosecond) processing electronics. The field of view of the camera should be at least \( \sim 3^\circ \) in order to contain the images of showers with core position up to 150-200 m from the telescope. While the pixels with relatively modest size of about 0.25\(^\circ\) provide an adequate quality of imaging of the air showers produced by TeV \( \gamma \)-rays, at low energies (\( E \leq 100 \text{ GeV} \)), especially for telescopes located at high mountain altitudes (\( \geq 3 \text{ km a.s.l.} \)), the pixel size should be close to 0.1\(^\circ\). A small pixel size is preferable also for lowering (at the given area of the optical reflector) the energy threshold, as well as for observations in the so-called regime of large zenith angles. The operation of IACTs in this regime can partially compensate the (typical) loss in \( \gamma \)-ray statistics at high energies by the significant increase of the collection area when the source is observed at large zenith angles (\( \geq 50^\circ \)). Presently, two IACTs equipped with finest pixelization (\( \sim 0.12^\circ \)) imaging cameras, one in the northern (CAT) and another in the southern (CANGAROO) hemispheres, can provide very effective study of \( \gamma \)-ray spectra of VHE sources beyond 10 TeV.

A remarkable feature of the atmospheric Cherenkov technique is the large integration area of air showers, \( A_{\text{eff}} \geq 3 \times 10^8 \text{ cm}^2 \), a consequence of the radius of the Cherenkov light pool \( R_C \geq 100 \text{ m} \). Since typically \( \gamma \)-ray fluxes rapidly increase at lower energies, the reduction of the energy threshold of Cherenkov telescopes would yield a significant gain in the detected \( \gamma \)-ray statistics. For comparison, the detection area of the GLAST at GeV energies is only \( \sim 0.8 \text{ m}^2 \). This implies that if the spectrum of a \( \gamma \)-ray source extends to
the VHE region, the rate of detection of $\gamma$-rays by a single 100 GeV threshold Cherenkov telescope would exceed the GLAST detection rate even for very steep spectra of $\gamma$-rays with a differential power-law index $\alpha \leq 3.3$. Since the spectra of many potential $\gamma$-ray sources are expected to be significantly flatter, this provides a principal basis for an astronomy rich by $\gamma$-ray photon statistics.

However, this goal cannot be achieved without effective methods of suppression of the heavy background produced by CR showers. Fortunately, the IACT technique does provide an adequate background rejection power $^{41,42}$. Indeed, a typical single imaging telescope can identify the electromagnetic showers produced by $\gamma$-rays from point sources with efficiency better than $99.7\%$. In particular, the Whipple 10 m imager, today’s most sensitive single telescope, provides $7\sigma$ detection of the Crab within only 1 h observation of the source. This implies that 100 h observations by this instrument could reveal point-like $\gamma$-ray sources above 250 GeV at the flux level of 0.07 Crab. This corresponds to the energy flux $f_E \sim 4 \times 10^{-12}$ erg/cm$^2$s, which sounds impressive even by standards of the satellite-based gamma ray astronomy (see Fig. 1). Significant improvement of the performance of this telescope is expected in 1998. After the replacement of the old camera by a new, very high resolution 541 pixel camera, the energy threshold will be lowered to $\sim 100$ GeV, and the flux sensitivity will be improved by a factor of three $^{43}$.

The ‘7-sigma-per-1 hour’ signal from the Crab, with the detection rate exceeding 100 $\gamma$/h, implies that any short outburst of a TeV source at the level exceeding the Crab flux can be discovered on timescales less than 30 minutes. This important feature of the IACT technique was convincingly demonstrated by the Whipple group when two dramatic flares from Mrk 421 were detected $^{44}$ in May 1996 (Fig. 3). During the first flare on May 7, lasted more than 2 hours, the $\gamma$-ray rate increased by a factor of 3, and reached the peak ten times the intensity of the Crab. The second flare on May 15 was less intensive, but remarkable for its brevity - it lasted only 30 minutes! Note that detection of an energy flux comparable with the flux of May 15th flare ($\sim 2 \times 10^{-10}$ erg/cm$^2$s), but at GeV energies by EGRET would require a duration of the $\gamma$-ray outburst of about several days.

Further qualitative improvement of the IACT technique in the next few years is likely to proceed in two general directions: (a) implementation of the so called stereoscopic approach, and (b) reduction of the energy threshold of detectors towards the sub-100 GeV domain.

3.2 Stereo Imaging

The concept of stereo imaging is based on the simultaneous detection of air showers in different projections by $\geq 2$ telescopes separated by the distance comparable with the radius of the Cherenkov light pool, $R_C \sim 100$ m. Compared to single telescopes, the stereoscopic approach allows unambiguous and precise reconstruction of the air shower parameters on the event-by-event basis. In particular the accuracy of reconstruction of the direction of individual $\gamma$-ray primaries can be as good as few arcminutes, which in the case of point-like sources already provides suppression of the CR background by a factor of 300 or more. A comparable reduction of CR contamination can be gained by exploiting the intrinsic differences between the electromagnetic and hadronic showers. Even though the images in different projections are not entirely independent of each other, the correlation is only
partial. Thus, in the case of point γ-ray sources the CR background could be suppressed by a factor of $\geq 10^5$. In addition, the stereo observations provide effective suppression of the background light of different origins (night sky backgrounds, local muons, etc.), that ultimately results in significant reduction of the energy threshold.

The recent observations of the Crab Nebula and Mrk 501 by the HEGRA stereoscopic system of 4 imaging telescopes located on Canary Island La Palma thoroughly confirm the early predictions for the performance of the instrument. Fig. 4a shows the angular distribution of showers detected from the direction of the Crab, and selected after the image ‘shape’ cuts. The confinement of the γ-ray signal from a point source in a very small region (with angular radius $\sim 0.1^\circ$) of the available two-dimensional phase space, in addition to the significant suppression of hadronic showers at the trigger level, results in a strong 4σ-per-1 h signal already before the gamma/hadron separation. The ‘shape’ cuts provide further, by a factor of 100, suppression of the hadronic background, while maintaining the efficiency of the acceptance of γ-ray events at the level of 50%. This leads to only $\sim 1$ background event in the ‘signal’ region while the rate of γ-rays from the Crab exceeds 20 events/1 h. This enables (1) an effective search for VHE γ-ray point sources with fluxes down 0.1 Crab at almost background free conditions, and thus drastic reduction of the observation time (by a factor of 10) compared to four independently operating telescopes, (2) detailed spectroscopy of strong (Crab-like) VHE emitters, (3) study of the spatial distribution of γ-ray production regions on arcminute scales, (4) effective search for extended sources with angular size up to $\sim 1^\circ$ at the flux level of 0.1 Crab. The exploitation of the ‘nominal’ 5-IACT HEGRA system with improved trigger condition should allow 5σ detection of faint γ-ray sources at the flux level of 0.025 Crab which corresponds to $\sim 10^{-12}$ erg/cm²/s energy flux above the effective energy threshold of the instrument of about 500 GeV (see Fig. 1).

