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VERY HIGH ENERGY GAMMA ASTRONOMY: WHERE DO WE STAND AND WHERE DO WE GO?*

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VHE gamma ray astronomy is an exciting blooming field of fundamental research at the frontier between astrophysics and particle physics. The fundamental concepts, techniques and physics highlights of this new field are briefly reviewed.

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1. Introduction

Very High Energy (VHE) cosmic gamma rays ($E_\gamma >$ few GeV) are the highest energy electromagnetic radiation detected so far from our Universe. Although in principle their study could be just a branch of astrophysics as happens with the rest of electromagnetic radiation wavelengths, their study has been a subject developed by the astroparticle physics community. The main reasons for this fact are:

- The **instruments** needed are based on the concepts developed for high energy particle detectors. Their philosophy and principles differ substantially from the one of the rest of astronomical instrument although share with them the operation strategies.
- The **techniques** used to analyze and understand the data are the ones used in experimental particle physics analysis. The interpretation of the observations relies on the Monte Carlo simulation of the complex interaction of the cosmic rays with matter.
- The **physics** potential addresses questions on the frontiers of our most fundamental physics knowledge in addition to the questions more traditionally addressed by astrophysicists.

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VHE cosmic gamma rays are, so far, the highest energy detected messengers from the universe which are stable particles and are not deflected by cosmic magnetic fields allowing therefore to pinpoint, identify and analyze the source. Their study has opened the door of a new branch in astronomy: the VHE gamma ray astronomy.

Two different kinds of information can be obtained from the study of VHE gamma rays:

- **The production mechanisms at the source.** VHE gamma rays are produced in the most energetic and violent phenomena in the universe:

  (a) Through the conversion of the strongest gravitational potential energies into particle accelerations near accreting compact objects (Black Holes, Neutron Stars, ...), providing a unique tool to probe extreme gravitational interaction;

  (b) In big explosions occurring during the evolution of some stellar systems (Supernovae, Hypernovae, ...) through the acceleration of particles in shock waves in ultrarelativistic plasma;

  (c) Through the annihilation or decay of very massive or energetic objects, such as dark matter, very massive particles at unification scales, relics of cosmological phase transitions, primordial black holes, ... providing a tool to search for new, massive particles and/or objects.

  The two first mechanisms constitute real Cosmic Accelerators and can produce gamma rays through two basic processes:

  (a) Hadron acceleration, in which gamma rays are mainly produced in the decay of the neutral pions produced in the hadronic interaction of the accelerated protons with target surrounding matter. In this interaction also charged pions are produced and their decay yield high energy neutrinos. Therefore, hadron accelerators are good candidates for being high-energy neutrino sources. On the other hand, they may be invisible (dark sources) when observed in other electromagnetic radiation wavelengths.

  (b) Electron acceleration, in which the electrons do emit synchrotron radiation in the magnetic field surrounding the source and by inverse-Compton scattering either with that synchrotron photon population (self-Compton) of with ambient photons, can produce upscatter very high energy gamma rays. In these sources the SED (spectral energy density) shows usually two correlated bumps, one at low energies due to the synchrotron emission and one at high energies due to the inverse-Compton process. Therefore the source is visible at different electromagnetic radiation wavelenghts and is not expected to be a source of high-energy neutrinos.

The VHE Gamma Rays are genuine messengers of the very-high-energy, non-thermal population of our Universe.

- **The propagation in the cosmic medium.** VHE are, so far, the most energetic messengers reaching us through a determinable path and this allows to use them to probe the Extragalactic Background Light (EBL), the expansion of our Universe and to explore the structure of space-time:

  (a) At long distances, taking advantage of the fact that VHE gamma ray sources may be found at cosmological distances;

  (b) At short distances, since they probe space-time at the highest detectable energies.

This potentiality is the main reason why the VHE gamma ray astronomy is an exciting blooming field of fundamental research in the starting stage and, therefore, mostly observation-driven at present.

2. The detection techniques

The Gamma Ray sources observed so far show typically in the VHE domain:

- Sharp power-law intrinsic spectra (see Fig. 1):

$$d\Phi/dE = AE^{-\alpha}\,,$$

  with $\alpha = O(2.3–2.7)$. Therefore, the fluxes decrease very quickly with increasing gamma ray energy.

- Some of them have strong and fast time variations (see Fig. 2).

Therefore, to detect cosmics VHE gamma rays one needs very large effective areas and/or long exposures.

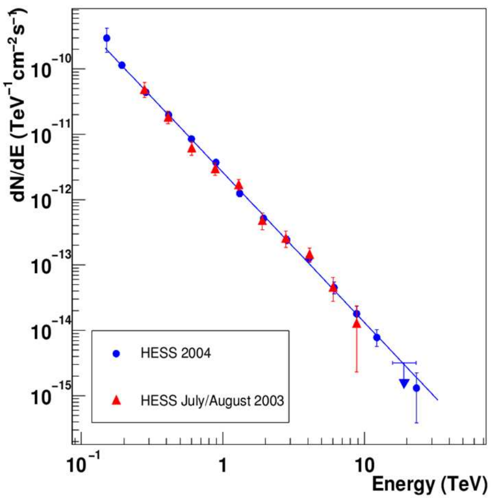

Fig. 1. Energy spectrum of the Galactic center as measured by H.E.S.S.