The potential of the HEGRA stereoscopic system has been nicely demonstrated by the
measurements of the flux, spectrum, and variability of TeV γ-rays from Mrk 501 during the state of high activity of the source started in March 1997. The almost background free detection of γ-rays with a rate exceeding 100γ/h, coupled with energy resolution of the instrument ∼ 20%, allowed a study of the flux variation on time scales between 5 min to days [5] (Fig. 5), evaluation of the differential energy spectrum based, during the strong flares, only on few hours of observations [46] (Fig. 6), and location of the position of the source within the statistical error of 30 arcsec (Fig. 4b).

Figure 5: Detection rate of γ-rays from Mkr 501 by the HEGRA IACT system on a night-by-night basis, for the whole data set (left), and in 5 minute intervals for the last three nights (right) [5].

Figure 6: Differential energy spectra of Mkr 501 measured by the HEGRA IACT system [46] during the strong flare on April 13, and averaged over the whole March-April period shown in Fig.5.

The continuous monitoring of Mkr 501 from March until September 1997 by the CAT, HEGRA, and Telescope Array groups showed that the source was in very active state with variable flux exceeding in average the Crab flux by a factor of 2 or more. The long-term behavior obtained by the Telescope Array is presented in Fig. 7. It shows not only dramatic day by day variability, but also a possible ∼ 25 day (quasi) periodicity in the signal [47].

More than 30,000 (!) γ-rays up to 10 TeV and beyond have been detected by the HEGRA IACT system during several months of observations. This demonstrates the remarkable feature of the IACT technique as a tool providing an astronomy rich by photon statistics.
3.3 Future 100 GeV Class IACT Arrays

One of the important issues for future detectors is the choice of the energy domain based on two principal arguments: (a) the astrophysical significance (goals) and (b) the experimental feasibility/reliability (cost). If one limits the energy region to a relatively modest threshold around 100 GeV, the performance of IACT arrays and their practical implementation can be predicted with high confidence. In practice, an energy threshold of 100 GeV can be achieved by a stereoscopic system of IACTs consisting of optical reflectors with diameter $\sim 10$ m like the Whipple mirror and equipped with conventional PMT-based high resolution cameras like the cameras recently built by the CAT and HEGRA groups. After reaching the maximum possible suppression of the CR background by simultaneous detection of air showers in different projections – limited basically by intrinsic fluctuations in cascade development – the further improvement of the flux sensitivities for a given energy threshold can be achieved by the increase of $\gamma$-ray statistics, i.e. by increasing the shower collection area. For a single telescope the effective detection area is determined essentially by the radius of the Cherenkov light pool. However, the effective shower detection area of the multi-telescope systems is determined by the total geometrical area of the array which may be gathered from individually triggered groups of telescopes, IACT cells, with an optimum linear size of the cell $L \sim R_C \sim 100$ m. The design of the cell depends on the specific detection requirements. However, since the quality of reconstructed shower parameters continues to be improved noticeably up to three or four telescopes operating in coincidence, the optimum design of the cell seems to be a triangular or quadrangular arrangement of IACTs. The stereoscopic approach with its powerful suppression of CR background requires cameras with relatively modest, e.g. 0.25° pixel size, and thus allows allocation of the available channels for enlarging the FoV to $\geq 5^\circ$, in particular for effective sky surveys, as well as for the increase of the collection area up to 1 km$^2$. A possible design of multi-cell array of 100 GeV class IACTs is demonstrated in Fig. 8a. The range of expected energy flux sensitivities studied recently by comprehensive Monte Carlo simulations is shown in Fig. 1.

Perhaps the idea of ‘1 km$^2$’ array of telescopes sounds too ambitious, but it is not unrealistic. In fact, such an array, containing as many as 100 telescopes each with an aperture 3 m and a 1024 pixel camera, has been proposed already in 1992 by the Tokyo group, with a dual aim of (1) detecting highest energy CRs above $10^{18}$ eV and (2) observing TeV
$\gamma$-ray sources. Although the successful detection of the Crab Nebula and Mrk 501 by the prototype 5-telescope-array in Dugway (Utah) is very encouraging, for future purposes of gamma ray astronomy it perhaps would be important to reduce the energy threshold of the telescopes, e.g. by using larger optical reflectors.

Among a variety of competing projects, the design of the 100 GeV class IACT array is the most likely to obtain a qualitative improvement in performance at an affordable cost. Presently two projects of similar philosophy, VERITAS (Very Energetic Radiation Imaging Telescope Array System) array of nine 10m diameter telescopes in the USA (Arizona), and HESS (High Energy Stereoscopic System) array of sixteen 10m telescopes to be installed in Spain or Namibia, are intensively discussed as two major instruments of the ground-based gamma ray astronomy at the entrance into the next millennium.

3.4 Sub-100 GeV Ground-Based Detectors

The strong scientific motivations to fill the gap between the space-based and ground based observations recently stimulated several interesting proposals for extending the atmospheric Cherenkov technique to sub-100 GeV region. Perhaps this ambitious goal could be best addressed by the same (above described) stereoscopic systems of IACTs but with the telescopes aperture $S_{\text{ph.e.}} = S_{\text{mir}} \chi_{\text{ph-e}} \geq 50 \text{m}^2$, where $S_{\text{mir}}$ is the mirror area and $\chi_{\text{ph-e}}$ is the photon-to-electron conversion factor (quantum efficiency) of the optical detectors. With development of the technology of novel, fast optical radiation detectors of high quantum efficiency ($\chi_{\text{ph-e}} \geq 50\%$) and design of (relatively inexpensive) 20 m class reflectors with adequate optical quality for the Cherenkov imaging on scales of several arcminutes, it would be possible to reduce the detection threshold down to 20 GeV, or even 10 GeV for an IACT system installed at high mountain elevations (e.g. 3.5 km a.s.l). Considerable R&D efforts, especially by the Munich group, are already started in both directions. If successful, this activity will result in construction of a large single reflector telescope (MAGIC) which, together with two ongoing projects of low energy threshold Cherenkov telescopes based on large mirror assemblies of the existing solar power plants in the USA (STACEE) and France (CELESTE), will start to explore the energy region between 20 and 100 GeV. Moreover, the MAGIC telescope could be considered as a prototype for the basic element in future (post ‘VERITAS/HESS’) arrays of 10 GeV class IACTs. Few MAGIC-type telescopes being combined in the stereoscopic system could not only intervene the domain of satellite-based gamma ray astronomy, but also could provide very large detection areas at higher energies, especially when observing $\gamma$-ray sources at large zenith angles. If high efficiency of this technique, that already has been demonstrated by the CANGAROO group at multi-TeV energies, could be extrapolated to the 0.1-1 TeV region, the use of an array consisting of few 10 GeV class IACT systems (with 3 or 4 telescopes in each) could cover very broad energy range extending from 10 GeV to 10 TeV.

A possible arrangement, operation modes, and predicted performance of an array of 10 GeV class telescopes are described in Fig. 8b. The expected range of the energy flux sensitivities of such arrays is shown in Fig. 1.
FUTURE GROUND-BASED GAMMA RAY DETECTORS

\[ f_E \sim 10^{-13}\text{erg/cm}^2\text{s} \]

\( E \sim 10^{-20}\text{GeV} \)

\( \sigma_0 \sim 0.3^\circ \text{ @ 10 GeV} \)

\( A \sim 1\text{ km}^2 \text{ @ 100 GeV} \)

\( f_E \sim 10^{-7}\text{erg/cm}^2\text{s} \text{ @ 1 TeV} \)

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4 VHE Gamma Rays – Carriers of Unique Astrophysical Information

With future systems of atmospheric Cherenkov telescopes, ground-based gamma ray astronomy will enter a new era with an ambitious aim of deep study of the \( \gamma \)-ray sky in broad energy region that extends from 10 GeV to \( \geq 10 \text{ TeV} \). In particular,

- Very large arrays of stereoscopic IACTs will be able to probe, typically during several weeks of observations, the potential VHE emitters of \( \gamma \)-rays at an energy flux \( f_E = E^2 dJ/dE \sim 10^{-13}\text{erg/cm}^2\text{s} \), i.e. by about three orders of magnitude lower than the sensitivities achieved at MeV and GeV energies by the current satellite-borne instruments. This allows study of different VHE source populations with apparent \( (4\pi) \) luminosities.

\( a \) The energy flux characterizes the relative release of the power (luminosity) of a source at different wavelengths (for an isotropically emitting source at a distance \( d \), \( L = 4\pi d^2 f_E \)). Therefore \( f_E \) is a meaningful and objective parameter, when comparing the sensitivities of instruments operating in different energy domains.
\( L_{\text{VHE}} \geq 10^{37} (d/1\text{Mpc})^2 \text{erg/s} \) – a very impressive achievement even by the standards of the classical branches of astronomy.

- The high sensitivity of multi-IACT arrays partially compensates the inefficiency of the technique regarding all-sky surveys. In particular, during a 1-year survey it will be possible to cover more than 1 steradian of the sky at the source detection threshold \( f_E \leq 0.1 \text{ Crab} \) (\( f_E \leq 10^{-11} \text{erg/cm}^2\text{s} \)).

- The multi-IACT arrays are very effective instruments for the search for highly sporadic nonthermal phenomena from different celestial objects which may appear below the detection threshold of satellite-borne instruments at MeV and GeV energies. In particular, the minimum detectable fluence \( \leq 10^{-8} \text{erg/cm}^2 \) of a burst lasting \( \leq 1 \text{ h} \) would allow detection of possible VHE counterparts of GRBs if even only a small part of the total energy of the event is released in \( \geq 100 \text{ GeV} \) photons.

- The IACT arrays provide the best angular resolution in gamma-ray astronomy from MeV to ultra-high energies, \( \delta \theta \leq 0.1^\circ \), and reasonable spectroscopic measurements with energy resolution \( \Delta E/E \leq 20\% \).

The expected performance of detectors as well as the recent theoretical/phenomenological predictions supply a strong rationale for the systematic study of primary \( \gamma \)-radiation in the VHE domain. Such efforts will provide crucial insight into the understanding of ultrarelativistic processes in astrophysical settings, on both galactic and extragalactic scales.

### 4.1 Origin of Galactic Cosmic Rays

**Shell-type SNRs.** Historically the first interest in gamma ray astronomy arose in connection with general idea on the crucial role of \( \gamma \)-ray observations in solving the problem of origin of cosmic rays (see e.g. [59, 60] and references therein). The future IACT arrays, with their excellent flux sensitivity and angular resolution, should finally address this fundamental issue. Of primary concern is the decisive test of the hypothesis that the SNRs are responsible for the bulk of observed CRs up to \( 10^{14} \text{eV} \). Conservative phenomenological estimates, as well as recent detailed calculations show that in the framework of diffusive shock acceleration many shell-type SNRs could be visible in VHE photons. Since the spectrum of the shock-accelerated particles is believed to be hard, \( \text{d}N/\text{d}E \propto E^{-\alpha} \) with \( \alpha \sim 2 \), the flux of VHE \( \gamma \)-rays, produced in a SNR at a distance \( d \) due to interactions of accelerated protons with the ambient gas of density \( n \), is easily estimated as \( J(>E) \approx 10^{-11} (E/1\text{ TeV})^{-1} (W_{\text{CR}}/10^{50} \text{erg})(n/1\text{ cm}^{-3})(d/1\text{kpc})^{-2} \text{ph/cm}^2\text{s} \), where \( W_{\text{CR}} \) is the total energy in accelerated CRs. The peak luminosity of \( \gamma \)-rays typically appears at the so-called late sweep-up phase, i.e. \( 10^3 - 10^4 \) years after the SN explosion, when the radius of SNRs exceeds several parsecs. This results in a typical angular size of relatively close \( (d \leq 1 \text{kpc}) \) SNRs of about \( 1^\circ \). Although the conflict between the angular size \( (\phi \propto 1/d) \) and the \( \gamma \)-ray flux \( (J \propto d^{-2}) \) significantly limits the number of SNRs detectable in \( \gamma \)-rays, the flux sensitivities of future IACT arrays are quite sufficient for detection of VHE \( \gamma \)-ray signals from SNRs if \( (n/1\text{ cm}^{-3})(d/1\text{kpc})^{-2} \geq 0.1 \) (see Fig. 9a).

\[ \text{Note, however, that presently some interesting ideas are circulating about the design of an imaging `All Sky Monitor’ telescope at VHE energies with FoV of about one steradian (T.Kifune, private communication).} \]
Figure 9: $\pi^0$-decay and inverse Compton $\gamma$-ray fluxes. 

**a (left):** The predicted $\gamma$-ray fluxes from a SNR located at $d = 1$ kpc. The $\pi^0$-decay $\gamma$-ray fluxes are normalized to the total energy in accelerated protons $W_{CR} = 10^{50}$ erg, and density of the ambient gas $n = 1$ cm$^{-3}$. The IC $\gamma$-ray fluxes are normalized to the synchrotron X-ray flux at 1 keV $S_{1\text{keV}} = 10 \mu$Jy for ambient magnetic fields $3 \mu$G and $20 \mu$G. Both the electron and proton acceleration spectra are taken in the form $\propto E^{-2} \exp(-E/100 \text{ TeV})$. The hatched region shows the IACT flux sensitivity corresponding to sources with angular size $\lesssim 0.1^\circ$ (lower boundary) to $\sim 1^\circ$ (upper boundary) during observation time $t_0$ by an array consisting of $n_0$ IACT cells; $n_0 \cdot t_0 = 100$ h.