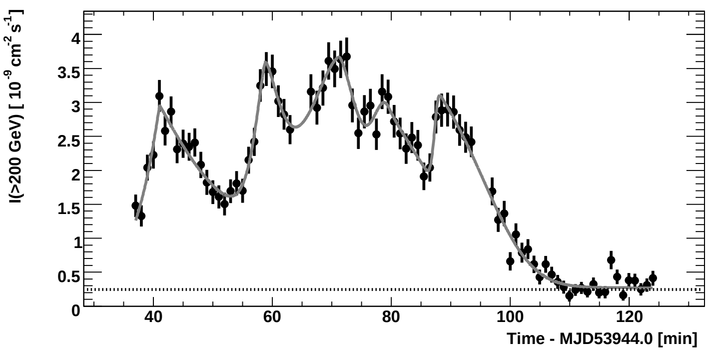

Fig. 2. Light curve of the blazar PKS2155-304 as detected by H.E.S.S. during a flare on July 28, 2006.

Fig. 3 sketches the three different detection techniques used so far for different gamma ray energy ranges:

- $0.1 < E_\gamma <$ **few GeV**. In this energy range the cosmic gamma rays are absorbed in the atmosphere and no useful information reaches ground level. The observation is done by using gamma ray detectors on satellites. These instruments provide a direct primary particle detection and very low background, although the effective area is small ($\simeq 1\mathrm{m}^2$) and this limits the actual observable energy range below few hundreds of GeV due to very low counting rates.

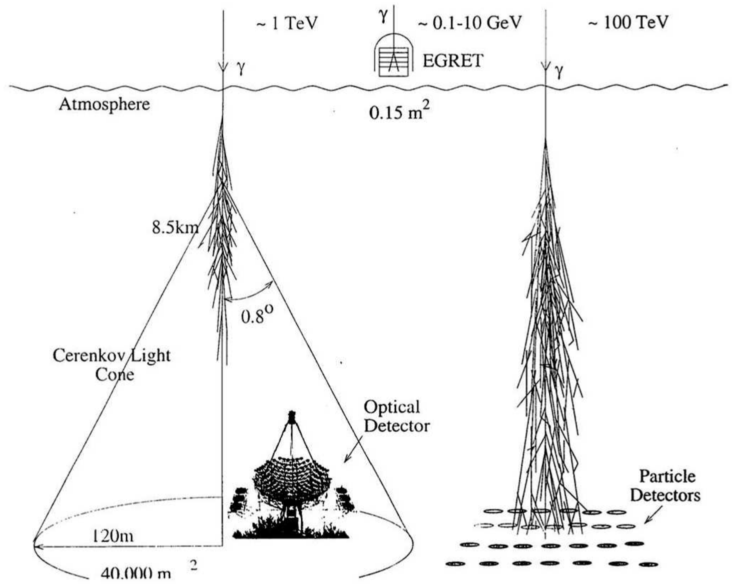

Fig. 3. Different detection techniques to observe cosmic gamma rays.

- **few tens of GeV** $< E_\gamma <$ **few tens of TeV**. In this energy range, the cosmic gamma rays initiate ultrarelativistic electromagnetic showers in the atmosphere capable of producing Cherenkov light flashes. The observation is done by using telescopes able to catch the image of the Cherenkov light flash on the ground. These special telescopes are called IACTs (Imaging Air Cherenkov Telescopes). Although IACTs are optical telescopes, their actual characteristics differ drastically from the requirements of the "conventional" optical telescopes: on the one hand the optical quality needed to properly record the Cherenkov light is much worse than the one required in optical telescopes due to the intrinsic fluctuations in the air showers, while on the other hand, the time response of the light-detecting camera in the focal plane for IACTs is much more stringent than for "conventional" optical telescopes due to the need to resolve a $O(1\ \text{ns})$ Cherenkov light pulse within an intense continuous background light. These instruments provide a secondary detection and are prone to have large backgrounds, mainly coming from night-sky-light and hadronic showers initiated by cosmic protons and ions, which have to be severely reduced to extract the signal, but at the same time, provide a huge effective area ($> 10^4$ m^2) and therefore can provide observations in the range from few tens of GeV to few tens of TeV.

- **few tens of TeV** $< E_\gamma$. In this energy range, the atmospheric shower initiated by the cosmic gamma rays reaches the ground and can, in principle, be detected by extended particle detectors or arrays of particle detectors distributed on the ground in a large area. Again, the observation is indirect and the backgrounds, mainly coming from hadronic showers as before, have to be drastically reduced.

The first two techniques have proven to be successful by a pioneering generation of detectors on satellites (EGRET) and on the ground (Whipple, HEGRA, Cangaroo, CAT). The last technique has been explored already by few experiments and is just now starting to prove its capability in detecting gamma ray sources.

These installations left a virtually unexplored energy gap (within few GeV and few hundred GeVs) in the frontier between the satellite and the ground-based observations. This unexplored energy region seemed to be specially interesting because there was a well populated sky-map of sources detected by EGRET (but more than half of them still unidentified due to poor angular resolution) below around 10 GeV (see Fig. 4) while just a handful of sources observed by the existing IACTs above 300 GeV (see Fig. 5).