**b (right):** Diffuse fluxes of $\gamma$-rays from the direction of the galactic center for galactic latitudes $|b| < 10^\circ$.

When extracting information about the shock accelerated protons, one has to subtract a possible non-negligible contribution to the $\gamma$-ray fluxes from directly accelerated electrons which upscatter the photons of 2.7 K background radiation to $\gamma$-ray energies. Typically the contribution of IC $\gamma$-rays is below of the fluxes of $\pi^0$-decay photons (except for the SNRs with low gas density, $n \leq 1$ cm$^{-3}$ and/or very low magnetic field, $B \sim B_{\text{ISM}} \sim 5 \mu$G) if one takes into account that the nonthermal synchrotron X-ray fluxes from most of shell type SNRs do not exceed $S_{1\text{keV}} = 10 \mu$Jy ($f_x \approx 2.5 \times 10^{-11}$ erg/cm$^2$s) (see Fig. 9a).

Recent discovery of nonthermal X-rays from SN1006\cite{1006}, which (almost unambiguously) implies the existence of electrons of energies $\geq 10$ TeV, motivated optimistic predictions about detectable VHE $\gamma$-ray fluxes of IC origin from this shell-type SNR\cite{1006}. Indeed, this object recently has been claimed to be seen in TeV $\gamma$-rays\cite{1006}, the estimated $\gamma$-ray flux being in a reasonable agreement with the theoretical calculations. Nevertheless, it is perhaps premature to draw final conclusion on the IC origin of the observed TeV radiation. In order to match the synchrotron X-ray and IC $\gamma$-ray fluxes, the magnetic field in the shell should not exceed $10 \mu$G. This is a rather bold requirement, being, for example, by a factor of 10 less than the value estimated from the condition of equipartition between the magnetic field and relativistic electron pressures. Obviously, the IC models of $\gamma$-radiation of SN1006 need independent arguments in favor of such small B-field in this young SNR. Otherwise, the remaining possibility could be $\pi^0$-decay origin (!) of detected TeV radiation.

Detection of $\pi^0$-decay $\gamma$-rays from SNRs would be the first straightforward proof of the shock acceleration of CR protons and nuclei in these objects. On the other hand, a failure to detect $\pi^0$-decay $\gamma$-ray signals from several selected SNRs would impose constraint on the energy in accelerated protons $W_{CR} \leq 10^{49}$ erg. Contrary to current belief, this would
indicate the inability of the ensemble of galactic SNRs to explain the observed CR fluxes.

Finally, another interesting possibility should be mentioned in the general context of visibility of SNRs in VHE \( \gamma \)-rays. In the case of explosion of a massive star as a supernova, the \( \gamma \)-ray luminosity could be extremely high during several months or more after the explosion due to (1) very effective particle acceleration at the shock front and (2) existence of relatively dense confining medium. In particular, \( \gamma \)-ray fluxes as high as \( 10^{-12} \) ph/cm\(^2\)/s above 1 TeV have been predicted for very powerful radio supernova SN1993J situated in the galaxy M81 at a distance \( d \approx 3.6 \) Mpc. If so, the future IACT arrays with their potential to find faint \( \gamma \)-ray sources with luminosities as low as \( L_{\text{VHE}} \sim 10^{37} \) (\( d/1 \) Mpc\(^2\)) erg/s, should be able to detect positive VHE \( \gamma \)-ray signals from recent extragalactic SNRs within the local group of galaxies at the early stages (\( \leq 1 \) yr) of their explosion.

GMCs as tracers of galactic cosmic ray accelerators. SNRs are still only one of the possible CR accelerators, and it is quite possible that different other classes of CR sources contribute comparable fractions to the observed CR flux. Thus, only direct identification of these sources as particle accelerators through their characteristic \( \gamma \)-ray emission can help to elucidate the origin of galactic CRs. The existence of an accelerator is by itself not enough for effective \( \gamma \)-ray production; one needs the second component, a target. The so-called giant molecular clouds (GMCs), with \( 10^4 \) to \( 10^6 \) solar masses, seem to be ideal objects to play that role. These objects are genetically connected with active star formation regions – the most probable settings (with or without SNRs) of CR production. At certain epochs, depending on the distance from the accelerator with total CR energy \( W_{\text{CR}} \geq 10^{49} \) erg, many clouds may become detectable in VHE \( \gamma \)-rays. Therefore, surveys of the galactic plane, that search for GMCs irradiated by CRs arriving from young, nearby accelerators may provide unique information about CR sources and their distribution in the Galaxy. Another interesting issue would be detection of diffuse \( \pi^0 \)-decay \( \gamma \)-radiation of the galactic disk formed due to superposition of contributions of faint (individually invisible) GMCs.

Diffuse galactic gamma ray background. The EGRET measurements of the diffuse background in the direction of the inner Galaxy show an excess in the GeV \( \gamma \)-ray flux, compared with the predictions (curve 1 in Fig. 9b) based on the assumption that the average spectrum of CRs in the Galaxy is represented by the locally measured CR spectrum. This effect formally can be explained by assuming harder (e.g. \( \propto E^{-2.5} \)) proton spectra in the regions where the bulk production of \( \gamma \)-rays takes place (curve 2 in Fig. 9b). Actually such assumption could be well justified by speculating that the main part of the observed diffuse \( \gamma \)-ray background is produced selectively, i.e. it is a result of radiation originating in regions which contain particle accelerators and massive gas clouds. Indeed, if \( \gamma \)-rays are produced at the interaction of a cloud with relatively fresh (recently accelerated) particles with hard spectra which have not yet suffered strong modulation (steepening) due to the propagation effects of CRs in the interstellar medium, the resulting \( \gamma \)-ray spectra could be significantly harder that the typical \( \gamma \)-ray spectra produced by the ‘sea’ of galactic CRs.

The excess above a few GeV in the diffuse galactic spectrum can be explained also by the IC photons. Note that this hypothesis requires very strong (by a factor of 10) enhancement of the average flux of \( \geq 100 \) GeV electrons in the galactic disk compared with the measured
Figure 10: Characteristic phase-averaged spectrum for a young γ-ray pulsar. Solid lines show the curvature (CR), synchrotron (Sy), and the thermal surface flux (kT). The dashed curve (CS) gives the TeV pulsed spectrum from Compton upscattering of the synchrotron spectrum on the primary e± [73].

flux of VHE electrons. However, formally it cannot be ruled out if one takes into account that the directly detected electrons of such high energies are produced within the nearest 100 pc region, and therefore do not carry information about the electron fluxes on the galactic (kpc) scales. This possibility is demonstrated in Fig. 9b where the IC γ-ray flux calculated for the locally observed electron spectrum (curve 3) is shown together with the IC flux calculated for some hypothetical spectrum of galactic electrons (curve 4) assumed in order to match the measured γ-ray fluxes at GeV energies.

While the predictions of diffuse galactic fluxes are still below the upper limits set both at TeV and PeV energies, the new stereoscopic IACT systems should be able, however, to probe the predicted range of diffuse π0-decay and IC γ-ray fluxes shown in Fig. 9b.

PULSARS AND PLERIONS. Presently six radiopulsars are firmly established by EGRET as GeV γ-ray emitters. Modulation of γ-ray light curves at the periods of rotation of these objects indicates that γ-rays are produced near the surface of neutron stars due to nonthermal cascade processes supported by curvature radiation, inverse Compton scattering and synchrotron radiation of accelerated electrons either at the polar cap or in the vacuum gaps at the outer magnetosphere (for review see e.g. [72]). Irrespective of details of the models, it is likely that flat GeV γ-ray spectra should significantly steepen at higher energies due to attenuation caused by pair production in the pulsar magnetic field. The position of the spectral turnover depends essentially on the localization of the γ-ray production region(s). Thus, the spectrometric measurements at energies above 10 GeV may provide a crucial test for different scenarios of particle acceleration in the pulsar magnetospheres. Since the fluxes of the EGRET pulsars at several GeV exceed 10\(^{-8}\) ph/cm\(^2\)/s, the future low-threshold ground based detectors, with predicted flux sensitivity \(\sim 10^{-10}\) ph/cm\(^2\)/s at energies between 10 - 30 GeV, will be able to provide such important information.

The search for TeV γ-rays from pulsars was started many years ago, but despite several claims of possible detections of pulsed TeV radiation, in particular from the Crab and Geminga pulsars, observations with more sensitive imaging telescopes failed to confirm these
early results. This is in agreement with the models which predict cutoffs of the radiation beyond 10 GeV (see Fig. 10). Meanwhile the recent developments of pulsar models predict the existence of a new component of $\gamma$-radiation produced due to the inverse Compton mechanism in the outer magnetosphere. An interesting feature of this radiation is its hard spectrum below 1 TeV, with sharp cutoff above $\sim 3$ TeV. Thus, the most promising energy region for detection of this component seems to be a rather narrow interval around 1 TeV. The pulsed TeV flux contains somewhat less than 1% of the pulsed GeV flux, and therefore some pulsars (like Vela and Geminga) could be considered as promising targets for future air Cherenkov experiments.

Besides the pulsed radiation produced in the pulsar magnetospheres, one may expect $\gamma$-rays from more extended regions - pulsar driven nebulae (plerions). Relativistic electrons accelerated by the pulsar wind termination shock up to energies $\geq 10 \text{ TeV}$ interacting with nebular magnetic and photon fields produce bright synchrotron and IC $\gamma$-ray emission. The Crab Nebula is the most powerful representative of this source population with nonthermal emission observed over 21 decades of frequency from $10^7$ to $10^{28}$ Hz. Due to the large magnetic field of the Crab Nebula, $B \geq 10^{-4}$ G, only $\sim 0.1\%$ of the energy of electrons is converted to IC $\gamma$-rays, the rest being radiated in the form of radio to X-ray synchrotron photons. The low efficiency of $\gamma$-ray emission of the Crab is compensated by the extremely high rate injection rate ($\sim 5 \cdot 10^{38} \text{ erg/s}$) of relativistic electrons by the pulsar into the nebula. This is the only reason why we see the Crab Nebula as bright TeV $\gamma$-ray emitter. The magnetic fields in other plerions are likely to be one or two orders of magnitude smaller, which makes these objects more effective $\gamma$-ray emitters, since the radiative energy loss of electrons is shared almost equally between the synchrotron and IC channels ($f_\gamma/f_\alpha = w_{\text{MBR}}/w_B \simeq 1 (B/3 \mu \text{G})^{-2}$). Note that since the IC cooling time of electrons $t_\text{IC} \propto 1/E$, this process works most effectively in the VHE domain. This raises the hope that, with forthcoming 100 GeV class IACT arrays with energy flux sensitivity of about $10^{-13} \text{ erg/cm}^2\text{s}$, IC $\gamma$-radiation will be observed from many plerions even though the pulsar spin-down luminosities of these objects does not exceed a few percent of the power of the Crab pulsar. In this context, the synchrotron X-ray nebulae recently discovered by the ASCA and ROSAT satellites around many radiopulsars at the flux level $f_\alpha \geq 10^{-12} \text{ erg/cm}^2\text{s}$ seem to be very attractive targets for VHE $\gamma$-ray observations. Detection of unpulsed TeV radiation by the CANGAROO group from the direction of Vela and PSR 1706-44 is likely to confirm this optimistic view.

4.2 Extragalactic Sources of VHE gamma Rays

ACTIVE GALACTIC NUCLEI. The discovery of $\geq 50$ $\gamma$-ray emitting AGNs by EGRET demonstrates that high energy $\gamma$-radiation above 100 MeV is a common feature of blazars – BL Lac objects, radio loud AGNs, and optically violent variable (OVV) quasars. The huge apparent $\gamma$-ray luminosities and rapid variability of the EGRET AGNs favor a strongly anisotropic character of high energy radiation which may be naturally attributed to the relativistic bulk motion of the jets, ejected from the central compact source, and directed almost along the observer’s line of sight. Also, the anisotropic character of $\gamma$-radiation seems to be the only way to avoid internal photon-photon absorption, as well as to reduce the
energy requirements to the central engines to a level which could be explained by accreting massive black holes – most likely powerhouses of AGNs. Even so, attenuation of $\gamma$-rays inside of distant (and typically most luminous) AGNs with redshift $z \geq 1$ is unavoidable well above 10 GeV. In addition, VHE radiation above 100 GeV emitted from cosmologically distant sources is absorbed in the intergalactic space. This determines the importance of sub-100 GeV ground-based detectors for the study of relativistic processes in distant AGNs.

Many famous extragalactic sources representing different AGN populations, and located within $\approx 10^3$ Mpc, can be considered as first priority targets for observations above 100 GeV. First of all this concerns the BL Lac objects, two representatives of which, Mrk 421 and Mrk 501, are already established as TeV emitters. Different mechanisms have been suggested for $\gamma$-ray production in AGN jets, attributed to both hadronic and electronic interactions. The variability of Mrk 421 and Mrk 501 on timescale $\sim 1$ day or less ($\Delta t_{\text{obs}} \sim 15$ min (!) during the flare of Mrk 421 on May 15; see Fig. 3) support the electronic models which assume that the $\gamma$-rays are produced due to interactions of electrons, accelerated in the jet, with the ambient photon fields. For characteristic jet parameters only the IC mechanism seems to be able to provide radiative cooling time shorter than the observed duration of the flares (in the jet frame $\Delta t' = \delta_j \cdot \Delta t_{\text{obs}}$). Meanwhile, a possibility for the hadronic models still remains within the scenario of “moving target crosses beam” (suggested originally for X-ray binaries in much smaller (galactic) scales), assuming that the episodic behavior of TeV radiation is due to the fast moving gas clouds crossing the jet and/or destruction (evaporation) of the targets under the powerful jet.