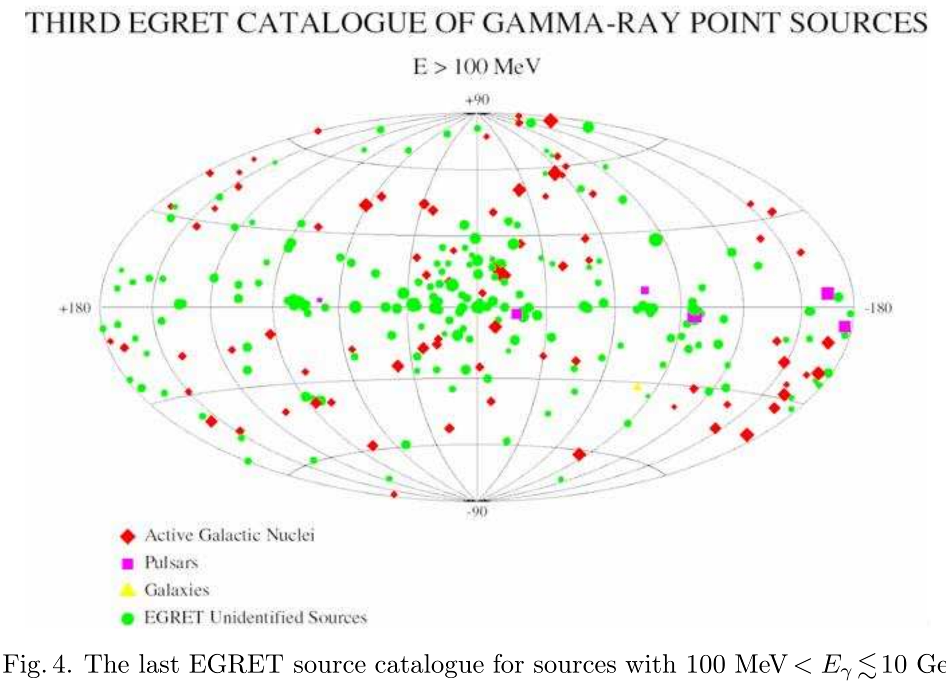

Fig. 4. The last EGRET source catalogue for sources with 100 MeV $< E_\gamma \lesssim 10$ GeV.

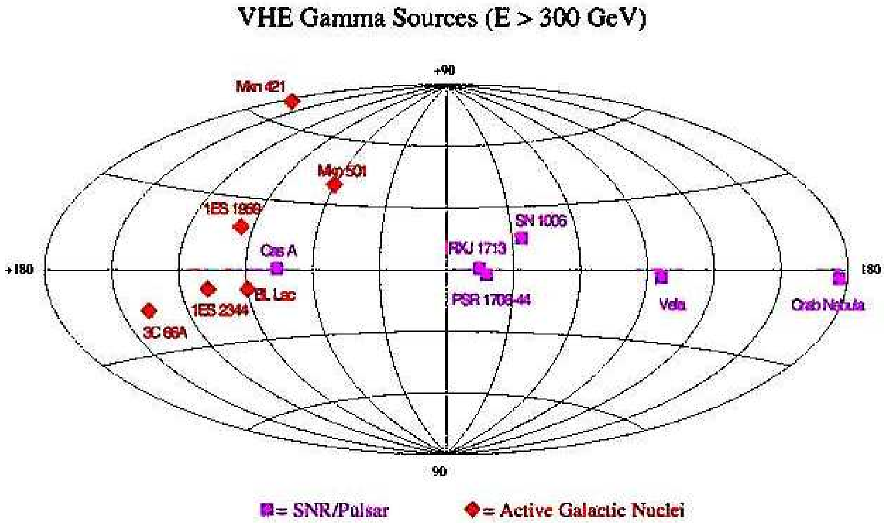

Fig. 5. The IACT source catalogue for $E_\gamma > \sim 300$ GeV in 2004. Some of these sources were still dubious because of the limited significance of their observation.

The reasons for this "disappearance of sources" were expected to be twofold: on the one hand, the intrinsic source cut-offs related the energy limits on the accelerating mechanisms, and on the other hand the absorption of VHE gamma rays traveling cosmological distances in their path to the Earth due to the $\gamma\gamma$ interaction with the EBL. Therefore, the study of VHE gamma ray sources in this energy interval was expected to provide strong constrains in the models describing the acceleration mechanisms for some sources and/or some means to measure the EBL and the cosmological parameters.

The basic concepts behind the Cherenkov Telescope technique are the following: VHE cosmic gamma rays interact in the atmosphere producing electromagnetic showers which reach their maximum development at about 10 kilometers height. The ultra-relativistic electrons and positrons in these showers emit Cherenkov light within a cone of typically about 1 degree aperture and therefore, making a light spot on the ground of about 150 meters radius. For this reason, the area illuminated on the ground is of about 50000 m^2 (see Fig. 6). This light flash lasts typically few nanoseconds and therefore, although it might be very dim, it might be distinguishable from the night sky light background if a telescope with the proper design is placed within the light spot.

The main characteristics needed for a Cherenkov Telescope are a large light collector and a fast and sensitive camera able to detect few photons in few nanoseconds. Nevertheless, another crucial characteristic is the capability of discriminating the Cherenkov flashes produced by gamma rays from those produced by hadrons, few orders of magnitude more frequent. That is achieved with a fine pixelization of the camera allowing imaging the shower development through its Cherenkov light emission. Typical gamma ray images have an elliptical shape and can be adjusted with a second moment analysis to the so-called "Hillas parameters" while hadronic images, due to the rich shower structure in hadronic interactions have a more complex image shape comprising islands from secondary interactions and pieces of muon rings.

One of the most powerful image parameters in discriminating gammas from hadrons is the so-called "alpha", given by the angle between the ellipse major axis and the direction linking the camera center and the ellipse center. For Cherenkov flashes coming from the telescope's pointing direction, "alpha" should peak at zero degrees. Given the fact that the arrival direction of hadronic cosmic rays is quite randomized by the action of galactic magnetic fields, their "alpha" distribution is, instead, flat.

Another concept which helps in the reduction of the hadronic background and hence, improves the sensitivity is the use of a system of telescopes within the Cherenkov light pool to provide simultaneous viewpoints of the shower development. This helps in addition in improving the energy and angular resolution.

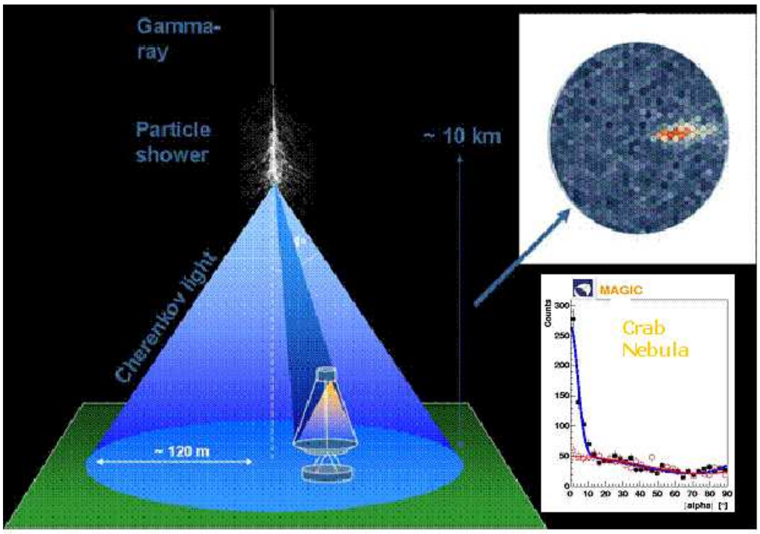

Fig. 6. Detection concept for a Cherenkov telescope. See text for an explanation.

3. Today

Since 2004 new installations started successively operating:

- **Satellites.** Three different projects are in different phases of development: AMS, Agile and GLAST. Out of these three the one more specifically designed to try to make a drastic step forward in VHE gamma ray astronomy and also to cover the energy gap is the GLAST satellite, which has been launched in June 2008 and should release soon its first data. It should provide an improvement of about one order of magnitude over EGRET in all aspects (flux sensitivity, angular resolution and energy resolution), reaching an energy threshold of about 300 GeV. GLAST will perform a long-exposure all-sky survey and is expected to produce a catalogue with thousands of new VHE gamma ray sources.

- **IACTs.** Without any doubt, since 2004 these installation have made a real revolution in the field and because of that we are going to discuss them, in greater detail.

With the experience acquired with the first generation of Cherenkov telescopes, the main goals motivating the design of the new generation were to:

- Reduce the energy threshold. Since all the sources show power law spectra, reducing the energy threshold should allow to observe larger fluxes. That requires the use of larger Cherenkov light collectors and therefore, the construction of large telescopes.

- Improve sensitivity. By improving the background rejection one can improve the analysis sensitivity and therefore increase the source discovery potential. As already mentioned, the use of telescope arrays with the proper spacing provides an improved gamma–hadron separation.

These two concepts are complementary but, within a limited budget, might be exclusive. The very large telescope design has been the main driving concept for the MAGIC telescope proposal while the telescope array was the option taken by the rest of proposals for the new-generation instruments (CANGAROO-III, H.E.S.S., VERITAS).

In addition, other important design concepts which characterize the new generation of instruments are:

- The use of wide-field cameras. This provides survey capability, the opportunity of having serendipitous discoveries and also the possibility of performing source morphology studies. For instance H.E.S.S. has a camera with 5 degree field-of-view.

- The use of a isochronous reflector together with a fast digitization. This provided the possibility of using the Cherenkov photon arrival time for improving further the gamma–hadron separation. For instance, MAGIC has reached sub-nanosecond timing.
- The use of a light telescope structure. This enables a fast transient phenomena follow-up, as is needed in the case of Gamma Ray Busts. MAGIC has, for instance, less than 20 second repositioning time.