The discovery by ASCA and Whipple of correlated flares of Mrk 421 in keV and TeV energy bands, as well as the recent multiwavelength observations of Mrk 501 in April 1997, indicate that both components originate in a relativistic jet, with Doppler factor $\delta_j \geq 10$, due to synchrotron and IC radiation of the same population of electrons. Remarkably, since the IC cooling time $t_C = -E_e/(dE_e/dt) \propto E_e^{-1}$, and the Compton scattering boosts the ambient photons of energy $\epsilon_0$ to $E_\gamma \approx \epsilon_0 \cdot (E_e/m_e c^2)^2$, the characteristic time of $\gamma$-ray emission decreases with energy as $\propto E_\gamma^{-1/2}$. This may naturally
explain less dramatic variation of GeV γ-ray fluxes during the keV/TeV flares; the relatively low energy electrons responsible for GeV radiation (as well as for synchrotron optical/UV photons) cannot promptly respond to changes of physical conditions in the jets. Very hard spectra of IC radiation below 100 GeV explain also the low flux of GeV γ-rays from Mkr 421, and their absence at all in the case of Mrk 501.

Although there could be several external sources of seed photons contributing to the IC processes in AGN jets [89], the recent theoretical studies [83,84] show that in Mrk 421 and Mrk 501 the synchrotron photons play a dominant role in production of IC VHE γ-rays (the so-called synchrotron-self-Compton (SSC) model). This reduces the number of model parameters, and allows for conclusive predictions about the broadband spectral and temporal characteristics of radiation. In practice, this implies that the VHE radiation, being combined with X-ray observations, is likely to be the most important window in the electromagnetic spectrum informing us about nonthermal processes in the BL Lac objects. This is demonstrated in Fig. 12 where the almost simultaneous spectral measurements of Mrk 501 flares in April 1997 by the BeppoSAX satellite (over the range 1-200 keV) and by Whipple and HEGRA telescopes (at TeV energies) are presented together with the theoretical spectra calculated in the framework of homogeneous SSC model [84].

VHE emission could be expected from many other BL Lac objects. The sensitivity of future IACT arrays $f_\delta \sim 10^{-13}$ erg/cm$^2$s implies that all blazars emitting γ-rays at $E' \geq 10$ GeV (in the frame of the jet) should be detected at energies $E \geq 100\delta_{10}$ GeV ($\delta_{10} = \delta_j/10$) if the intrinsic γ-ray luminosity of the source exceeds $L' = 4\pi d^2 f_\delta/\delta_j^4 \simeq 2 \cdot 10^{38} (z/0.1)^2 \delta_{10}^{-4}$ erg/s - a rather small amount of energy compared with the total energy budget (bolometric luminosity) of these most powerful objects in the Universe !

Note however that, due to highly sporadic behavior of these objects, the γ-ray emission may become visible only in short time episodes. Therefore detection of VHE outbursts from these objects with the small FoV Cherenkov telescopes require well justified search strategies. As an effective guide in such studies could be immediate information about the X-ray activity obtained on the daily basis by the all-sky X-ray monitors like ASM detector on RXTE satellite (R.Remillard, private communication).
SOURCES OF HIGHEST ENERGY COSMIC RAYS. There is little doubt that the highest energy particles observed in CRs up to \( E \geq 10^{20} \) eV are produced outside of the Galaxy. Powerful nonthermal objects like radiogalaxies, AGNs, and clusters of galaxies, as well as more exotic objects, e.g. enigmatic \( \gamma \)-ray burst sources, are all suggested as possible sites of acceleration of these particles. In many cases, these objects may contain sufficient target material in the form of gas and photon fields to convert the energy of the parent particles into detectable VHE radiation. A special interest may present the clusters of galaxies, since the \( \gamma \)-rays produced at interactions of relativistic protons with the ambient intracluster gas carry important information about the ‘cosmological’ cosmic rays. The efficiency of production of \( \pi^0 \)-decay \( \gamma \)-rays, due to the low density of the ambient gas in these objects \( n \sim 10^{-5} - 10^{-4} \) cm\(^{-3}\), is not high. However, the enormous energy in the relativistic protons, accumulated over the life time of the Universe, \( t = 1/H_0 \sim 10^{10} \) yr, in the rich clusters of galaxies could be as high as \( 10^{62} - 10^{63} \) erg, leading to fluxes which, in principle, could be marginally detected by 100 GeV threshold IACT arrays.

More effective could be production of \( \gamma \)-rays due to interactions of protons with the ambient photon fields, provided that the spectrum of accelerated particles extends beyond \( 10^{20} \) eV. Even if these particles do not spend much time in their production region, but quickly leave the source, they unavoidably collide with photons of 2.7 K MBR at relatively small (on the cosmological scale) distances from the source (see Fig. 2). The secondary electrons and photons – the products of photo-meson reactions – initiate pair cascades in the 2.7 K MBR, leading eventually to a flat standard (\( dJ/dE \propto E^{-1.5} \)) \( \gamma \)-ray spectra extending up to energy 100 TeV. However, due to the further interaction with the extragalactic infrared/optical photon fields, this radiation arrives to the observer with a cutoff at much lower energies, \( E_{\text{cut}} \leq 10 \) TeV (see Fig. 2). Since the flux of \( \gamma \)-rays below \( E_{\text{cut}} \) is determined essentially by the cascade processes, it is possible to give a model-independent estimate of expected VHE fluxes: \( J(\geq 100 \text{GeV}) \sim 10^{-12} \left(W_\text{p}/10^{60} \text{erg}\right) \left(d/1000 \text{Mpc}\right)^{-2} \text{ph/cm}^2\text{s} \), emitted within the angle \( \theta \sim l/d \) from an extended region surrounding the source of \( E \geq 10^{20} \) eV protons with total energy \( W_\text{p} \). The linear size of the region \( l \) emitting \( \gamma \)-rays is limited by the attenuation length of rectilinearly propagating \( \geq 10^{20} \) eV protons in the 2.7 K MBR, \( l \sim \lambda_{\text{pr}} \leq 100(1 + z)^{-3} \) Mpc. Thus, the angular size of the source does not significantly exceed 1°, provided that the source is located at \( d \geq 1000 \) Mpc. In fact, the \( \gamma \)-ray production region could be significantly smaller due to non-rectilinear propagation of protons in strong magnetic fields, which may exist in the several Mpc proximity of extragalactic sources. Since the nonthermal energy of many powerful extragalactic sources, like radiogalaxy Cygnus A, could significantly exceed \( 10^{60} \) erg, we may conclude that 100 GeV threshold IACT arrays could be able to provide search for potential accelerators of highest energy CRs up to distances \( d \leq 1000 \) Mpc.