These concepts have been the key design elements implemented in the new generation instruments which are the following (see Fig. 7):

- H.E.S.S. is presently a telescope array composed by four 12 meter diameter telescopes placed at Namibia, which started regular operation in 2004 [1].
- MAGIC is presently a single, 17 meter diameter telescope installation placed at the Canary Islands, which started regular operation in 2005 [2].
- CANGAROO-III is a telescope array composed by four 10 meter diameter telescope placed at Australia, which started operation in 2005 [3].

Fig. 7. The installations of the second generation of Cherenkov telescopes, which have made a real revolution in the field.

• VERITAS will be a telescope array composed by four 12 meter diameter telescopes placed at Arizona, which started operation in 2006 [4].

These four installations, out of which two are in the northern hemisphere and two in the southern, given their different latitude do provide good time coverage around the globe for source follow-up.

The huge success of these installations, specially of the European H.E.S.S. and MAGIC, can be judged from the about 80 sources already observed by those IACTs above 30 GeV (see Fig. 8) [5]. Nevertheless, the success is not just due the huge increase in the number of sources but also due to the extremely high quality detections allowing unprecedented detailed studies which has unveiled new populations of sources and new phenomena.

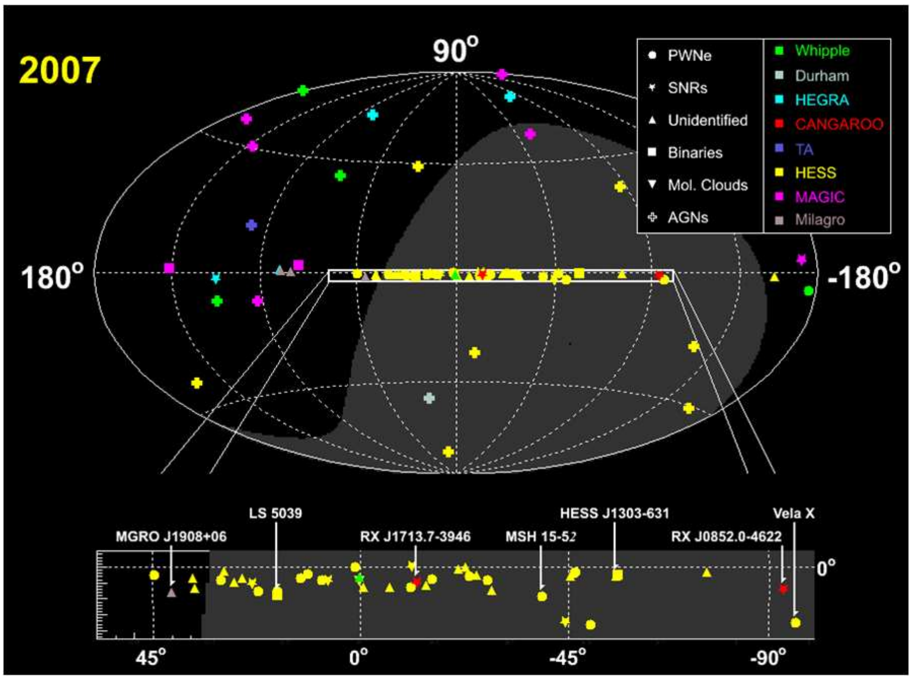

Fig. 8. The IACT source catalogue for $E_\gamma >\sim 30$ GeV in 2007.

3.1. Some scientific highlights and observations

Since the start of their operation, the new installations which are already active have made observations leading to a series of scientific results which are the basis of the claim for a real revolution in the field. Some of the main scientific highlights coming from these observations are the following:

- Discovery of many new Galactic sources by H.E.S.S.: H.E.S.S. has performed a Galactic Plane survey extending from −60 to 60 degrees in galactic longitude and + − 3 degrees in latitude expending several hundred hours of observation. This scan allowed the discovery of a plethora of new galactic sources (see Fig. 9). Some of the sources have been observed afterwards to confirm the signal and perform detailed studies. Most of these new sources are shell-type Supernovae and pulsar-wind Nebulae although still many remain unidentified and some of them belong to a new class of objects observed for the first time emitting in gamma rays [1].

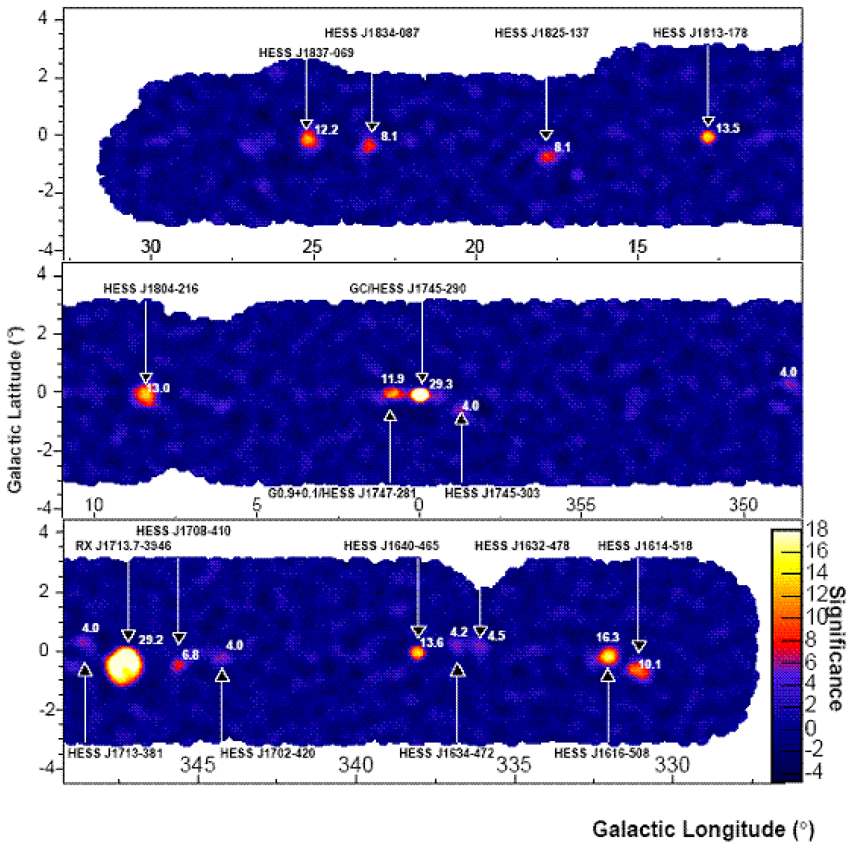

Fig. 9. The sources detected by the H.E.S.S. array during the scan of the Galactic plane. For each source, the significance of the detection is quoted.

- Detailed studies of Galactic sources by H.E.S.S., MAGIC and VERITAS: The quality of the observations for some of these sources is such that studies with unprecedented detail and accuracy have been possible. For instance, for some of the Shell-type supernovae, morphological studies have been carried out allowing not just the detailed study of the correlation of the emission region shapes with the observation on other wavelengths (see Fig. 10) but also the study of the emission spectra in different regions of the Supernova shell. This high quality of the observational data allows a precise check with the theoretical models and should allow an unprecedented understanding of the source physics [1].

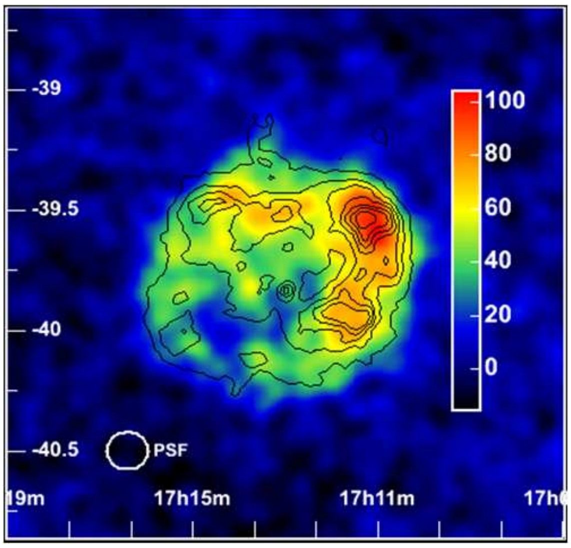

Fig. 10. The Shell-type supernova remnant RX J1713-3946 with the number of gammas observed by H.E.S.S. in a color scale superimposed to the X-ray observation contours.

- Discovery of new classes of Galactic VHE gamma ray emitters by H.E.S.S. and MAGIC: a handful of the new Galactic sources discovered by H.E.S.S. and MAGIC correspond to new classes of VHE gamma ray emitter such as for instance X-ray binary systems in which a black-hole or a pulsar orbits around a massive star and the gamma rays are produced either due to the accretion of material from the massive star into the black hole companion (Microquasar) or the collision of the winds of the massive star and its pulsar companion.

- Detailed study of the Galactic Center by H.E.S.S. and MAGIC: The galactic center has been independently observed by H.E.S.S. and MAGIC (in this case at large zenith angle) providing spectrum measurements in nice agreement which contradict the measurements previously published by the CANGAROO Collaboration [2]. The observed signal is consistent with point-like emission from Sgr A* (with a slight hint for extension), is steady from year to minute scales and the spectrum is very well fitted by an unbroken power law with index 2.3 from about 150 GeV up to almost 30 TeV, which rules out most of the possible interpretations in terms of Dark Matter annihilation.

- Discovery of around 15 new AGN by H.E.S.S., MAGIC and VERITAS. That AGN list contains sources of all the different kinds proposed in the "Blazar sequence" classification and even a Flat-Spectrum-Radio-Quasar (FSRQ). The unprecedented large distance to some of these new AGNs (for instance the FSRQ 3C279 discovered by MAGIC is at $z = 0.536$) has allowed the use of the measured gamma ray spectra to place already strong constraints on the Extragalactic Background light (EBL) density by unfolding the expected effect due to the gamma–gamma absorption [2]. The conclusions of the H.E.S.S. and MAGIC Collaborations agree in pointing to a more transparent universe to gamma rays that predicted by most of the theoretical models and with very small EBL densities with saturate the lower limits provided by the determinations obtained from galaxy counts.