GAMMA RAY BURSTS. The \( \gamma \)-ray bursts (GRBs) - accidental events of impulsive radiation of soft (tens to several hundred keV) \( \gamma \)-rays with duration from about \( 10^{-2} \) s to \( 10^{3} \) s - represent an isotropically distributed source population of transient astrophysical objects of unknown origin. One of the key aspects of this phenomenon – the distance scale to the sources (“galactic or cosmological ?”) – which since its discovery in 1973 was a topic of intense theoretical speculations, finally seems to have been settled. After recent localization by BeppoSAX the
coordinates of 2 GRB events on Feb 28 and May 8 (1997) within a few arcminutes, afterglows in X-ray, optical, and radio bands were discovered. The observed redshifted optical (absorption) lines with $z \geq 0.7$ is a strong evidence that the GRBs have cosmological origin, and are located at the edge of the Universe (see e.g. [98] and references therein), which implies enormous energy, most probably in the nonthermal form, released on very short timescales.

This poses a challenge for explanation of the production and escape of $\gamma$-rays from very compact regions, especially if one takes into account that high energy $\gamma$-radiation above 100 MeV detected by EGRET from several GRBs, may be common for all bursts. Actually, within the framework of the most popular cosmological models of GRBs which assume that the radiation is produced (independent of the nature of the energy source) in the so-called relativistic fireballs, the $\gamma$-ray production spectrum could extend beyond 100 GeV. But this still does not imply VHE visibility of GRBs due to the internal $\gamma$-$\gamma$ absorption. The problem of self-opacueness of the source can be effectively overcome as assuming bulk motion with Lorentz factor $\Gamma \gg 1$, which actually is the case of the relativistic fireballs. However, in cosmologically distant GRBs even extremely large Lorentz factors, $\Gamma \geq 1000$, cannot prevent significant absorption of VHE $\gamma$-rays (Fig. 13). Moreover, further strong attenuation of VHE $\gamma$-rays takes place also in the intergalactic space. Whether or not the spectra of GRBs continue to the VHE region is a question which remains one of the interesting issues for ground-based $\gamma$-ray observations. Irrespective of uncertainties of model parameters, the fact of delayed high energy $\gamma$-ray emission, including a 18 GeV photon detected by EGRET after 1.5 h of the famous February 17 event GRB940217 seems to be a warrant for a success provided that the the energy threshold of detectors would be reduced down to 20 GeV. Hopefully, the minimum detectable fluence of low-threshold Cherenkov detectors estimated for a burst with duration $\Delta t$ as $S(\geq 20 \text{ GeV}) \sim 10^{-9}(\Delta t/1 \text{ s})^{1/2} \text{erg/cm}^2$ would allow detection of high energy tails of many GRBs.

### 5 Observational Cosmology with VHE Gamma Rays

The extension of the spectra of extragalactic sources to beyond 100 GeV opens a new exciting aspect of ground-based gamma ray astronomy - *observational cosmology*. The promise here is connected with *energy-dependent* interaction of VHE $\gamma$-rays with the diffuse extragalactic background radiation (DEBRA). The absorption features in the spectra of
extragalactic sources\cite{103,105,106}, as well as secondary pair cascade radiation\cite{07,108,110} contain unique cosmological information about the intergalactic photon and magnetic fields.

PHOTON-PHOTON ABSORPTION FEATURES. An observer looking within a narrow cone centered on the source at a distance $d = cz/H_0$ will see an absorbed spectrum $J(E) = J_0(E) \exp(-\tau)$, where $J_0(E)$ is the initial $\gamma$-ray spectrum, and $\tau(E, z)$ is the optical depth to $\gamma-\gamma$ pair production on isotropically distributed photons of DEBRA. Except for the 2.7 K MBR our knowledge of density of the DEBRA today and its evolution in time, $u_\epsilon = c^2 n(\epsilon, z)$, is rather limited. This results in large uncertainties in the optical depths (see Fig. 2 and Fig. 14). Therefore the study of the VHE $\gamma$-ray spectra from extragalactic objects may provide important information about $u_\epsilon$ at different cosmological epochs. Indeed, no deviation of the observed spectrum from the intrinsic (source) spectrum at energy $E$, e.g. by a factor of $\leq 2$ implies $\tau(E) \leq \ln 2$. For a low-redshift source ($z \ll 1$) this gives (with accuracy $\leq 50\%$ connected with the uncertainty of the spectral shape of the DEBRA) an upper limit on the current density of DEBRA at $\epsilon \approx 1$ ($E/1\,\text{TeV})^{-1}$ eV: $u_\epsilon < 3.5 \cdot 10^{-3} (z/0.1)^{-1} (E/1\,\text{TeV})^{-1} (H_0/100\,\text{km/s/Mpc})\,\text{eV/cm}^3$.

Now, if one interprets the lack of an obvious cutoff in the measured $\gamma$-ray spectra of both Mrk 421 and Mrk 501 ($z \approx 0.03$) up to $10\,\text{TeV}$ as an indication for a negligible absorption of $\gamma$-rays in the DEBRA, and assuming for the Hubble constant the maximum possible value $H_0 = 100\,\text{km/s/Mpc}$, a conservative upper limit on $u_\epsilon$ could be derived from this simple, but model independent estimate: $u_\epsilon \leq 1.1 \times 10^{-3} \text{eV/cm}^3$. The recent detailed theoretical studies of the problem\cite{109,110}, based, in particular, on realistic assumptions about the spectral shape of the DEBRA, give similar results. One of the interesting consequences of such a strong upper limit on the infrared background could be an argument in favor of absence of strong evolution of galaxies beyond $z = 3$ (see Fig. 14).

Formally, this upper limit can be extrapolated to shorter wavelengths by assuming a priori power-law spectrum of DEBRA with differential index $> 2$ (e.g. [111]), and thus to get more “valuable” (restrictive) information about the DEBRA. But given the strong energy-dependence of the pair production cross-section, this hardly can be justified. The model-independent constraint, for example at $3\,\text{eV}$, could be derived only from the lack of absorption feature at $E \sim 300\,\text{GeV}$. In the case of Mrk 421 and Mrk 501 this implies a rather high upper limit $u_\epsilon \leq 4 \times 10^{-2} \text{eV/cm}^3$. Deeper probe of the DEBRA at optical wavelengths is contingent only on the discovery of distant ($z \geq 0.1$) VHE sources.