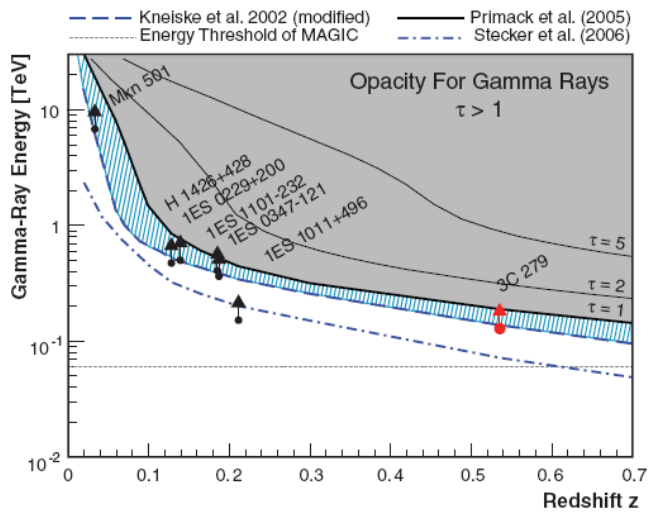

Fig. 11. The constraints in the Extragalactic Background Light coming from the MAGIC observation of the Flat-Spectrum-Radio-Quasar 3C279 at redshift $z = 0.536$.

- High time-resolution study of AGN flares by MAGIC and H.E.S.S.: MAGIC has observed an intense flare of the well-known Mkr501 Blazar which reached an intensity equivalent to 4 times the one of the Crab Nebula and H.E.S.S. recorded a huge flare of the Blazar PKS2155 (see Fig. 2). Due to the high sensitivity of these instruments, the rate of gamma rays recorded was so high that, for the first time, bins of 2 minutes in the light curve have been possible allowing an unprecedented accuracy in the study of the time variation of the emission. This data provides already the strongest constraints in the light speed dispersion relations predicted in Quantum Gravity theories.

- Prompt GRB follow-up by MAGIC: The extremely fast repositioning of the MAGIC telescope has allowed already the follow-up of a several Gamma Ray Burst. For instance GRB050713a was observed only 13 seconds after the reception of the alert provided by the SWIFT satellite and only 40 seconds after the actual gamma ray burst happened. MAGIC observed the GRB in coincidence with the BAT and XRT instruments and while the X-ray activity was still high (see Fig. 12). So far no significant gamma ray emission has been detected in the recorded MAGIC data and this provides already strong constraints in many GRB models.

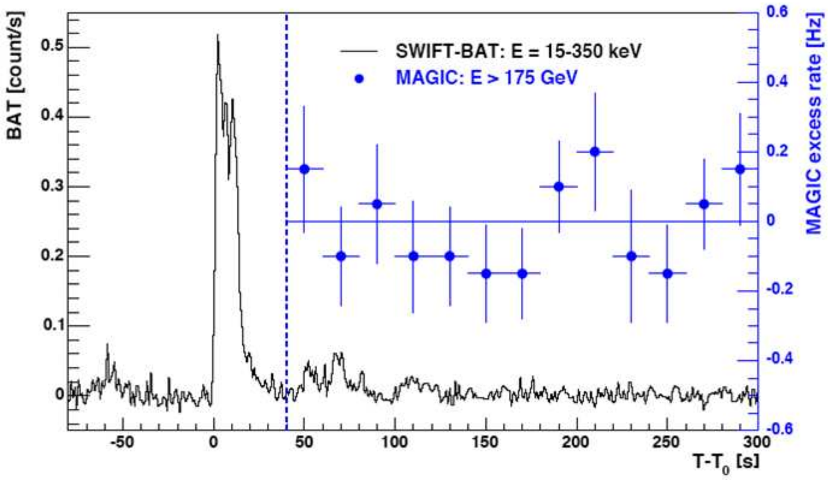

Fig. 12. MAGIC follow-up of the Gamma Ray Burst GRB050713a.

- A new trigger scheme has allowed MAGIC to observe gamma rays from the Crab pulsar for the first time in the energy domain in which the different pulsar emission mechanism models predict the existence of a strong cutoff in the energy spectrum. The Crab pulsation has been detected above and energy as low as 25 GeV, a real breakthrough in low-threshold measurements which will certainly have an unpredictable large impact in this field.

4. Tomorrow

In the coming years further developments are already on the way which will boost even further the field:

- The GLAST satellite was successfully launched in June 2008 and after a short commissioning will start releasing data already after the summer 2008. It should discover thousands of new HE sources and the LAT instrument, covering an energy range between 20 and 300 GeV should provide overlap with the observations of the Cherenkov telescopes.

- The MAGIC Collaboration is completing the construction of a new 17 meter diameter telescope with improved camera, digitizers and mirrors, which will be inaugurated in September 2008 and should produce new results already in 2008 and transform MAGIC into the installation with the lowest energy threshold and the largest sensitivity worldwide (see Fig. 13) [2].

Fig. 13. The MAGIC-II telescope, which will be inaugurated in September 2008, with MAGIC-I at the rear.

- The H.E.S.S. Collaboration is already building a giant 28 meter telescope to be placed at the middle of the H.E.S.S. array by the end of 2009 boosting the response at low energies [1].