Obviously these interesting possibilities can be successfully utilized only in the case of proper spectroscopic $\gamma$-ray measurements, as well as good understanding of the intrinsic source spectra. The last condition seems to be crucial, especially since the cutoff in a $\gamma$-ray spectrum does not yet unambiguously imply an evidence for the intergalactic absorption, and vice versa, the lack of the cutoff still does not automatically imply an absence of intergalactic absorption. Interestingly, some DEBRA models predict a modulation, rather than cutoff, in the energy spectra of nearby AGNs ($d \sim 100\,\text{Mpc}$), at least up to $10\,\text{TeV}$. Such modulation makes steeper the primary spectrum, but still keeps it in the (quasi) power-law form (see Fig. 14). From this point of view the above stated upper limit on the DEBRA based on the observed power-law spectra of Mrk 421 and Mrk 501 up to $10\,\text{TeV}$ should be taken as rather circumstantial estimate. Note that in the case of realization of the
Figure 14: Optical depth $\tau(E, z)$ (left) and the spectrum attenuation factor $J(E)/J_0(E) = \exp(-\tau)$ (right) versus the energy for $\gamma$-rays emitted by close (Mrk 421), moderately distant (3C 273), and very distant (PKS 0528+134) EGRET AGNs for different cosmological scenarios of formation and evolution of DEBRA [37]. The solid line corresponds to the models of early ($z_{\text{form}} \sim 5$) formation of galaxies and stars in the Universe; the short dashed line and dotted line show the case of late ($z_{\text{form}} \sim 1$) and intermediate ($1 \leq z_{\text{form}} \leq 3$) stages of galaxy formation which roughly correspond to so-called Hot-Cold Dark Matter and Cold Dark Matter cosmological scenarios [106]; the long dashed curve corresponds to the DEBRA density today, taken in the form $n(\epsilon) = 10^{-3}\epsilon^{-2}\text{ph/cm}^3\text{eV}$, with a naive assumption about the evolution of DEBRA back in redshifts as $n(\epsilon) \propto (1 + z)^3$.

SSC models which assume a common population of parent electrons producing synchrotron X-rays and IC $\gamma$-rays, the simultaneous keV and TeV observations of AGNs could provide an important, although not completely model-independent, information about the intrinsic spectra of VHE $\gamma$-rays.

**Signatures of Intergalactic Pair Cascades.** The intergalactic absorption features, in the form of cutoffs or spectral modulations, depend on the product $u_e \times H_0$, thus formally they provide information about the Hubble constant as well [112]. However, the measurements of the absorption features alone cannot decouple $u_e$ and $H_0$. Separation of these two parameters requires more observables. In principle, this can be done by studying the spectral and angular characteristics of VHE radiation from the presumable pair halos [108] expected around the powerful extragalactic VHE sources as a result of electromagnetic cascades initiated by primary $\gamma$-rays in DEBRA. The radiation of the halo can be recognized by its distinct spectral and angular features which only weakly depend on the details of the central source. Therefore detection of a halo would give us two observables, i.e. angular and spectral distributions of the radiation, and thus would allow us to disentangle the two variables $u_e$ and $H_0$. Remarkably, since the apparent angular size of the halo around a source with known redshift $z_0$ is determined by the level of DEBRA at the epoch $z_0$, this allows an important study of the cosmological evolution of DEBRA by observing pair halos from sources at different redshifts. Also, detections of both the primary (point source-like and variable) and the halo (extended and steady) components of VHE $\gamma$-ray emission from extragalactic sources allow us to estimate the instantaneous and time-integrated VHE power of sources,
and thus to measure the total nonthermal energy released by individual extragalactic sources during their active phase (thought to be $\sim 10^6 - 10^8$ years).

Obviously, VHE radiation from pair halos might be detectable around many more objects than the ones presently active. The mapping and spectroscopy of extended pair halos is a difficult technical task, but it is feasible with the new generation 100 GeV threshold IACT arrays, provided that the total VHE luminosity of the central source at a distance $d$ exceeds $L_{\text{VHE}} = 10^{46}(d/1\text{ Gpc})^2\text{ erg/cm}^2\text{s}$ (see Fig. 15)

![Figure 15: Expected halo radiation fluxes integrated within 1° above 100 GeV, 250 GeV, and 500 GeV as a function of the source distance, calculated for two extreme ('Low' and 'High') levels of DEBRA. The assumed VHE luminosity of the central source above 10 TeV is $L_{\text{VHE}} = 10^{46}(d/1\text{ Gpc})^2\text{ erg/cm}^2\text{s}$.](image)

The formation of isotropic pair halos around the extragalactic objects requires intergalactic magnetic fields (IGMF) exceeding $10^{-12}$ G. At much weaker IGMF, which formally cannot be excluded, instead of detection of the extended and persistent isotropic halos, one should expect cascade radiation propagating almost rectilinearly from the source to the observer. Even so, the small deflections of the cascade electrons by the extremely weak magnetic fields may induce noticeable time delays of the arriving high energy photons, as far as cosmological distance scales are concerned. If such delays would be possible to distinguish from the intrinsic time structure of a compact variable source, this would a valuable tool for a probe of primordial intergalactic magnetic fields down to $\leq 10^{-15}$ eV.

Irrespective to the structure and strength of IGMF, the ensemble of all VHE sources in the Universe produce isotropic cascade $\gamma$-radiation. The spectrum of this component is rather insensitive to the spectrum of the primary VHE radiation. Furthermore, at low energies, $E \leq 100\text{ GeV}$, where the detection of the isotropic component of $\gamma$-radiation are available by space-based $\gamma$-ray instruments, the spectrum of the cascade radiation is only weakly sensitive also to the details of the spectrum and the flux of DEBRA. Therefore, the recent spectral measurements of the extragalactic $\gamma$-ray background by EGRET provide a robust constraint on the average VHE emissivity allowed in the Universe in form of of any VHE phenomena (e.g. $\gamma$-ray emission of AGNs or decays of hypothetical relic objects like topological defects\cite{37,114,115}) comparing the calculated cascade $\gamma$-ray background flux accumulated over the Hubble time with the measured diffuse flux at GeV energies\cite{37}: $L_{\text{VHE}} \leq (1 - 3) \times 10^{50}\text{ erg/s}$. In fact this upper limit could be interpreted also as a measure of VHE luminosity of the Universe as a whole, if one assumes\cite{116} that the hard EGRET spectrum is explained by the cascade component, initiated in the intergalactic medium by VHE $\gamma$-rays from AGNs, rather than by direct contribution of $\gamma$-ray emitting AGNs to the extragalactic diffuse background.
In conclusion, the recent results of ground-based gamma ray astronomy as well as exciting theoretical/phenomenological predictions show that the Universe likely to be well populated by a variety of TeV $\gamma$-ray emitters. The further study of the sky in VHE $\gamma$-rays by forthcoming powerful instruments promises a new path towards the understanding of the nonthermal high energy phenomena in the Universe.

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