5. The near future: Conclusions and outlook

Just ten years ago, in 1995, just three VHE gamma ray sources were known (Crab, Mkn421, Mkn501). Since then, sources were discovered by the instruments of the first generation at a rate of about one new source per year and up to 2003 about 12 sources were detected (although not all of them were confirmed). Since the start of the operation of the new generation of Cherenkov telescopes, the situation has made a quantitative and qualitative revolution. Now the sky is already populated by as many as 80 VHE sources and many others have already tentative detections which should be confirmed in the coming months. Many more new VHE sources have been discovered in the last few years as in the previous 20 years... and likely many more are just around the corner! But not just the number of sources has increased drastically; also the quality of the data recorded has improved dramatically enabling studies with unprecedented precision in fluxes, spectra, morphology and light curves and unprecedented short follow-up times. This big revolution is occurring in VHE gamma ray astronomy due to the fact that the new generation of Cherenkov telescopes is yielding outstanding results, even beyond expectations, and are establishing VHE gamma ray installations as astronomical observatories rather than as experiments: VHE gamma ray is now consolidating as a solid new astronomy.

But this is not the end of the story. The spectacular astrophysics results from current Cherenkov instruments have generated considerable interest in both the astrophysics and particle physics communities and have spawned the urgent wish for a next-generation, more sensitive and more flexible facility, able to serve a large community of users.

The answer of the whole European VHE gamma ray community together to this wish is the "Cherenkov Telescope Array" (CTA) [6]. CTA will be an advanced facility for ground based very-high-energy gamma ray astronomy, based on the observation of Cerenkov radiation. It builds on the mastering of the Imaging Atmospheric Cherenkov Telescope technique developed by the H.E.S.S. and MAGIC installations. From the successes of H.E.S.S. it exploits the concept of telescope arrays and stereoscopic analysis for improving the current sensitivity by one order of magnitude. From the success of MAGIC it exploits the use of large telescopes to attain the lowest possible threshold. Both approaches have proven to be extremely successful for gamma rays of energies above few tens of GeV and have wide-open a new window in astronomy: the detailed study of the universe at the largest energies to study the most extreme astrophysical phenomena and fundamental physics.

The 3 main wishes of the European VHE gamma ray community to be fulfilled by CTA are (see Fig. 14):

1 A wide energy coverage: four decades, from 10 GeV to 100 TeV.

2 A sensitivity at least one order of magnitude better than any existing installation: better than 1 miliCrab at the intermediate energies.

3 Two observatories for all-sky monitoring capability: a northern observatory with emphasis on extragalactic studies and a southern one mainly for galactic studies.

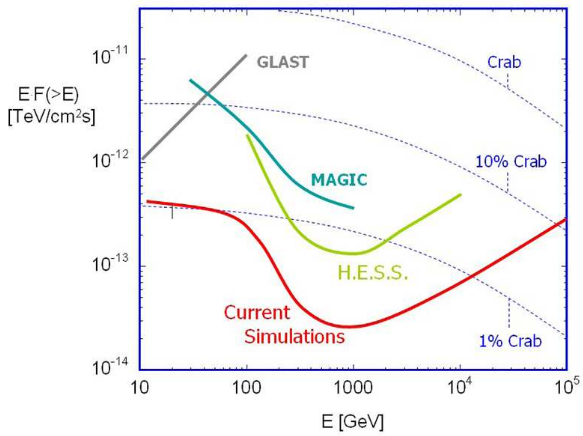

Fig. 14. The goal sensitivity of the CTA installation.

This facility will consist in an array of several tens of Cherenkov Telescopes probably of two or three different sizes: few large telescopes in a compact configuration for the lowest threshold, few tens of mid-size telescopes for the high-sensitivity intermediate-energy region, several tens of small telescopes spread in a large area for the for the highest energies (see Fig. 15).

CTA may discover and study in detail around thousand sources and shall be in operation while GLAST is still active since both installations nicely complement each other.

We are at the down of a golden age in VHE gamma ray astronomy which has started with a brilliant present and has an exciting and extremely promising opportunity open for new ideas and developments in the near future.

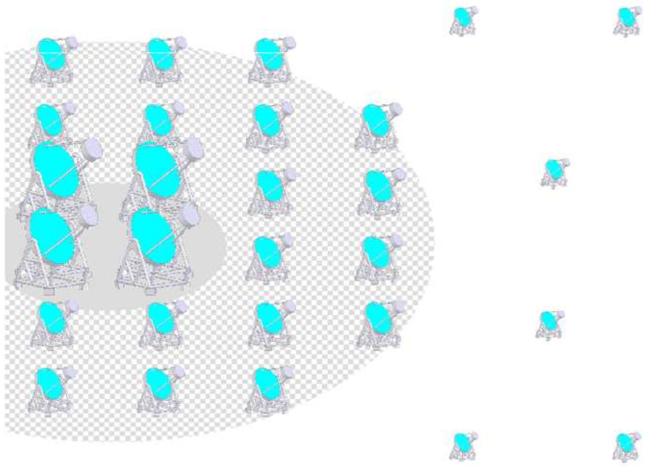

Fig. 15. A sketch of the possible layout of one of the CTA sites (not to scale).

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